सामिप्रवाहकोपकरणानि

SEMICONDUCTOR DEVICES

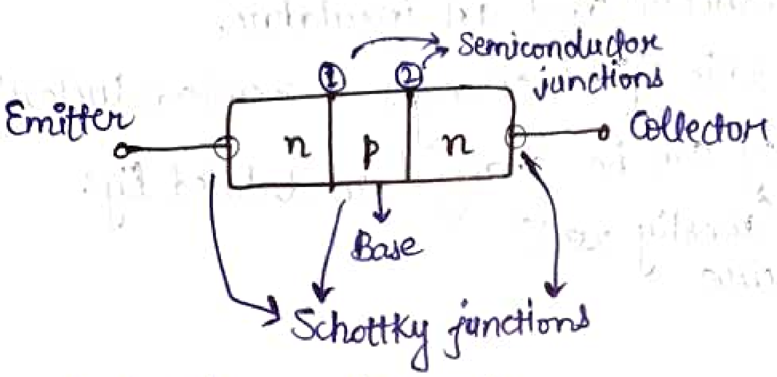
08-01-2024

SEMICONDUCTOR

→ Before transistor → Vaccum tube

Books
- Solid State Electronic Devices by Ben G. Streetman
- Semiconductor Physics & Devices by Donald A. Neamen
- Physics of Semiconductor Devices by S. M. Sze & Kwok K. Ng

Transistor
↳ Solid state
↳ A small voltage at the base terminal can control or switch a much larger current b/w the conductor and emitter terminals.



E-B : forward biased
B-C : reverse biased

11-01-2023

The Semiconductor Revolution

Moore's Law I : Device downsizing

→ With the passing years → Power consumption ↓
→ Speed ↑
→ Size ↓

Integrated Circuit : Different elements which perform different tasks are on a single chip.

Scaling : Reduction in the size of a transistor.
Microprocessor : Does computation.
Turn around time : Time difference b/w getting o/p and giving i/p.

Moore's Law II : chip density

↳ The no. of transistor on a single chip gets doubled every 18 months

→ The rise of Information and communication by 'light'.

↳ Compound Semiconductor Laser

↳ Optic fiber.

Semiconductor :

↳ A semiconductor is a material that has an electrical resistivity b/w that of a conductor and an insulator.

↳ An external electric field changes a semiconductor's resistivity.

↳ Their conductivity can be changed/modulated by:

- doping (mostly used)
- temperature
- voltage
- light
- Pressure

Devices :

Diode, Transistor, MOSFET } Electronic devices

LED, LASER, Solar cell } Opto-electronic devices

#	III	IV	V
	^{5}B	^{6}C	^{7}N
	^{13}Al	^{14}Si	^{15}P
	^{31}Ga	^{32}Ge	^{33}As
	^{49}In		^{51}Sb

→ Elemental semiconductors : Si, Ge } mostly used semiconductor due to abundance

↓

extracted from Silica (SiO_2)

→ Compound semiconductors : (or Binary semiconductors) AlP, AlAs, GaP, GaAs, InP

→ $\boxed{\text{Ternery \& Quertornary semiconductors}}$

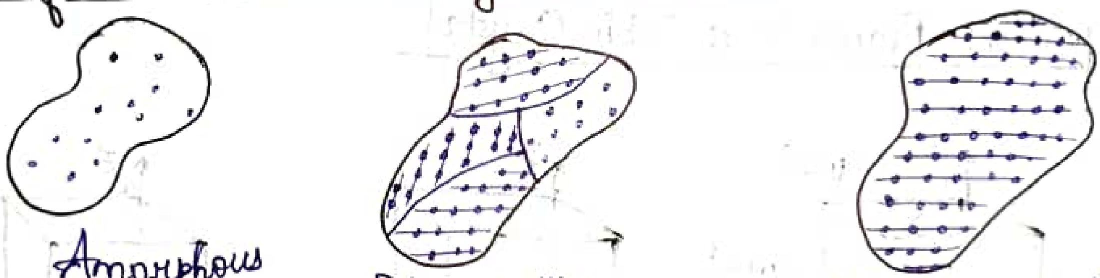
→ Silicon is prepared by Czochralski process.
From this process, we get silicon ignot ; we slice it and get Si wafers.

Metal Si $\xrightarrow[\text{Crystallization}]{\text{Single}}$ Silicon ignot $\xrightarrow{\text{slice}}$ Si wafers/Substrate

→ Si wafer or substrate is the base to form all the semiconductor devices.
↳ Produced in clean rooms.
↳ "Clean room" based on dust particle per meter cubic of air.

class 10,000
class 1,000
class 100
class 10
class 1
Class 0.1

Types of Solids Based on Crystal Structures



Amorphous

Polycrystalline

Single-crystalline
↳ most difficult to manufacture
↳ best quality

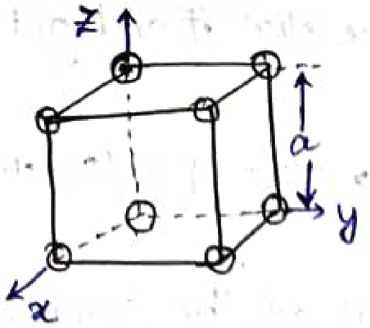
→ Si can exist in all crystal structures.

Lattice: Atoms arranged in order.

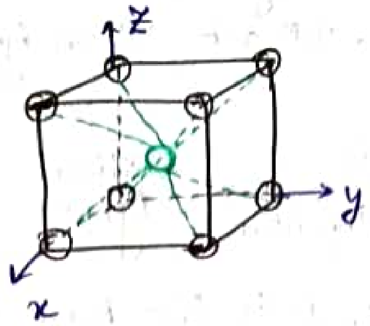
Unit cell: A small volume of the crystal that can be used to reproduce the entire crystal.

Primitive cell: The smallest unit cell which can be repeated to form the lattice.

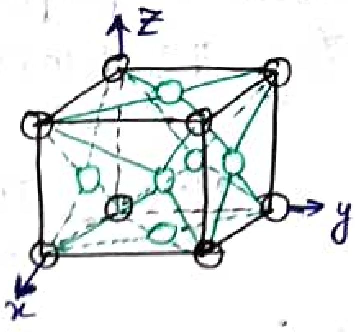
→



Simple Cubic (SC)

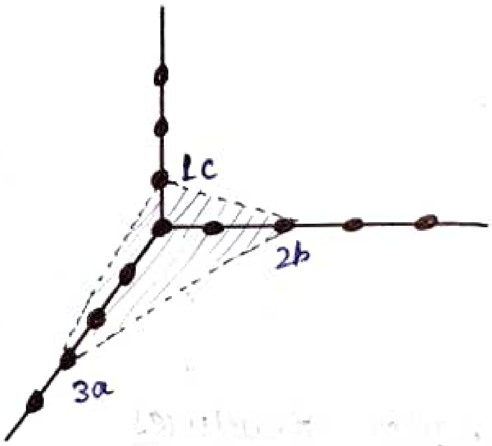


Body-centred cubic (BCC)

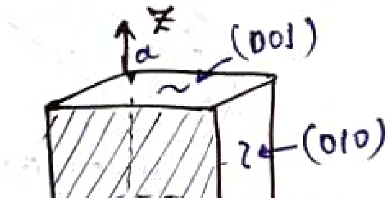


Face-centred cubic (FCC)

→ <u>Crystal Planes and Miller Indices:</u>

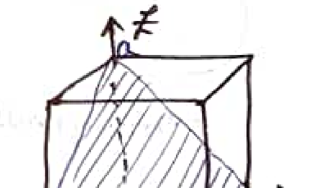


→ <u>Important Planes in a Cubic Crystal</u>



(100)

(110)



(111)

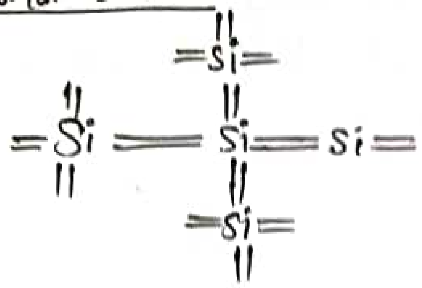
<u>Semiconductor Devices:</u>

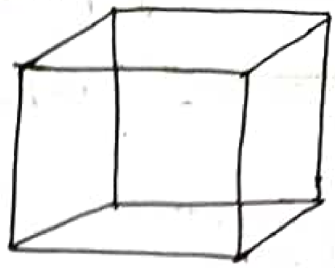
Voltage (i/p) ⟶ Current (o/p)

→ Current : flow of e^- in a plane in crystal structure.

→ Force on e^- will be different on moving in different planes in different cubic structures.

Diamond lattice:

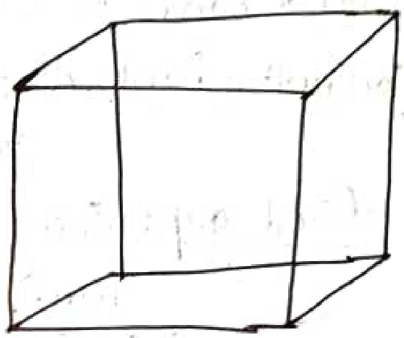




$^{14}Si : 1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^2$

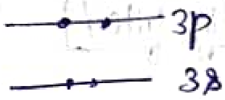
Zinc-blende or Sphalerite Lattice:

Ga. As : Binary / 3-5 semiconductors
III V



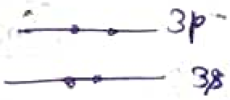
→ Isolated Si atom

Si — no force acting on the atoms



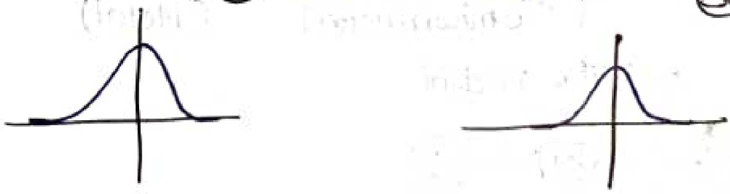
Another isolated Si-atom

Si

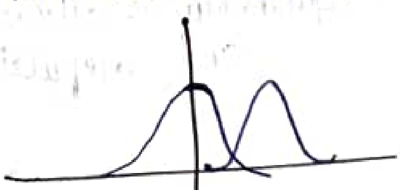


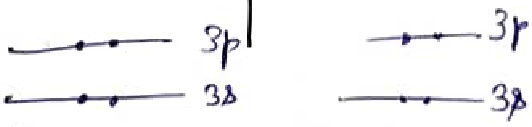
Wave function: Square of it tells the probability of finding the e⁻ at a location

Si Si



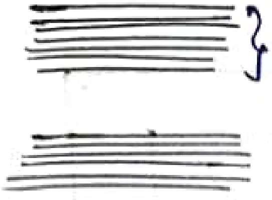
On bringing the atoms closer,





Now, the discrete energy levels of 3p and 3s will divide into levels because of Pauli's exclusion principle.

Then, these levels will become bands.



"Energy gaps"

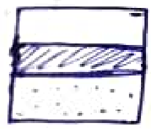
$1s^2 \mid 2s^2 \mid 2p^6 \mid 3s^2 \mid 3p^2$

"forbidden energy gap" or "Band gap (E_g)" ⇝ unit : eV

<u>Valence Band</u>: At 0K, the lowest energy band which is full of e⁻s.

<u>Conduction band</u>: At 0K, the lowest energy band which is completely empty of e⁻s.

<u>Band gap</u>: Energy difference b/w conduction band and valence band.
↳ Order of 0.4eV – 4eV.



Conduction band

(Insulator)	(Semiconductor)	(Metal)
Empty	Empty	Partially filled
$E_g > 6eV$	$E_g = 0.4-4eV$	
Filled	Filled	Filled

Valence band

a_0 : lattice constant

Si — Si — Si

+ve nucleus
-ve nucleus

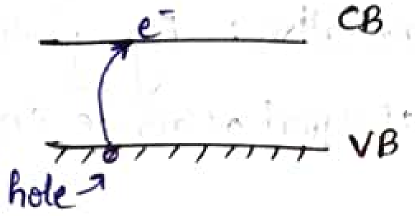
equilibrium in attractive forces and repulsive forces.

12-01-2024

→ For metals, $E_g = 0\,eV$
For semiconductors, $E_g = 0.4 - 4\,eV$
For insulators, $E_g > 6\,eV$.

→ Free electron: e^- present in conduction band
↳ not free but almost free or quasi-free e^-
↳ e^- present in valence band.

Breaking a bond:



Band gap: Energy required to break a bond (or covalent bond).
For Si, band gap = 1.1 eV.

Excitation: Process of moving the electron from VB to CB.

Lifetime of electron: Time for which e^- sits in CB after moving from CB. After that, e^- again falls back to VB.

De-excitation: Process of moving of the e^- from CB to VB.

Classification of Semiconductor based on the energy of e^- released during de-excitation:

① Direct band-gap: Released energy is EM radiation.

② Indirect band-gap: Released energy is heat (or thermal energy).

→ On giving energy more than E_g, e^- climbs up CB, then comes down at CB edge to attain stability.

CB Edge: Bottom-most point of CB

→ Hole resides at VB edge.

VB Edge: Top-most point of VB.

Generation: Process of generating of mobile carriers.

Recombination: Process of combining of e^- with vacancy and forming covalent bond again.

→ There are two types of excitation:

① **Photoexcitation/Photogeneration:** By giving light.

↳ e^- absorbs photons of equal or more energy than E_g and climbs upto CB.

② **Thermal generation:** By giving heat.

Avg. thermal energy $= \frac{3}{2}KT$, T: absolute temp.
K: Boltzmann constant.

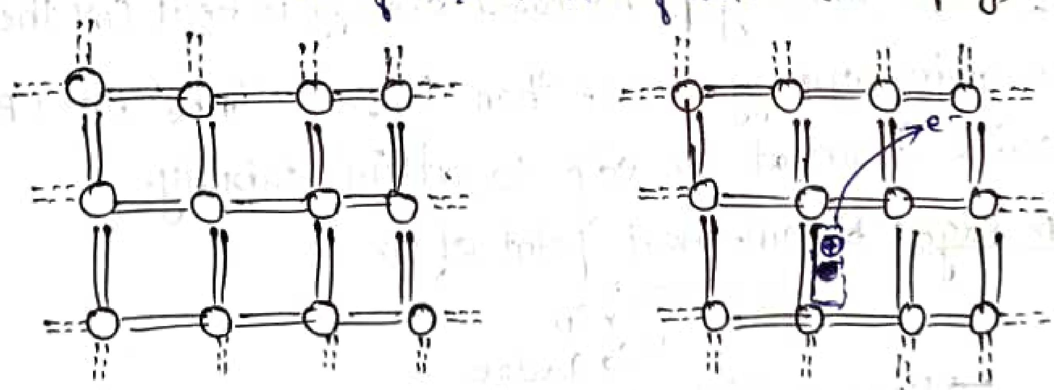
15-01-2024

↳ Both e^- generation methods generate equal no. of electrons and holes.
- ↳ generated in pairs
- ↳ called as EHP (electron-hole pair).
- ↳ Known as thermal carries (in case of thermal generation).

Voltage generation

→ **Doping:** No. of charge carriers can be precisely controlled.

↳ To get no. of holes > no. of e^-s (p-doping)
or
no. of e^-s > no. of holes (n-doping)



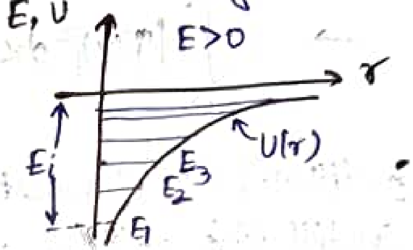
2-D representation of covalent-bonding in a semiconductor at T=0K. ⇝ Bond picture or bond diagram

Semiconductor: Periodic arrangement of atoms (called as lattice)
↳ Distance b/w atoms: lattice constant
↳ e^-s move in periodic lattice generating current.

Behaviour of electrons inside a lattice
(Properties displayed by microscopic Particles)
Electrons inside various potentials:

$$V(r) = -\frac{e^2}{4\pi\epsilon_0 r}$$ ⇝ lattice potential
⇝ different in different directions.

Energy quantization: Electrons can take only discrete energy values (not continuous).
Eg. $1s^2, 2s^2, 2p^6, 3s^2, \ldots$



→ Before the discovery of electrons, protons, etc., heavenly objects' behaviour were discussed using classical mechanics.
Newton's law like $F = m \times a$.
Then, microscopic particles were studied, understanding them through the Newton's law.

Photoelectric Effect
↳ Expected more electrons ejection by giving more intensity of light, but it didn't happen.
↳ Newton's law was not applicable.
↳ Replaced by wave mechanics / Quantum mechanics.

Schröndinger's Wave Equation
We use parameter called wave function, $\psi(x)$.
$\psi(x)$: Wavef^n: Doesn't represent anything physical.
$V(x)$: Potential f^n of crystal/system (or simply potential)
E: Allowed energy values of e^-s.

$|\psi|^2$: Probability density function (or probability function)

↳ Probability of finding a particle at a particular location.

↳ $\psi(x,y,z)$: f^n of 3 coordinates.

$$-\frac{\hbar^2}{2m} \cdot \frac{\partial^2 \psi(x,t)}{\partial x^2} + V(x)\psi(x,t) = j\hbar \frac{\partial \psi(x,t)}{\partial t}$$

$$\psi(x,t) = \psi(x)\,\phi(t)$$

$$\boxed{\frac{\partial^2 \psi(x)}{\partial x^2} + \frac{2m}{\hbar^2}(E - V(x))\,\psi(x) = 0}$$, $\hbar$: reduced Planck's constant $= \frac{h}{2\pi}$

$$\rightarrow \boxed{\int_{-\infty}^{\infty} |\psi(x)|^2\, dx = 1}$$

<u>Condition-1:</u> $\psi(x)$ must be finite, single-valued and continuous.

<u>Condition-2:</u> $\partial\psi(x)/\partial x$ must be finite, single-valued and continuous.

<u>Electrons in Free Space:</u>

$V(x) = 0$, m: mass of electron.

$$\therefore \frac{\partial^2 \psi(x)}{\partial x^2} + \frac{2mE}{\hbar^2}\psi(x) = 0$$

18-01-2024

The solution to this differential eq^n can be written in the form

$$\psi(x) = A e^{\left[\frac{jx\sqrt{2mE}}{\hbar}\right]} + B e^{\left[\frac{-jx\sqrt{2mE}}{\hbar}\right]}$$

or $\psi(x) = Ae^{jkx} + Be^{-jkx}$,

↳ e^- moving in ⊕ve and ⊖ve x

where $k = \sqrt{\frac{2mE}{\hbar^2}}$

$$\phi(t) = e^{-j(E/\hbar)t} = e^{-j\omega t}$$

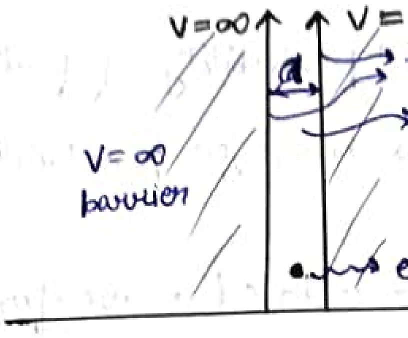
$$\therefore \psi(x,t) = Ae^{j(kx-\omega t)} + Be^{-j(kx+\omega t)}$$

↳ There is always a finite probability of finding an electron anywhere in x-dim / space (universe).

→ Minimum energy of e^- (KE + PE) = 0 : (for free e^-)

<u>Confined electron</u>: Motion of the electron is restricted.

<u>Infinite Potential well Arrangement</u>:



→ barrier

→ Well (Infinite potential well)

↳ Location where e's can stay

→ electrons will be somewhere due to finite energy

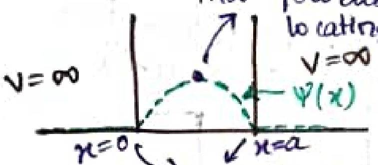
↓ cannot jump to the right or left due to infinite V

↓ Bound / confined e^-

↓ called as zero potential energy

a : width of the well

$$\boxed{E = \frac{\hbar^2 n^2 \pi^2}{2ma^2}} \Rightarrow e^- \text{ energy}$$



→ wave f^n terminates here

a : width of well

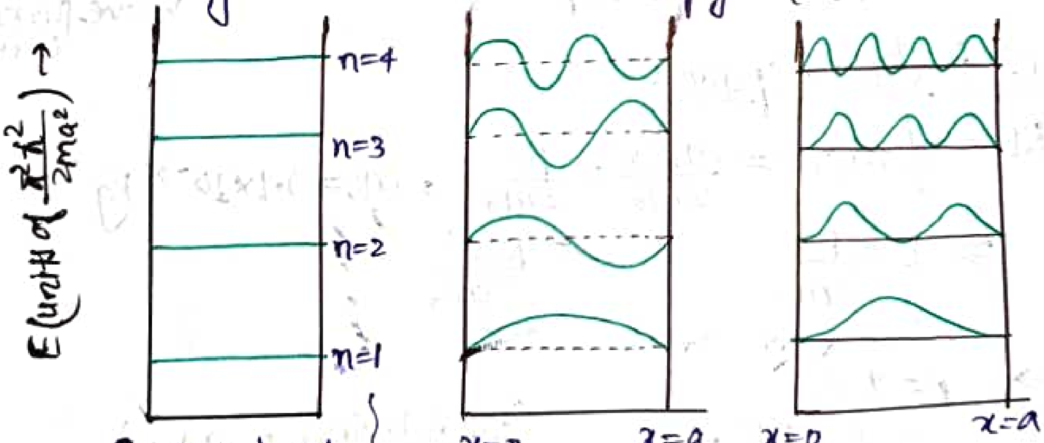
m : mass of e^-

↓

Discrete energy level

19-01-2024

→ A single electron would occupy $n=1$.



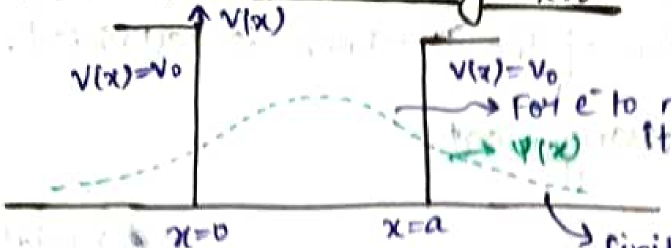
Energy level

Wave f^n

Probability density f^n

energy level will will be band for atom.

Finite Potential Well Arrangement:

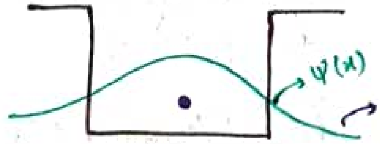


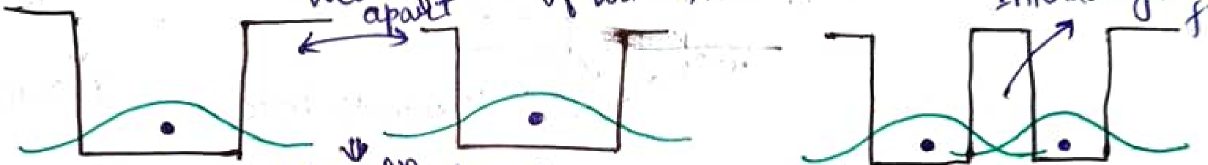
→ For e^- to move to the other side, it would need $V=V_0$.

finite probability of finding e^-

\# Quantum mechanics 'tunneling' ⇝ wave f^n penetrating the barrier.

→ Every classical particle has an associated wave function called matter wave.





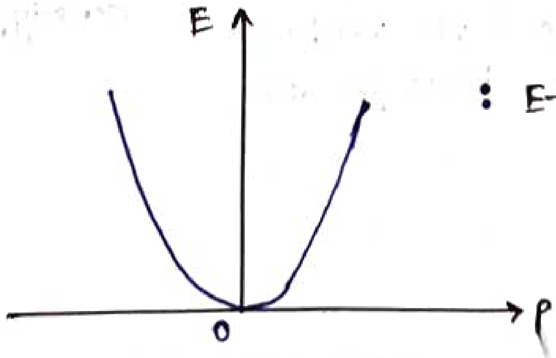
Electrons in Free Space:

$$KE = \frac{1}{2} m_0 v^2 = \frac{m_0^2 v^2}{2m_0} = \frac{p^2}{2m_0} \quad , m_0 = 9.1\times10^{-31}\,kg$$

$$\Rightarrow E = \frac{p^2}{2m_0} \qquad = \frac{\hbar^2 k^2}{2m_0}$$

$$\rightarrow \quad p = \hbar k = \frac{h}{2\pi}\cdot\frac{2\pi}{\lambda} = \frac{h}{\lambda}$$

(considering e^- as classical particle)



: E-P diagram
or
E-K diagram
or
Band structure

Electrons inside a lattice:

$F = m_0 a$

↳ Two forces: $F_{external}$: Force to move (applied force)

$F_{internal}$: Repulsive force by e^- and attractive force by nucleus.

→ $F_{total} = F_{ext.} + \cancel{F_{int.}}$ → (ignore, to study through Newton mechanics) → Mass is modified

⇒ $F_{total} = m_0^* a$, m_0^* or $m_{e,n}^*$: effective mass of $e^- \neq m_0$

↳ by considering the internal forces

↳ applicable when e^-s are moving inside a lattice

$\therefore E = \frac{p^2}{2m_0^*}$

23-01-2024

→ $m^* > m_0$ or $m^* < m_0$ depending upon the type of material.

→ $m_{e,n}^* = 0.98\, m_0$, $m^*_{p,h} = 0.16\, m_0$ } Silicon

$m^*_e = 1.64\, m_0$, $m^*_h = 0.044\, m_0$ } Ge

$[m_0 = 9.1 \times 10^{-31}\ kg]$

m^* of GaAs is lesser than that Si.

↳ devices made of GaAs would be much faster.

- $\mu_{e(GaAs)} > \mu_{e(Si)}$

Mass ↑ ⇒ Speed ↓

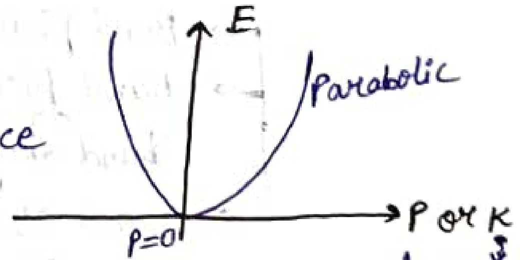
For same force applied, e^- in Si would travel faster than that in Ge.

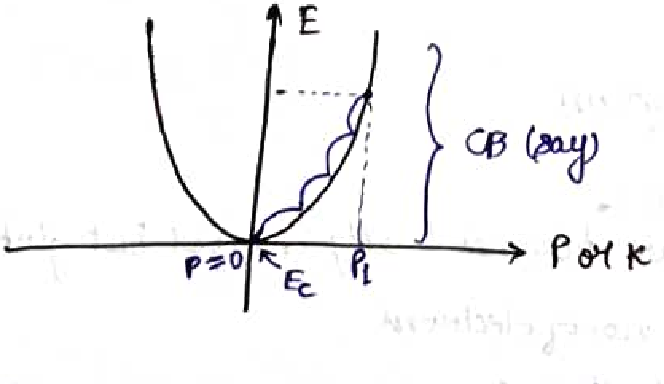
→ m^* ↑ ⇒ mobility ↓ (μ)

→ m^* : mass when all quantum mechanical forces are considered.

→ $E = \frac{\hbar^2 k^2}{2m_0} = \frac{p^2}{2m_0}$: Free electron

→ $E = \frac{\hbar^2 k^2}{2m^*_n}$: e^- inside a lattice





E_c : Conduction band edge

P or K → wave no. $K = \frac{2\pi}{\lambda}$

Hot electron : e^- with very large KE

↳ (e^- at top of CB)

→ Hot electrons (excited e^-s) collide with the lattice when they move inside a lattice and lose energy, coming to the least energy point of $P=0$ (E_c or conduction band edge).
· This process is called thermalization.

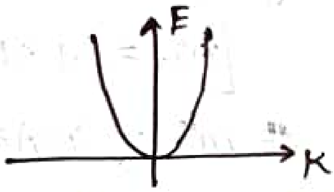
→ $E = \frac{\hbar^2 k^2}{2m^*}$

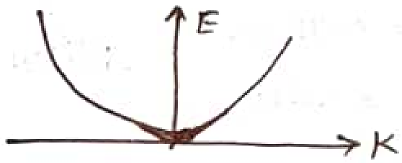
$\Rightarrow \frac{dE}{dk} = \frac{\hbar^2 k}{m^*} = \frac{\hbar k \cdot \hbar}{m^*} = \frac{P\hbar}{m^*} = v\hbar$, v: velocity of the particle

$\Rightarrow v = \frac{1}{\hbar}\frac{dE}{dk}$ = velocity ~ 1st derivative
≈ slope

2nd derivative: $\frac{d^2E}{dk^2} = \frac{\hbar^2}{m^*}$
⇓
curvature

$\Rightarrow m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)} \propto \frac{1}{\text{curvature}}$
↳ curvature





↳ curvature ↑
⇒ m^* ↓
⇒ Speed ↑.

→ $F = m^* a$ = charge × applied electric field
$= -eE$

$\Rightarrow a = -\frac{eE}{m^*}$ $\quad \overleftarrow{E}$, $\overrightarrow{a}$

- Bond picture
- Band picture or band diagram
- Band structure or E-K or E-P diagram

<u>Bond picture</u>: For $T > 0$ K,
- semiconductor becomes locally charged but globally neutral.
- T↑ ⇒ more no. of electrons
- T↑ ⇒ conduction ↑

→ At room temperature, thermal energy, E = 26 meV.

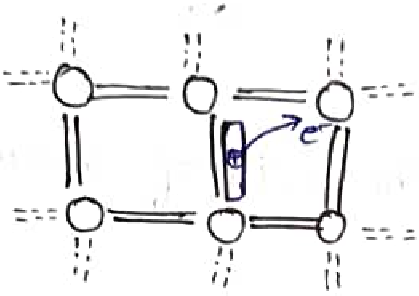
or $E = KT\ eV$

$= 0.0256\ eV$

$[1\ eV = 1.6\times10^{-19}\ J]$

24-01-2024

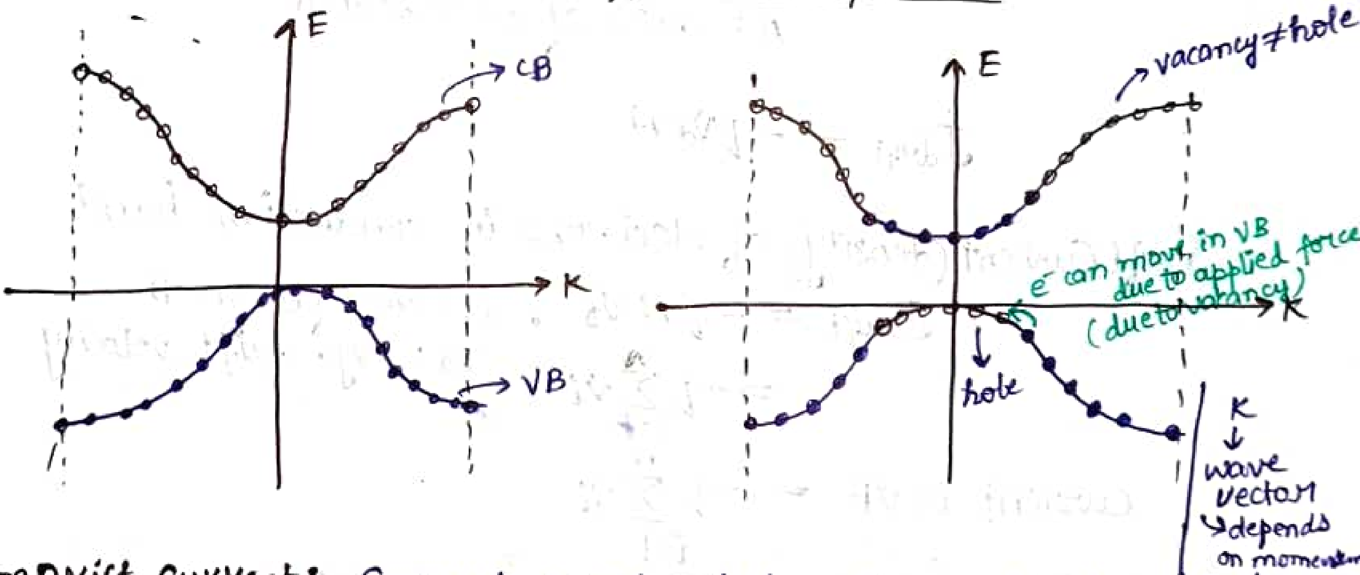
Concept of Hole



Hole: Vacancy ⇝ missing bond

EHP (Electron Hole Pair): Electrons and holes are generated in pair.

E-K for CB and VB and different temperatore :

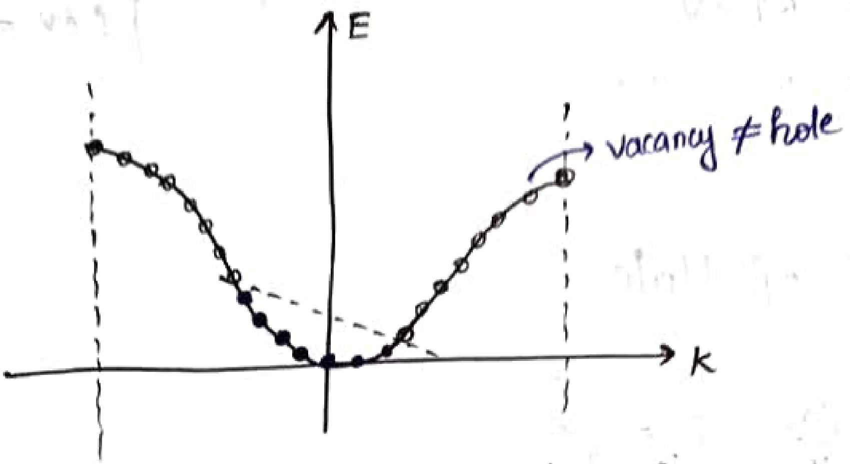


Electron Drift current: Current produced by electric field applied on the electron.

Hole drift current: Current produced by electric field on hole.

Drift current: Current produced by electric field on a charged particle.

E-K diagram when external field is applied



Drift current density due to the motion of electrons,

$$J = -e \sum_{i=1}^{n} v_i$$

$$I_{drift} = q\,(v_d)\,N.A \text{ (Ampere)}$$

v_d : drift velocity
N : no. of particles per unit volume
A : area of cross section

$$J_{drift} = -q\, v_d\, N$$

Drift Current (density) of electrons in conduction band,

$$J_{drift} = -q N v_D \quad , \quad N : \text{no. of } e^-\text{s in CB}$$

$$= -q \sum_{i=1}^{N} v_i \qquad v_D : \text{avg. drift velocity}$$

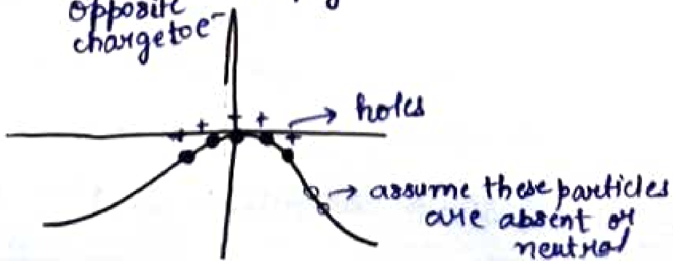
$$\text{Current in VB} = -q \sum_{i=1}^{N} v_i$$

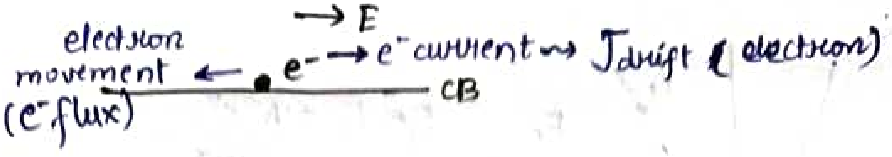
$$= -q \left[\cancel{\sum_{full}}^{\,0} - \sum_{empty} \right]$$

current when VB is completely filled

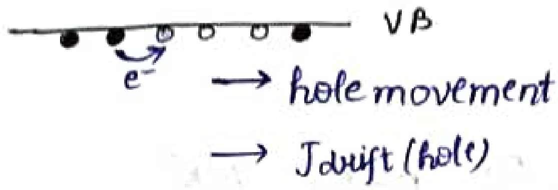
$$= q \sum_{empty}$$

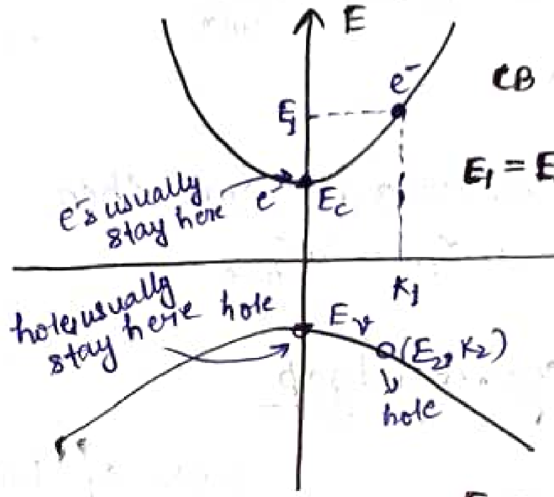
opposite charge to e⁻



→ 

$$J_{drift} = J_{drift}(e^-) + J_{drift}(\text{hole})$$



→ 

$$E_1 = E_c + \frac{\hbar^2 K_1^2}{2m_n^*}$$

$$E_2 = E_v - \frac{\hbar^2 K_2^2}{2m_h^*}$$

→ $E = \dfrac{\hbar^2 k^2}{2m^*}$

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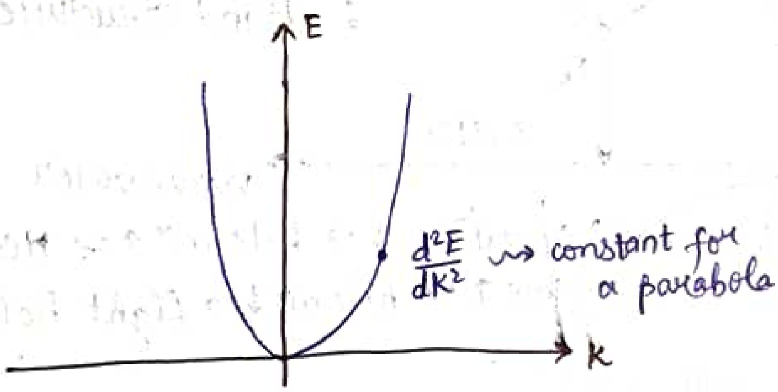
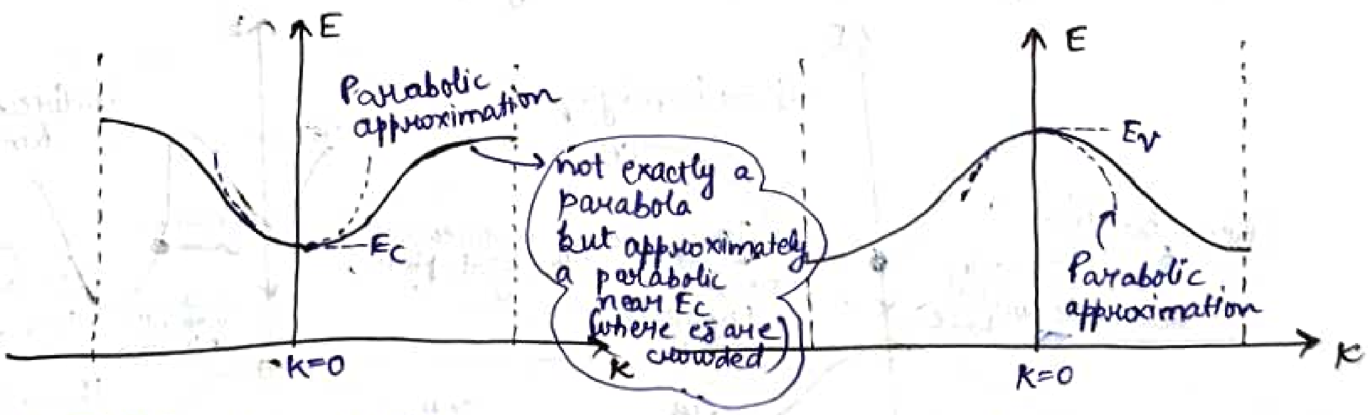
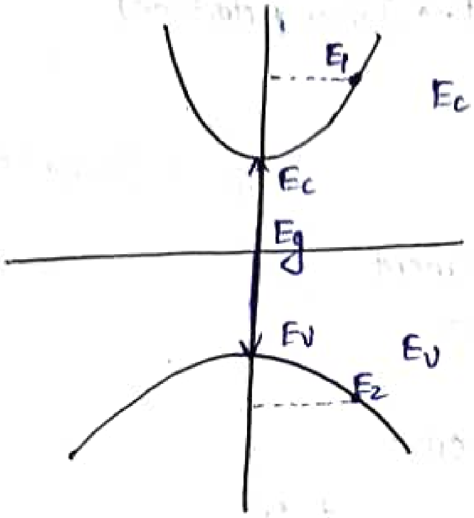


$\dfrac{d^2E}{dK^2}$ ⇝ constant for a parabola

E-K diagram and Parabolic Approximation



→ Solution of $\dfrac{d^2\psi(x)}{dx^2} + \dfrac{2m}{\hbar^2}(E - V(x))\psi(x) = 0$ (Schröd. eqⁿ) gives the curve (E & $\psi(x)$).

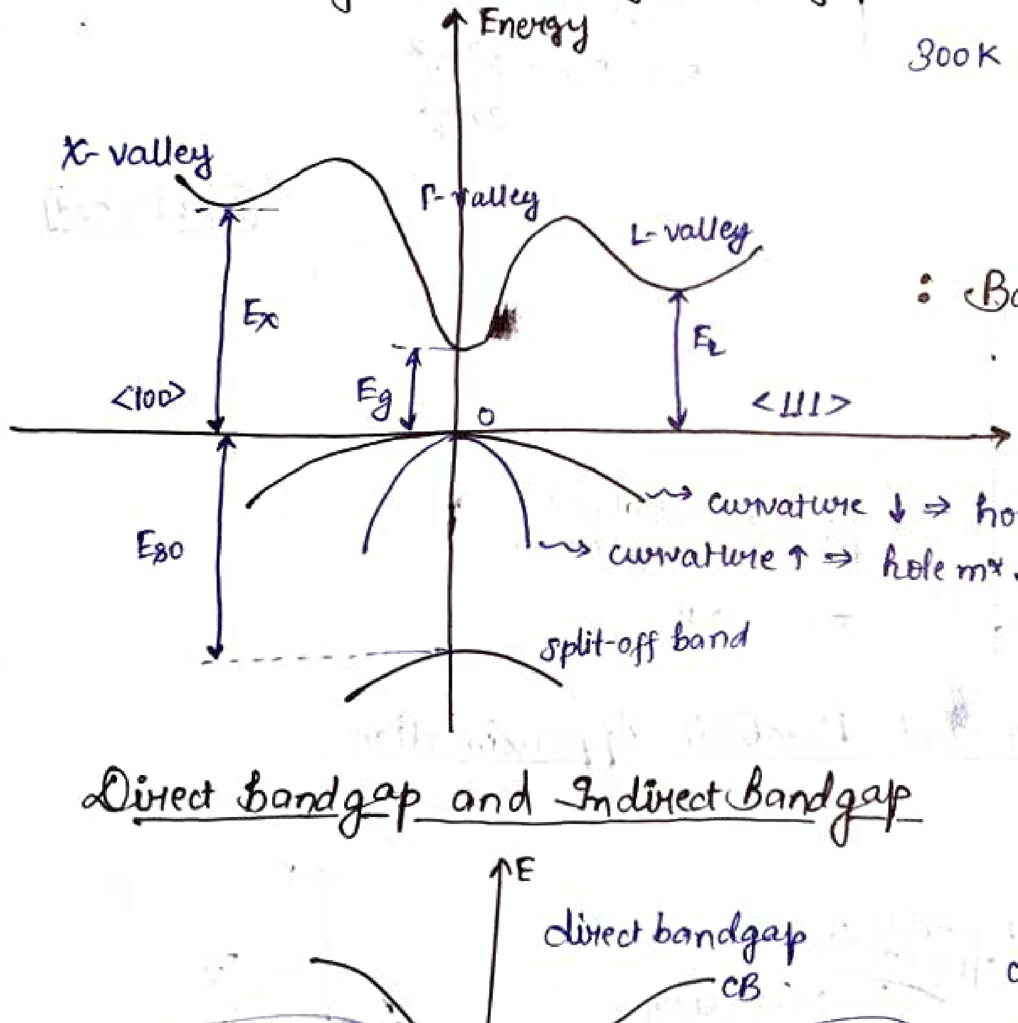


E_c $\quad E_1 = E_c + \frac{\hbar^2 k^2}{2m^*}$

E_v $\quad E_2 = E_v - \frac{\hbar^2 k^2}{2m^*}$.

↳ If both the curvatures are same, then
$m^*_{e^-} = m^*_{hole}$.

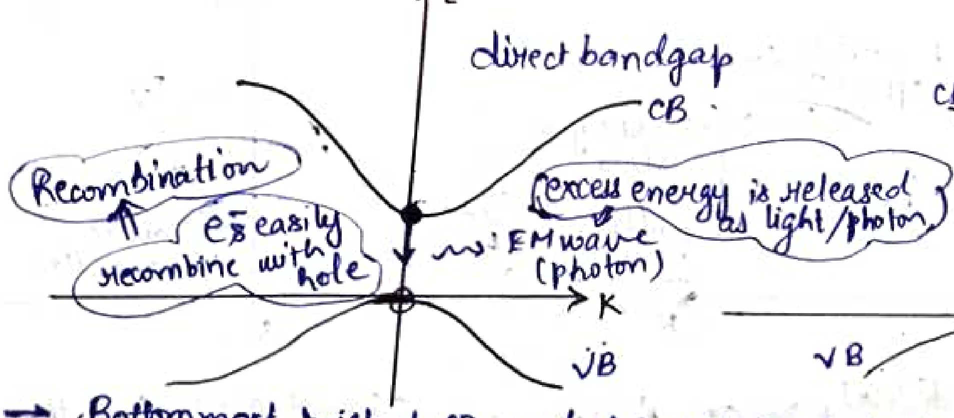
Heavy hole, light hole, valleys, bandgap

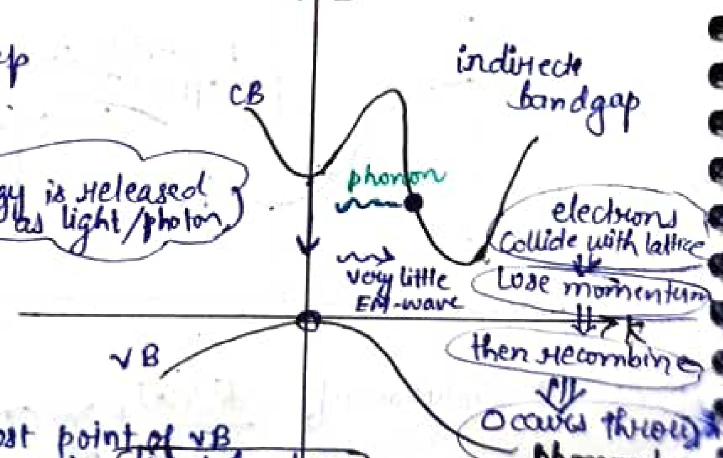


300K $\quad E_g = 1.42\,eV$
$E_L = 1.71\,eV$
$E_X = 1.90\,eV$
$E_{80} = 0.34\,eV$

: Band structure

Direct Bandgap and Indirect Bandgap





→ Bottommost point of CB and topmost point of VB have same K-value ⇒ $\boxed{\text{direct Bandgap}}$

Energygap : Energy difference b/w bottom-most point of CB and top-most point of VB.

At room T, $E_{g,Si} \cong 0.6$ eV.

$E_{g,GaAs} \sim 1.4$ eV.

Γ_1 valley : deepest valley.

Satellite valley: valleys adjacent to the deepest valley.

→ Most of the electronic transitions happen at the edges.

Intrinsic Semiconductor material (Pure semiconductor):

↳ no. of free electrons = no. of free holes

$n = p = n_i$, n_i: intrinsic carrier concentration. (per unit volume)

↳ Only Si (say) atom.

Extrinsic Semiconductor material :

$p > n$: p-type extrinsic material

$n > p$: n-type extrinsic material

→ One which is larger in no. : majority charge carrier.
One which is smaller in no. : minority charge carrier.

Thermal equilibrium :

↳ Keeping the temperature constant and no force, stimuli applied.

$n_0 = p_0 = n_i$

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① Fix the temperature.

② No external stimulus.
— electric field
— photons
— stress

Intrinsic or pure semiconductor (undoped sc):

$n_i = n_0 = p_0$, n_i : intrinsic carrier concentration. (no. per unit volume)

[$\circ$: represents thermal equilibrium]

$n_i = 10^{10}/cm^3$
$= n_0 = p_0$

$p > n$: p-type [holes: majority carriers, e^-: minority carriers]
$n > p$: n-type [e^-: majority carriers, holes: minority carriers]

↳ ~~Extensi~~
Extrinsic or doped or impure semiconductor.
↳ Representation:
n–Si
p–Si

Law of Mass Action

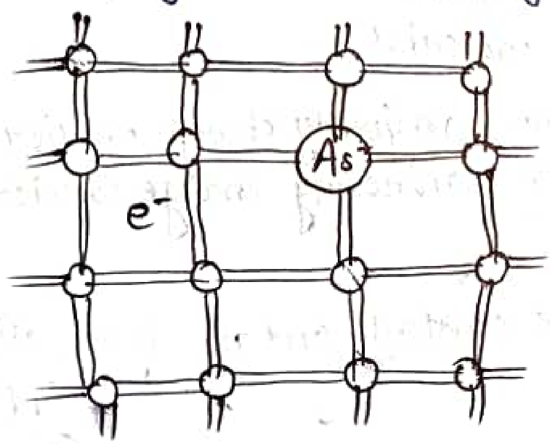
$n_0 p_0 = n_i^2$, [valid only at thermal equilibrium]

$n_i = 10^{10}/cm^3$: intrinsic carrier concentration.

→ No. of Si atoms/$cm^3 \approx 10^{22}/cm^3$ [= ideal no. of e⁻s when Si atom is broken]

Doped Semiconductors

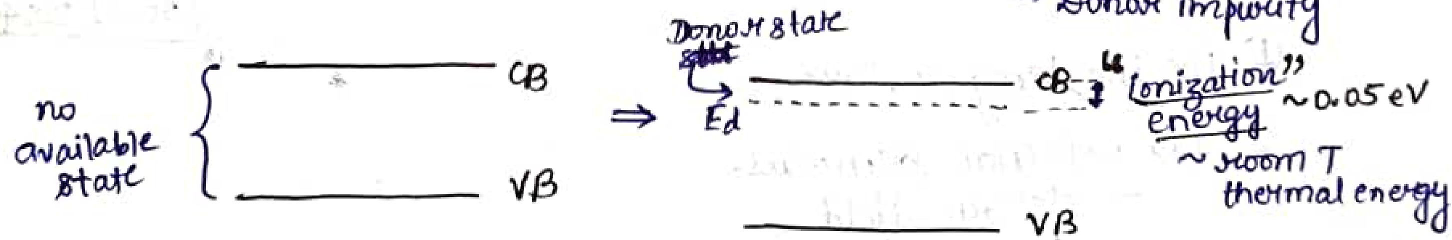
↳ Doping is done to change the conductivity of the material.



Doping: Donors (n-type)

- The 4 valence e⁻s of As allow it to bond just like Si but the 5th e⁻ is left orbiting the As site.
- The energy required to release free the 5th e⁻ into CB is very small.

Dopants : As
↳ Donor impurity

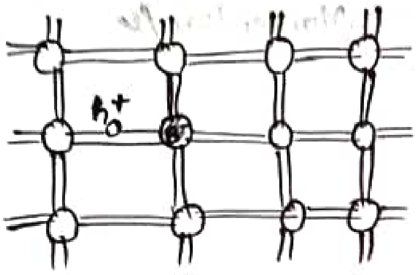


→ Complete ionization: As atoms in donor state are ionised.
→ Electrons produced by thermal energy (creating e⁻s in CB and holes in VB, equal in no.) are not considered as they are equal in no. as the holes in VB (thus not forming PN-junction)
→ Globally, doped semiconductor is still neutral.

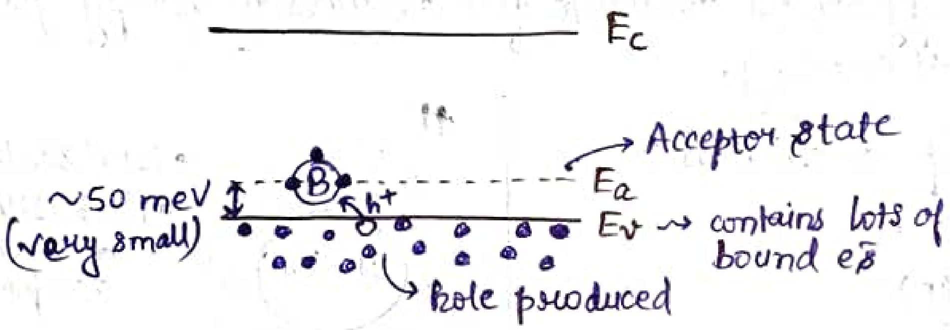
Partial ionization: Some As in donor state may not donate electron to conduction band.

Freeze Out: At $T=0K$, no electrons are donated, thus no ionization.

Doping: Acceptors (p-type)



→ Hole concept is valid only in VB.



→ Complete ionization: All B in E_a accepts e^-s from CB.
→ Partial ionization: Partial e^-s accepted.
→ Free-out: No e^-s are accepted.

Doping
- Light doping: $10^{14}-10^{15}/cm^3$ (for Si). ⇝ $\frac{10^{14}}{10^{22}} \rightarrow 1$ in 10^8.
- Moderate doping: $10^{16}-10^{18}/cm^3$
- Heavy doping: $10^{19}-10^{20}/cm^3$.

I-V characteristics

↳ For a given voltage in a SC device, current depends on:
- no. of e^-s and holes.
- no. of states (density of state: DOS).

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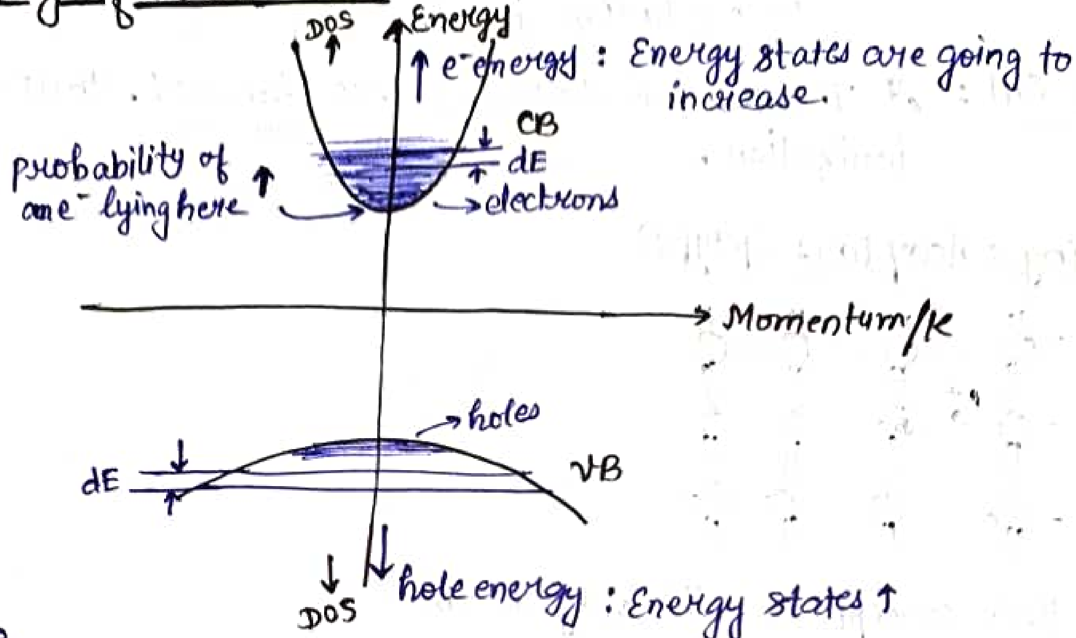
Density of States (DOS)



↳ The no. of energy states available for carriers to occupy per unit volume per unit energy.

↳ V-I relationship calculation.
e⁻ holes

$DOS_{(E)} = g_{CB}(E) = f_{CB}(E)$

→ 3D-Semiconductor or bulk semiconductor

↳ Electrons are allowed to move in 3 dimensions, x, y, z.

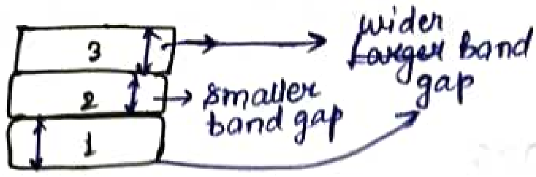
#

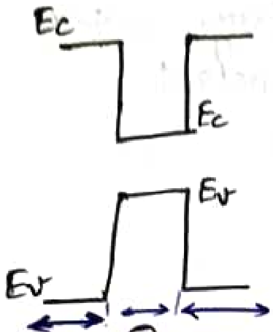
- Total seats = 10K
- Probability that a seat is occupied = 0.9
- Total people = $10 \times 0.9 + 15 \times 0.9 + \ldots$ $= 10K \times 0.9$ $= 9K$

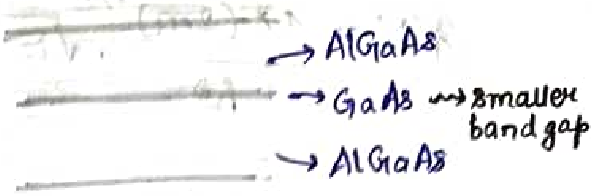
Seat : DOS

	Degree of confinement	Degree of freedom	
3D	0	3	→ Bulk
2D	1	2	→ Quantum well
1D	2	1	→ Quantum wire
0D	3	0	→ Quantum dot (artificial atoms)

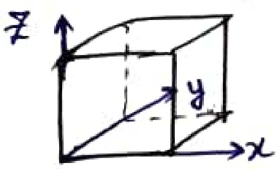
Electrons in 2D : Quantum well structure



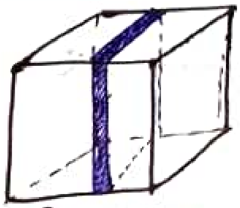




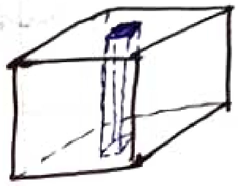
Semiconductor Quantum Structures



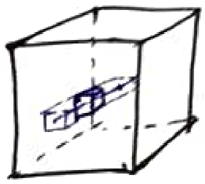
Bulk SC



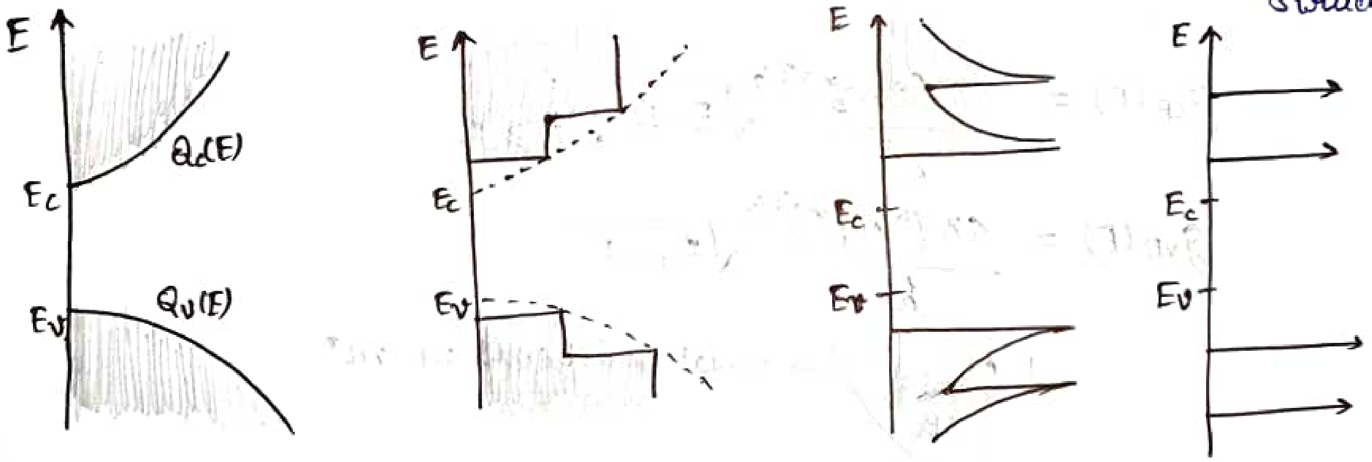
Quantum well



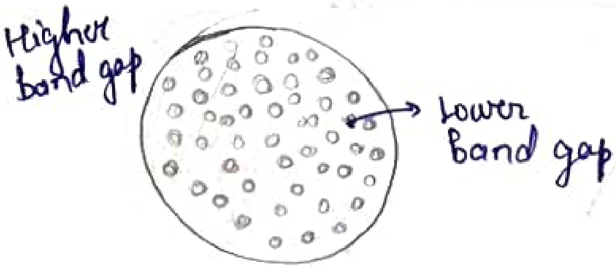
Quantum ~~line~~ wire



Quantum Dot
↳ Semiconductor ~~Quantum~~ Nano Structure



Quantum dot:



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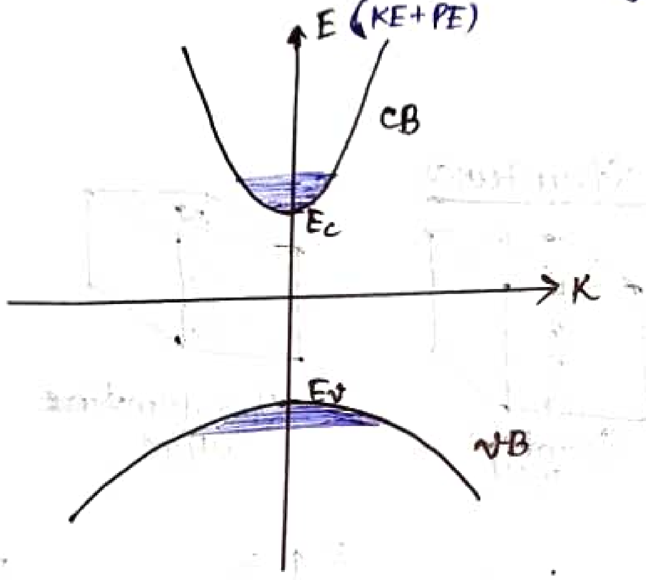
DOS: dependent on energy
↳ cm^3/unit energy.

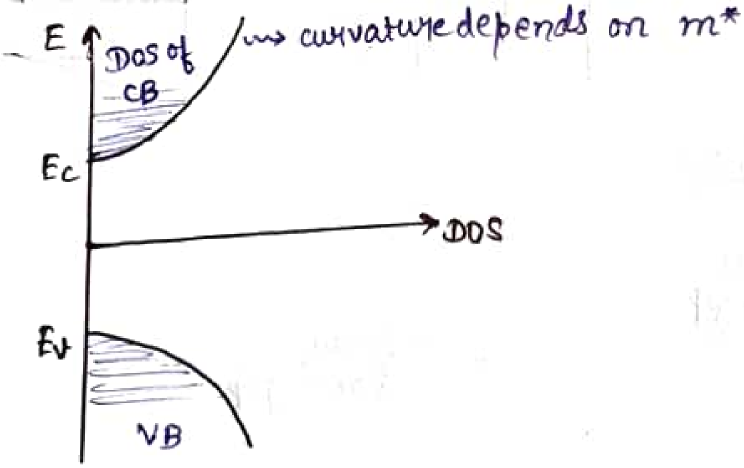
$$g(E) = \frac{4\pi(2m)^{3/2}}{h^3}\cdot\sqrt{E}$$: DOS

m: mass of charge carrier
h: Planck's constant
E: Energy.



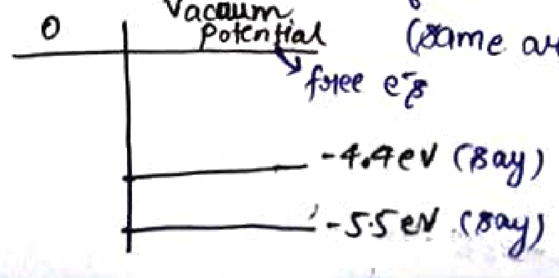
$$g_{CB}(E) = \frac{4\pi(2m_e^*)^{3/2}}{h^3}\sqrt{E-E_c}, \quad E \geq E_c$$

$$g_{VB}(E) = \frac{4\pi(2m_h^*)^{3/2}}{h^3}\sqrt{E_v-E}$$



→ If DOS of CB and VB states have same curvature, no. of e^-s will be same as the no. of holes states. (same area under the curve)

#



→ $\boxed{E_c - E_v = E_g}$: Band gap

→ $\boxed{\frac{E_c + E_v}{2} = \text{Midgap}}$

States : groups of levels
band : group of states
↳ closely-spaced energy levels.

Defect states: states b/w E_c and E_v due to defects in the lattice.

Statistical Law

Statistical Mechanics: Branch of physics dealing with the distribution of microscopic particles in different states (energy levels).

Sub-atomic particles : ① Gas molecules $\xrightarrow{\text{obeys}}$ Maxwell-Boltzmann law (or Statistics)

② Photons (Bosons) $\xrightarrow{\text{obeys}}$ Bose-Einstien law

③ Electrons and holes (Fermions) $\xrightarrow{\text{obeys}}$ Fermi-Dirac law

⇓

All are exponential functions

Fermi-Dirac Distribution Function
(or Fermi-Dirac statistics)

$$f(E) = \frac{1}{1 + e^{\left[\frac{E-E_f}{kT}\right]}}$$

⇝ gives probability that a given state E will be occupied by electrons

E_f : Fermi energy level

Universal Relationship

↳ Occupational probability for an electron

$0 < f(E) < 1$

→ Occupational probability for a hole : $1 - f(E)$

→ $f(E) = \frac{n(E)}{g(E)}$, | $n(E)$: no. of e^-s
$g(E)$: DOS
$f(E)$: (Probability function.

$\Rightarrow n(E) = f(E) \times g(E)$

$\Rightarrow \int_{E_c}^{\infty} n(E) = \int f(E)\, g(E) = n_0$: Total no. of electrons in CB. (e^- carrier density)

Thermal eq^m

→ $P_0 = \int_{-\infty}^{E_v} (1 - f(E)) \cdot g_{VB}(E)$: (holes carrier density) Total no. of holes in VB = $\int_{-\infty}^{E_v} P(E)$

02-02-2024

→ $f(E) = \frac{n(E)}{g(E)} = \frac{\text{no. of carriers}}{\text{total no. of states}}$

→ $n_0 p_0 = n_i^2$ (at thermal equilibrium)

→ $f(E) = \frac{1}{1 + e^{\left[\frac{E-E_f}{KT}\right]}}$ ⇝ Fermi-Dirac distribution function
⇝ Universal relationship for electrons and holes

↓
Electron occupational probability

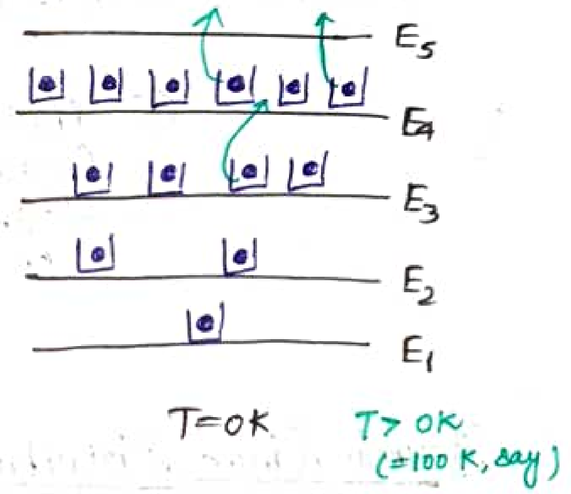
E_f : Fermi energy (reference energy level)

→ T=0 K

① $E > E_f$

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

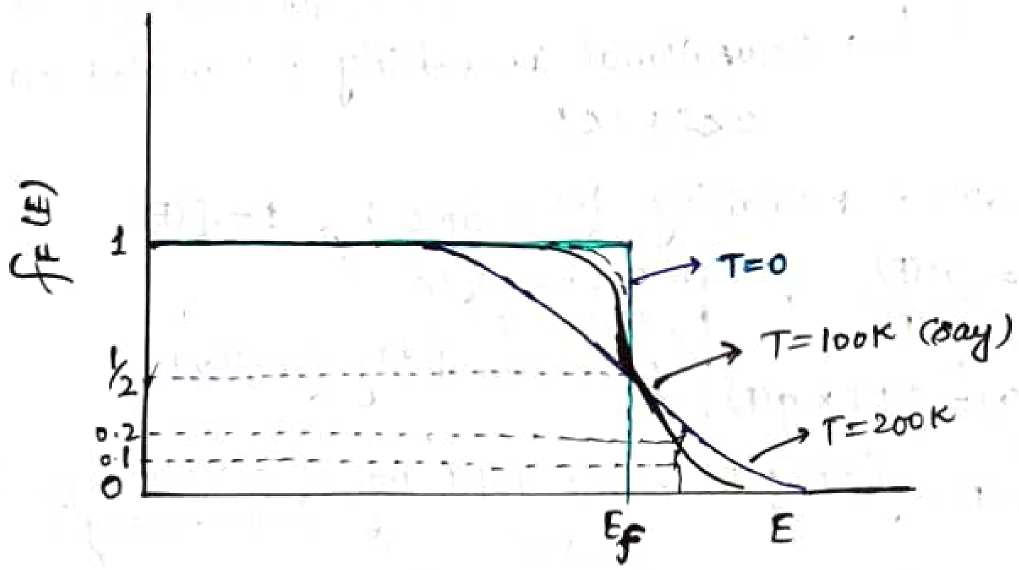
→ No electron will be found above E_f at T=0K.



② $E < E_f$

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

→ All the energy states ~~at~~ below E_f will be occupied at 0K.

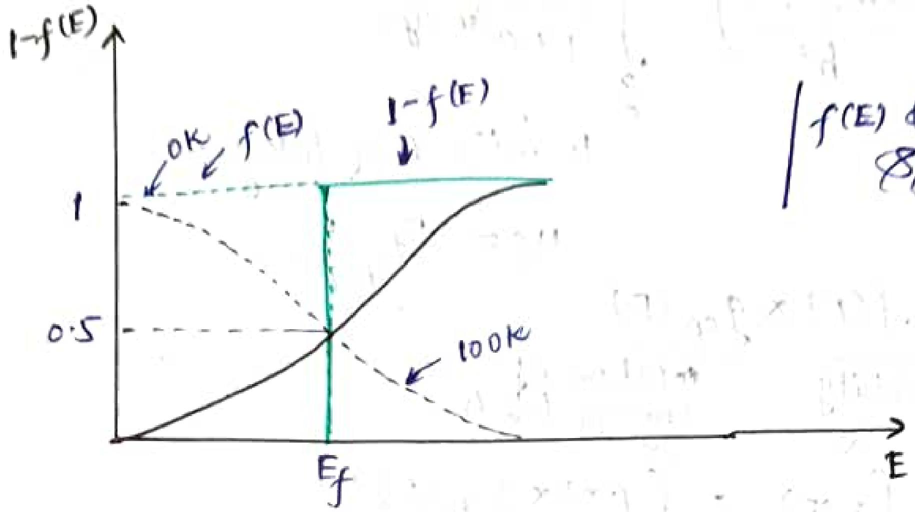


Fermi-Smearing

→ $T > 0K$

At $E = E_f$,

$$f(E) = \frac{1}{1+e^{\left(\frac{E-E_f}{KT}\right)}} = \frac{1}{1+1} = \frac{1}{2}$$

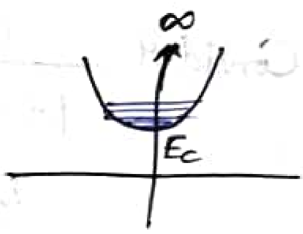


f(E) & 1-f(E) are Symmetric about E_f.

→ E_f (Reference energy level): Energy level above which no electrons will be found at 0K.

Number of Electrons in CB

$$n_0 = \int_{E_c}^{\infty} n(E) = \int_{E_c}^{\infty} g_{CB}(E) \cdot f(E)$$



$$= \int_{E_c}^{\infty} \frac{4\pi (2m_n^*)^{3/2}}{h^3} \sqrt{E-E_c} \times \frac{dE}{1+e^{\left(\frac{E-E_f}{KT}\right)}}$$

$$= \frac{4\pi (2m_n^*)^{3/2}}{h^3} \int_{E_c}^{\infty} \frac{\sqrt{E-E_c} \quad dE}{1+e^{\left(\frac{E-E_f+E_c-E_c}{KT}\right)}} \times (KT)^{3/2}$$

$$\left[\begin{array}{l} \text{Let } \frac{E-E_c}{KT} = u \\ \Rightarrow du = \frac{dE}{KT} \\ \text{when } E = E_c,\ u = 0 \\ \qquad E = \infty,\ u = \infty \end{array}\right] \qquad \left[\begin{array}{l} \frac{E_f - E_c}{KT} = u_F \\ \hookrightarrow \text{constant} \\ \hookrightarrow \text{numerical value} \end{array}\right]$$

$$\text{Integral} = \int_0^{\infty} \frac{\sqrt{u}\ du}{1+e^{u-\left(\frac{E_f-E_c}{KT}\right)}} = \int_0^{\infty} \frac{\sqrt{u}\ du}{1+e^{(u-u_f)}}$$

: Fermi's Half Integral $= F_{1/2}(u_f)$

$$\frac{4\pi\,(2m_n^* KT)^{3/2}}{h^3} = N_c = \text{effective density of states of CB.}$$

$n_0 = N_c \times$ Fermi's half integral

[07-02-2024]

$$\rightarrow\ n_0 = 4\pi\left(\frac{2m_n^* KT}{h^2}\right)^{3/2} \underbrace{\int_0^\infty \frac{u^{1/2}\,du}{1+e^{(u-u_f)}}}_{\text{Fermi's half-integral}}$$

$$u_f = \frac{E_f - E_c}{KT}$$

$$\rightarrow\ n(E) = \underbrace{f(E)}_{\text{probability}} \times \underbrace{g_{CB}(E)}_{\text{total no. of energy levels}}$$

$$\rightarrow\ n_0 = \int_{E_c}^{\infty} n(E) = \int_{E_c}^{\infty} f(E) \times g_{CB}(E)$$

$$= \int_{E_c}^{\infty} \frac{1}{1+e^{\frac{E-E_f}{KT}}} \times 4\pi\,\frac{(2m_n^*)^{3/2}}{h^3}\sqrt{E-E_c}\; dE$$

Consider $\dfrac{1}{1+e^{\left(\frac{E-E_f}{KT}\right)}}$

E_c

E_v

E_f : Fermi-energy level

E : energy of state under consideration

Consider $E >> E_f$

or

$E - E_f >> KT$

E

E_f

$$\therefore\ \frac{1}{1+e^{\left(\frac{E-E_f}{KT}\right)}} \approx \frac{1}{e^{\left(\frac{E-E_f}{KT}\right)}} \approx \boxed{e^{-\left(\frac{E-E_f}{KT}\right)}}$$

Fermi-distribution

Boltzmann distribution

... Boltzmann's approximation

$$\therefore\ n_0 = \sqrt{KT}.K' \int_{E_c}^{\infty} \sqrt{\frac{E-E_c}{KT}}\; dE \times e^{-\frac{(E-E_c)}{KT}}$$

$$= K'' \int_{E_c}^{\infty} \sqrt{\frac{E-E_c}{KT}}\; e^{\frac{-(E-E_f+E_c-E_c)}{KT}}\, dE \quad , K', K'' = \text{constants}$$

$$\left[\text{Take } u = \frac{E-E_c}{KT} \Rightarrow du = \frac{dE}{KT}\right]$$

$$= K'' \int_{0}^{\infty} \sqrt{u}\; e^{-\left(\frac{E-E_c}{KT}\right)}\, e^{-\left(\frac{E_c-E_f}{KT}\right)} du$$

$$= K'' \int_{0}^{\infty} \sqrt{u}\; e^{-u}\, e^{-\left(\frac{E_c-E_f}{KT}\right)} du$$

$$= K''\, e^{-\left(\frac{E_c-E_f}{KT}\right)} \underbrace{\int_{0}^{\infty} e^{-u} u^{1/2}\, du}_{\text{gamma function } = \frac{\sqrt{\pi}}{2}}$$

$$= \frac{\cancel{4}^{2}\pi(\cancel{2}m_n^*)^{3/2}}{h^3} (KT)^{3/2} \cdot \frac{\sqrt{\pi}}{\cancel{2}}\, e^{-\left(\frac{E_c-E_f}{KT}\right)}$$

$$\therefore \boxed{n_0 = 2\left[\frac{2\pi m_n^* KT}{h^2}\right]^{3/2} \times e^{-\left(\frac{E_c-E_f}{KT}\right)}}$$

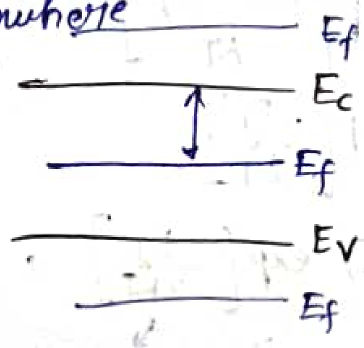
For holes:

$$P_0 = \int_{-\infty}^{E_v} p(E) = \int_{-\infty}^{E_v} [1-f(E)]\, g_{VB}(E)$$

$$\Rightarrow \boxed{P_0 = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} \times e^{-\left(\frac{E_f-E_v}{KT}\right)}}$$

E_f : fermi (reference) energy-level

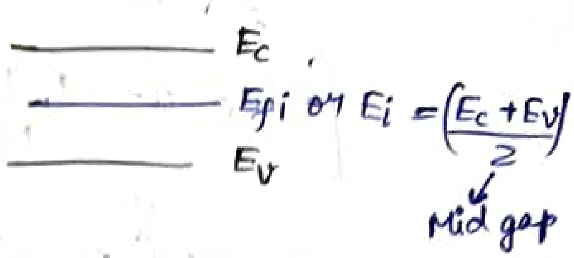
↳ could be anywhere



For intrinsic semiconductor:

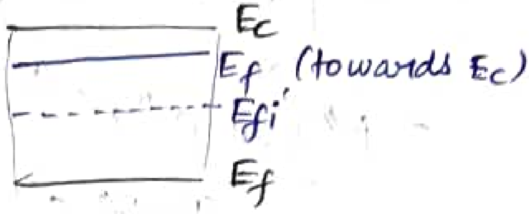
↳ Fermi-energy level lies at the mid.

↳ intrinsic fermi energy-level: E_{fi} or E_i



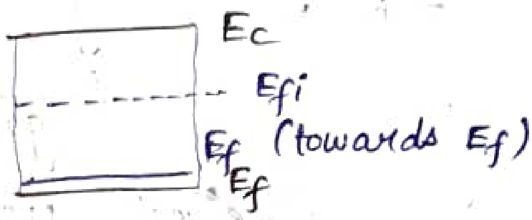
For n-type:

$E_{fi} < E_f$



For p-type:

$E_{fi} > E_f$



If the relative position of E_f w.r.t. E_c and E_f are known, n_0 and p_0 can be easily calculated.

$\boxed{08\text{-}02\text{-}2024}$

Intrinsic Semiconductor:

$$n_0 = p_0 = n_i$$

$$\Rightarrow n_0 p_0 = n_i^2$$

and, $E_f = E_{fi}$

$$\therefore \quad n_i = n_0 = N_c \exp\left[\frac{-(E_c - E_{fi})}{KT}\right] \text{ —(1)}, \text{ where } N_c = 2\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2}$$

$$n_i = n_p = N_v \exp\left[-\frac{(E_{fi} - E_v)}{KT}\right] \text{ —(2)}, \text{ where } N_v = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}$$

effective density of state of VB.

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{KT}\right]$$

$$= N_c N_v \exp\left[\frac{-E_g}{KT}\right]$$

$$\Rightarrow n_i = \sqrt{N_c N_v} \exp\left[-\frac{E_g}{2KT}\right], \quad E_g = (E_c - E_v) : \text{Band gap}$$

strong f^n of temp.

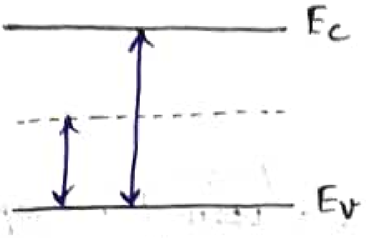
strong f^n of temp.

$[T \uparrow \Rightarrow n_i \uparrow]$

→ E_g is related to temperature. | $E_g \uparrow \Rightarrow n_i \downarrow$

<u>Varshney's Equation</u>

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}$$, $E_g(0)$: Band gap of sc material at 0 K.



$$\frac{E_c + E_v}{2} = E_{fi} = \frac{E_g}{2}$$

$n_0 = p_0$

$$N_c \exp\left[-\frac{(E_c - E_{fi})}{KT}\right] = N_v \exp\left[-\frac{(E_{fi} - E_v)}{KT}\right]$$

$$\Rightarrow E_{fi} = \frac{E_c + E_v}{2} + \frac{KT}{2} \ln\left[\frac{N_v}{N_c}\right]$$

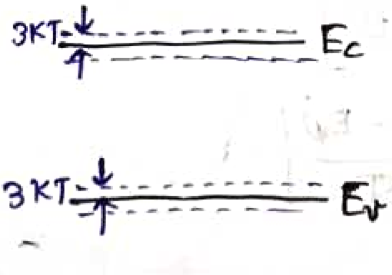
$$\Rightarrow E_{fi} = \frac{E_c + E_v}{2} + \underbrace{\frac{3KT}{4} \ln\left[\frac{m_h^*}{m_n^*}\right]}$$

=0, E_{fi} lies at the middle.
>0, E_{fi} lies above mid.
<0, E_{fi} lies below mid.

\# For all practical cases, assume $E_{fi} = \frac{E_c + E_v}{2}$.

→ For moderately doped sc, E_f lies somewhere in b/w E_c and E_v.

→ For heavily doped sc (doping of $10^{18} - 10^{19} /cm^3$),
E_f lies in b/w $(E_c - 3KT)$ and $(E_c + 3KT)$
or b/w $(E_v - 3KT)$ and $(E_v + 3KT)$



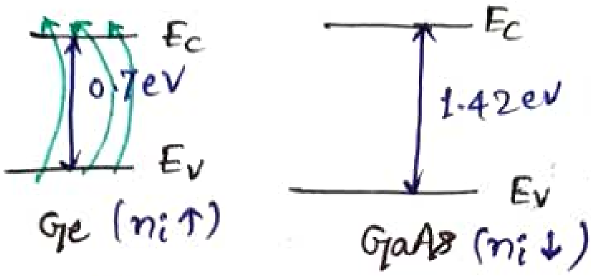
↳ "Degenerate Semiconductors"
↳ Boltzmann's approximation is not applicable.

At room T (27°C),

	n_i	E_g
Ge	$\sim 10^{13}/cm^3$	0.7 eV
Si	$\sim 10^{10}/cm^3$	1.1 eV
GaAs	$\sim 10^{6}/cm^3$	1.42 eV

→ The larger the bandgap, the smaller the intrinsic carrier density.

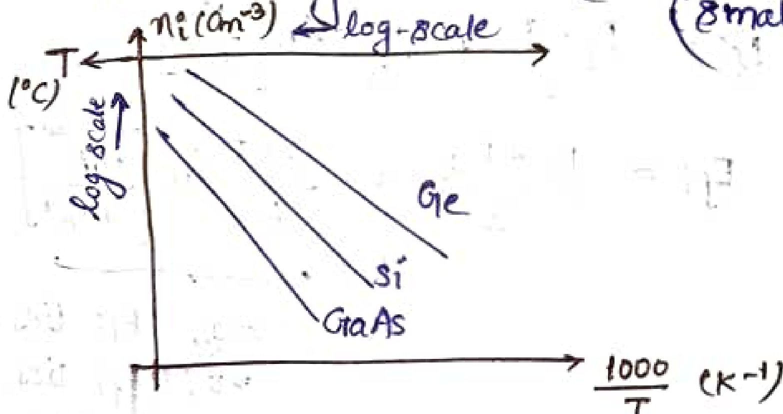
300K



⇝ Larger ~~state~~ bandgap
⇓
Difficult ~~[illegible]~~ to take e^- from E_v to E_c.
⇓
$n_i \downarrow$

$T \uparrow \Rightarrow n_i \uparrow$

↳ Ge has larger reverse saturation current (smaller gap; less T-dependent).



$\boxed{09\text{-}02\text{-}2024}$

Equations for calculating carrier densities:

$$n_o = N_c \exp\left[\frac{-(E_c - E_F)}{KT}\right]$$

$$p_o = N_v \exp\left[\frac{-(E_F - E_v)}{KT}\right]$$

$$= \frac{n_i^2}{n_o}$$

$\boxed{n_o p_o = n_i^2}$ (thermal eq^m)
↳ Law of Mass Action

[N_c, N_v ⇝ effective density of state
$\sim 10^{19}/cm^3$]

For intrinsic SC material,

$$n_o = p_o = n_i$$

$$n_i = N_c \exp\left[-\frac{(E_c - E_{fi})}{KT}\right]$$

$$= N_v \exp\left[-\frac{(E_{fi} - E_v)}{KT}\right]$$

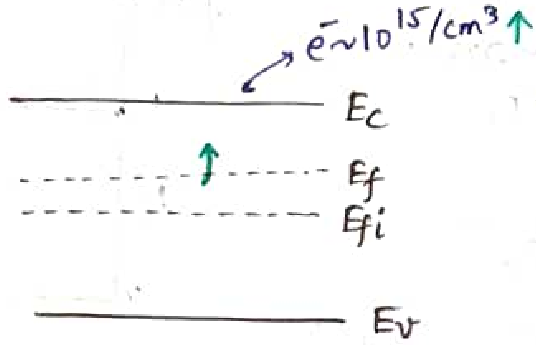
$$\Rightarrow n_0 = N_c \exp\left[-\frac{(E_c - E_f + E_{fi} - E_{fi})}{KT}\right]$$

$$= N_c \exp\left[\frac{-(E_c - E_{fi})}{KT}\right] \exp\left[\frac{E_f - E_{fi}}{KT}\right]$$

$$\boxed{n_0 = n_i \exp\left[\frac{E_f - E_{fi}}{KT}\right]}$$

[For any SC at thermal equilibrium] (Universal)

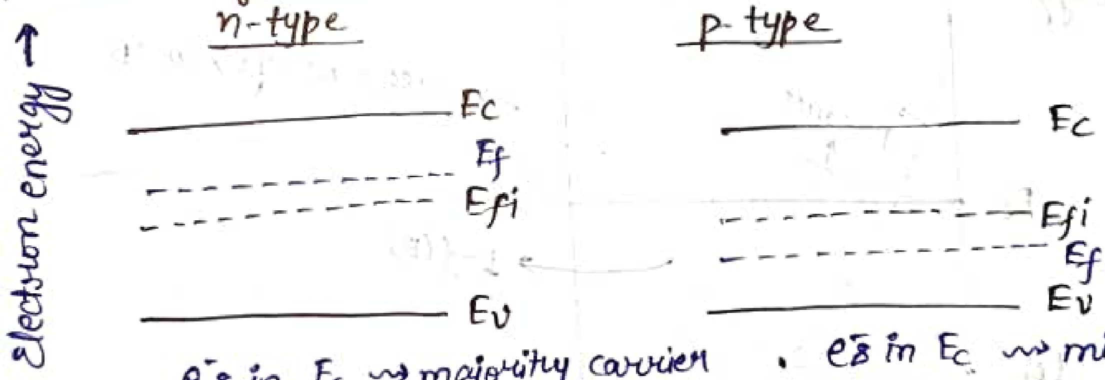
and, $\boxed{p_0 = n_i \exp\left[-\frac{(E_f - E_{fi})}{KT}\right]}$



→ The e-concentration increases exponentially as E_F moves away from E_{fi}, towards E_c.

→ If $E_f = E_{fi}$, then $n_0 = p_0 = n_i$.

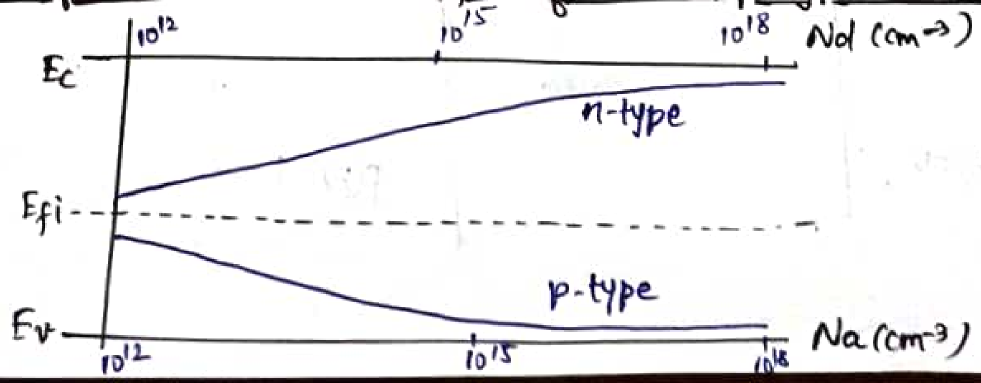
Position of Fermi level



e^-s in E_c ⇝ majority carrier
holes in E_v ⇝ minority carrier
($N_D > N_A$)
no. of donors, no. of acceptors

e^-s in E_c ⇝ minority carrier
e^-s in E_v ⇝ majority carrier
($N_D < N_A$)

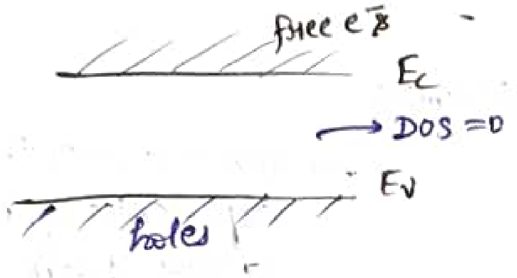
Position of Fermi level as a f^n of n and p-type dopant density:

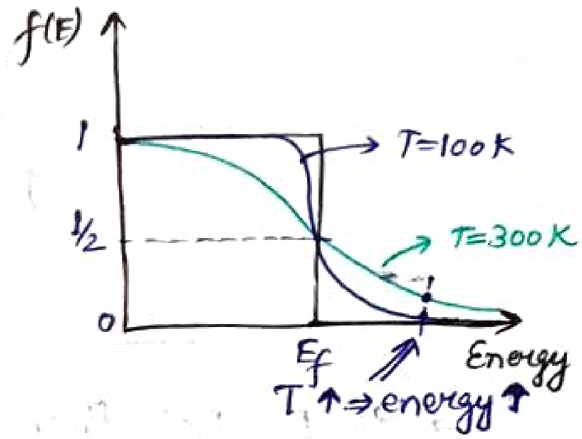


$$n_0 = \int n(E)\,dE = \boxed{\int_{E_c}^{\infty} DOS \times f(E)\,dE} \rightsquigarrow$$ Graphically, common area of DOS & f(E) plot.

$$= \int_{E_c}^{\infty} g(E) \frac{dE}{1+e^{(E-E_f)/kT}}$$

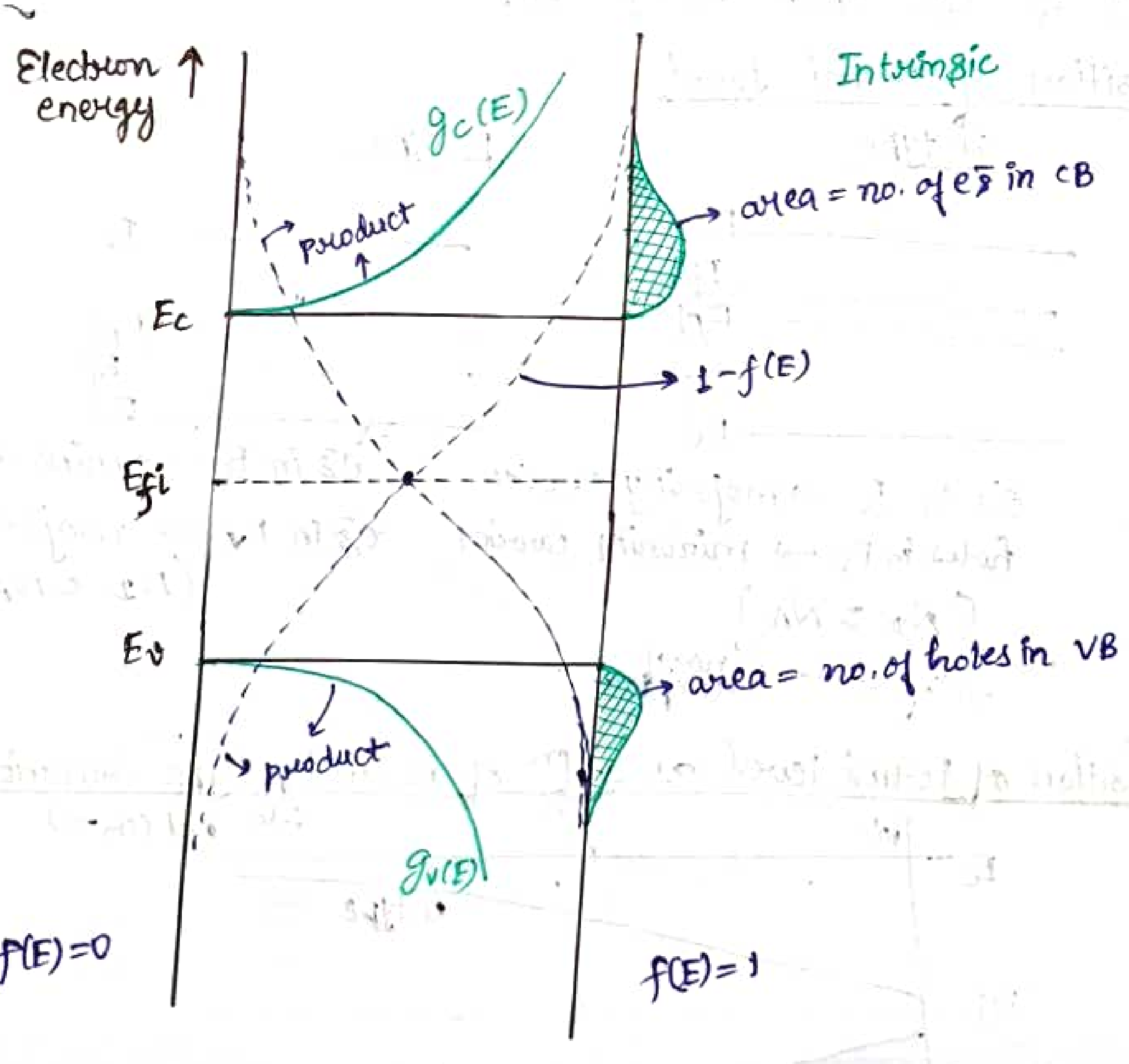
$$= N_c \exp\left[-\frac{(E_c-E_f)}{kT}\right]$$





$$g_{CB}(E) = \sqrt{E-E_c}$$

$$g_{VB}(E) = \sqrt{E_v-E}$$



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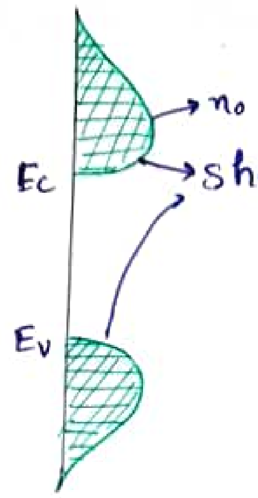


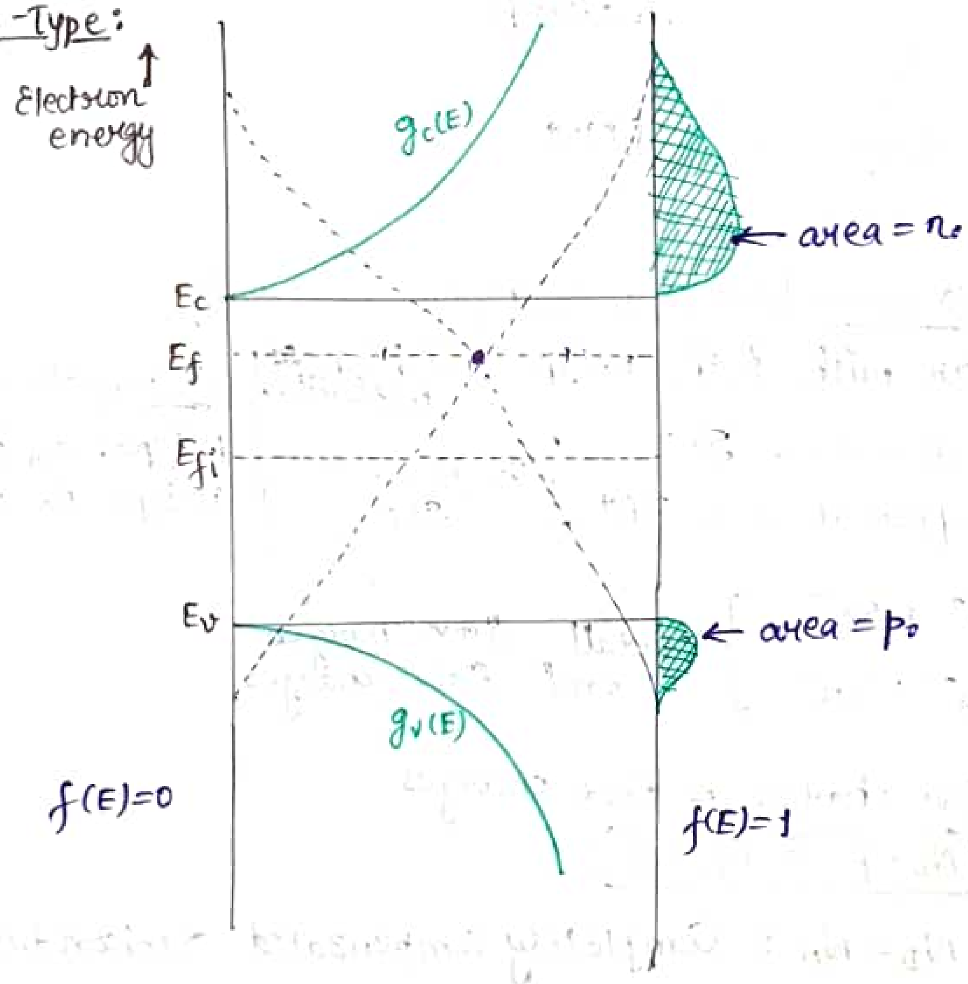
shape can be different but the area will be the same.

Different area due to different curvatures of $f(E)$.

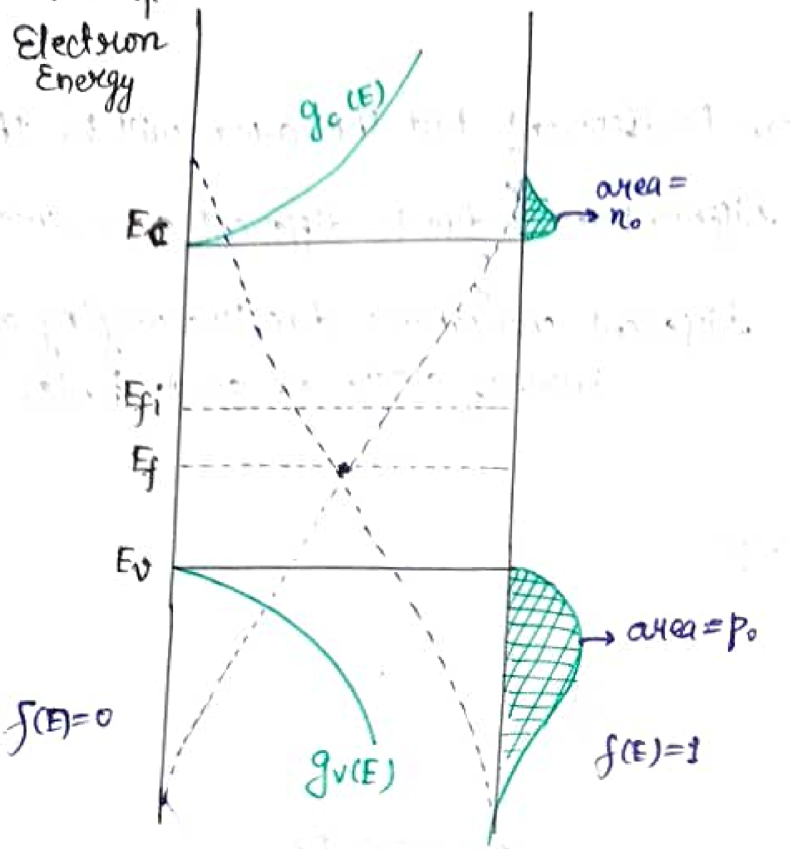
Different curvatures due to varying effective mass of electrons and holes.

Extrinsic Semiconductors

n-Type:



p-Type:



Compensated semiconductor and charge neutrality

↳ Semiconductor with both n-type and p-type impurities.

Extrinsic semiconductors:
p-type: N_A (acceptors)
n-type: N_D (donors)

Eg. 5 donor atoms → $5e^-$
3 ~~do~~ acceptor atoms → $3h^+$
} Compensated SCs

$\xrightarrow[\text{donors}]{\text{ionising 5}} 5N_D^+ + 5e^-$
$\xrightarrow[\text{acceptors}]{\text{ionising 3}} 3N_A^- + 3h^+$
} overall 8 ⊕ve charges and 8 ⊖ve charges.

→ ⊕ve charges = ⊖ve charges

$$\boxed{N_D + p_o = N_A + n_o}$$

→ $N_D = N_A$: Completely Compensated semiconductor

As $n_o p_o = n_i^2$

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

$$\Rightarrow n_o^2 + (N_A - N_D)n_o - n_i^2 = 0$$

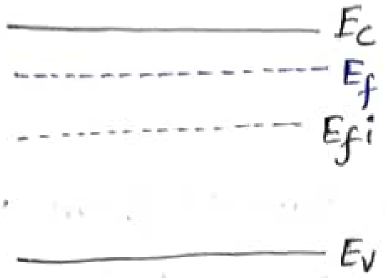
$$\Rightarrow \boxed{n_o = \frac{(N_D - N_A)}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}}$$

Similarly,

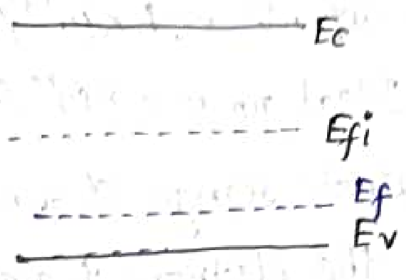
$$\boxed{p_o = \frac{(N_A - N_D)}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}}$$

14-02-2024

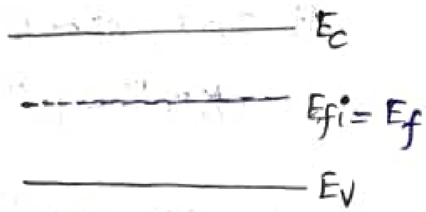
→ $N_D > N_A$: n-compensated SC
$N_A > N_D$: p-compensated SC
$N_A = N_D$: Completely compensated SC
↳ behaves similar to intrinsic SC



n-compensated



p-compensated

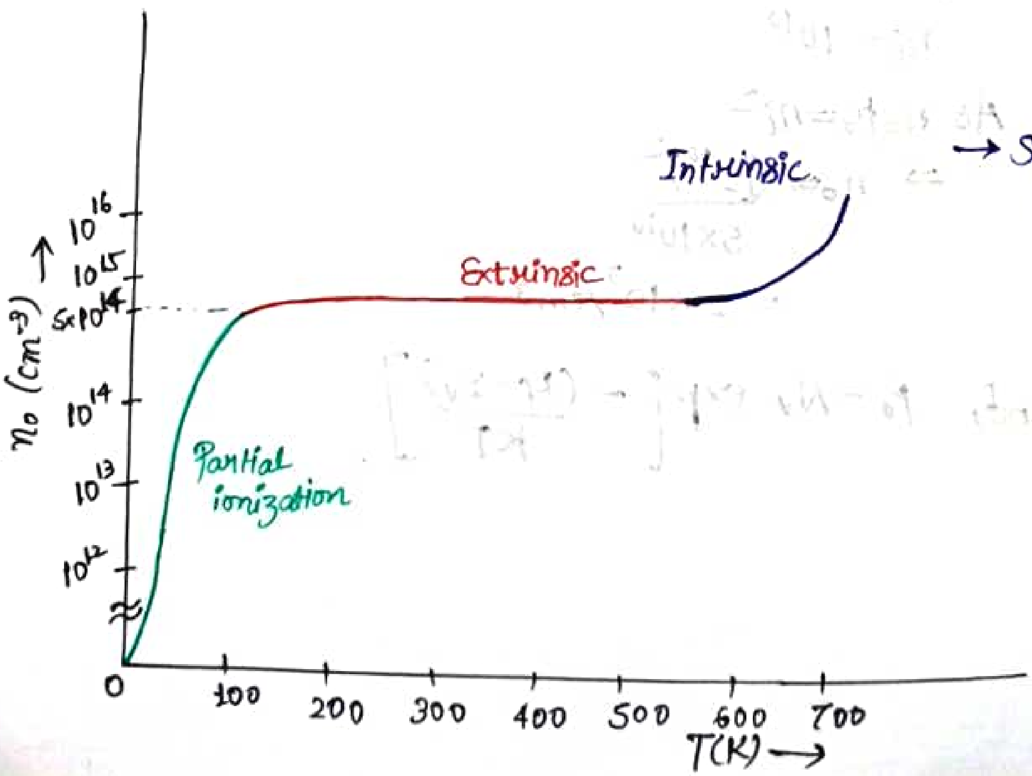


Completely compensated

Charge Neutrality : In any doped semiconductor, total no. of positive and negative charges are the same.

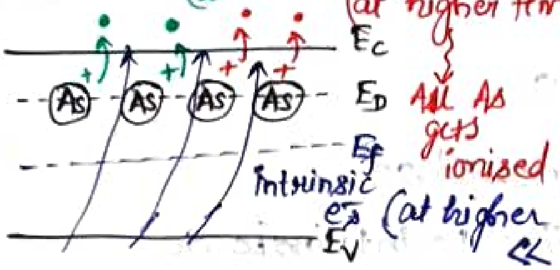
$$N_D + P_0 = N_A + n_0$$

Carrier Concentration as a function of temperature :



→ Semiconductor devices are generally operated in extrinsic region (200 K – 400 K).

(at 50K) ⇝ some As release e^-s (donor e^-s) ⇝ dominates



At 0K, no e^-s in CB : Freeze-Out Zone

As dopants $\sim 5\times10^{14}/cm^3$

Ideal $n_0 = 5\times10^{14}/cm^3$

→ In extrinsic range (higher temp.), some e^-s from VB excite to CB.

↳ But the electrons from dopants (donor electrons) still dominate over intrinsic e^-s

At 300 K, $n_i \sim 10^{10}/cm^3$ (for Si)

$5\times10^{14} + 10^{10} \approx 5\times10^{14}$

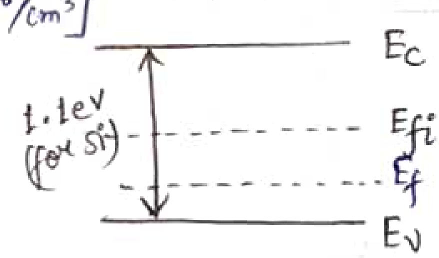
Q) A silicon sample is doped with 5×10^{16} Boron atoms/cm^3. Assuming complete ionization, calculate the equilibrium electron concentration n_0 at 300K. What is the position of Fermi level with respect to the valence band edge and intrinsic Fermi level?

Assume $n_i = 10^{10}/cm^3$; $N_V = 10^{19}/cm^3$.

Soln: For complete ionization, [p-type material]

$p_0 = 5\times10^{16}/cm^3$ [$\because N_A = 5\times10^{16}/cm^3$]

$n_i = 10^{10}/cm^3$



As $n_0 p_0 = n_i^2$

$\Rightarrow n_0 = \dfrac{(10^{10})^2}{5\times10^{16}}$

$= 2\times10^3/cm^3$

and, $p_0 = N_V \exp\left[-\dfrac{(E_f - E_V)}{KT}\right]$

$\Rightarrow E_f = E_V + KT \ln\left[\dfrac{N_V}{p_0}\right]$ [$KT \approx 25meV$ at room T $\approx 26meV$]

$\Rightarrow E_f = E_V + 25m \ln\left(\dfrac{10^{19}}{5\times10^{16}}\right)$

$\Rightarrow (E_f - E_V) = 0.132 eV$

15-02-2024

and, $E_f - E_{fi} = (E_V + 0.132) - (E_V + 0.55)$

$= 0.132 - 0.55$

$= -0.418\ eV$

$\Rightarrow E_f = E_{fi} - 0.418\ eV$

Q) A silicon sample is doped with 10^{17} As atoms/cm^3. Assuming complete ionisation, what is the equilibrium hole concentration p_0 at 300K? Where is E_f relative to E_i? [Take $n_i = 10^{10}/cm^3$, $N_V = 10^{19}/cm^3$]

Soln: $N_D = 10^{17}/cm^3$

For complete ionisation,

$n_0 = 10^{17}/cm^3$

As $n_0 p_0 = n_i^2$

$\Rightarrow p_0 = \frac{(10^{10})^2}{10^{17}}$

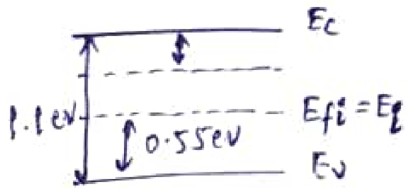
$= 10^3/cm^3$

and, $n_0 = n_i \exp\left[\frac{E_f - E_{fi}}{KT}\right]$

$\Rightarrow 10^{17} = 10^{10} \exp\left[\frac{E_f - E_i}{25m}\right]$

$\Rightarrow \ln[10^7] \times 25m = E_f - E_i$

$\Rightarrow E_f - E_i = 0.4eV$



For $N_C = N_V$

$E_{fi} = \frac{E_C + E_V}{2}$

22-02-2024

GaAs doped with Silicon

Ga → (3) As → (5) Si (4) → dopant

→ If Si replaces Ga, it would be n-type.
→ If Si replaces As, it would be p-type.

Carrier Transport

→ When the electrons or holes move, they take charge with them.
→ Carriers can move, recombine or generate.
$\underbrace{\text{move}}_{\text{transport}}$

Transport Mechanism

- Drift
- Diffusion

Drift: Motion of charge carriers under the application of an electric field [Drift current]

Diffusion: Particles move from region of higher concentration to region of lower concentration.

Drift:

$$J_{drift} = \text{charge} \times \text{no. of charges} \times \text{Drift velocity}$$

$$\Rightarrow \text{current density (holes)} = \underbrace{q}_{\text{charge}} \cdot \underbrace{p}_{\text{no. of holes}} \cdot \underbrace{V_d}_{\text{drift velocity}}$$

and, $J_e = q \cdot n \cdot V_d$

$$\therefore \boxed{J_{drift} = q\,[n+p]\,V_d}$$

$$\underset{(i/p)}{E} \longrightarrow \underset{(o/p)}{V_D}$$

$V_D \propto E \Rightarrow V_D = \mu E$ → macroscopic picture of carrier mobility

μ → mobility of carriers

$$J_p = q\,n \cdot \mu_h E$$

$J_n = q \cdot n \cdot \mu_e E$ ⟶ charge is $\ominus q$, velocity is $-\mu_e E$.

$\therefore$ $J_{drift} = q \cdot p \cdot \mu E$

or, $\boxed{J = \sigma E}$ ... Ohm's law

Macroscopic Picture:

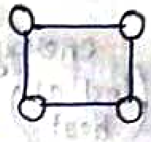
$V_D = \mu E$

Perfect crystal lattice:

- No defects
- No impurities
- No lattice vibration $[T = 0K]$

↳ Electrons and holes will feel zero resistance while moving in perfect crystal lattice.

→ At T finite temperature, particles will have thermal energy. These atoms will vibrate about a mean position due to thermal energy.



Real Crystal Lattice:

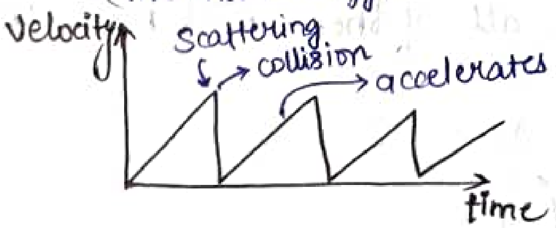
- Defects
- Impurities
- Lattice vibration

↳ e^-, h will be impeded/obstructed by lattice while moving.

Obstruction or impedance } Resistance

$$\underbrace{\frac{3}{2}KT}_{\text{(average thermal energy)}} = \frac{1}{2} m^* V_{Th}^2$$

V_{Th} ↳ thermal velocity



→ Thermal energy is always there.

→ Larger the no. of scattering, larger will be resistance of the materials.

→ The distance that particle travels between consecutive collision : mean-free path

→ The time between two successive collisions : Relaxation time (τ)

↳ It accelerates for 'τ' time.

→ Larger τ, lesser resistance. [Like walking on a crowded plateform]

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$\rightarrow \boxed{V_D = \mu E}$

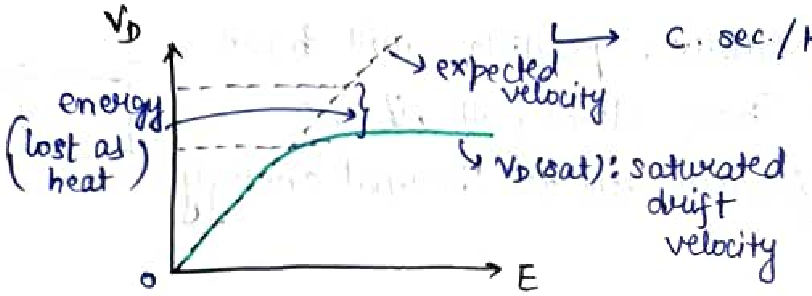
$F = m^* a = qE = m^* \frac{V_D}{\tau}$

$\Rightarrow \boxed{V_D = \frac{q\tau E}{m^*}}$

$\mu = \frac{q \cdot \tau}{m^*}$: Microscopic picture of carrier mobility

$V_D = \mu \cdot E \Rightarrow \mu = \frac{V_D}{E} \equiv \frac{LT^{-1}}{MLT^{-2}AT^{-1}}$

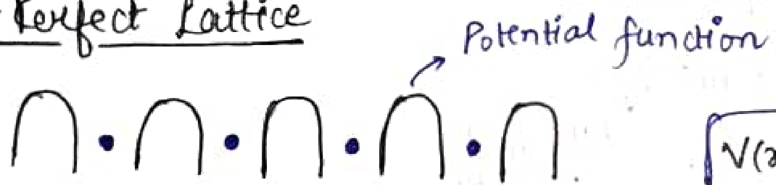
$\hookrightarrow$ C. sec./kg



Factors affecting mobility :

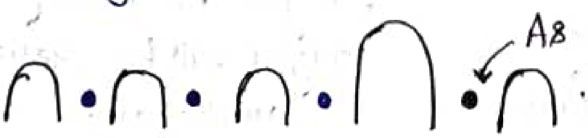
$\hookrightarrow$ Scattering due to
- impurities : impurity scattering
- lattice : lattice scattering OR phonon scattering

Si - Perfect Lattice



$\boxed{V(r) \propto \frac{1}{r}}$

$\hookrightarrow$ Periodic potential ; all of them will have the same potential.



$\hookrightarrow$ Potential is different when impurities are there because of which scattering occurs.

In lattice scattering, Si atoms are vibrating about mean position due to thermal energy which results in scattering.

μ_L : mobility due to lattice scattering.

$\mu_L \propto T^{-3/2}$ [T↑ ⇒ more scattering ⇒ μ↓]

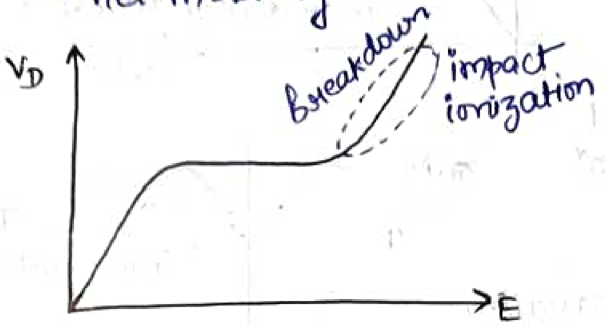
μ_I : ~~sca~~ mobility due to impurity scattering

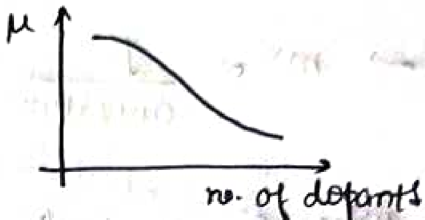
$\mu_I \propto \frac{T^{3/2}}{N}$, N: no. of impurities at smaller velocity at smaller temp. e^-, As^+ interact more, so mobility will be less.

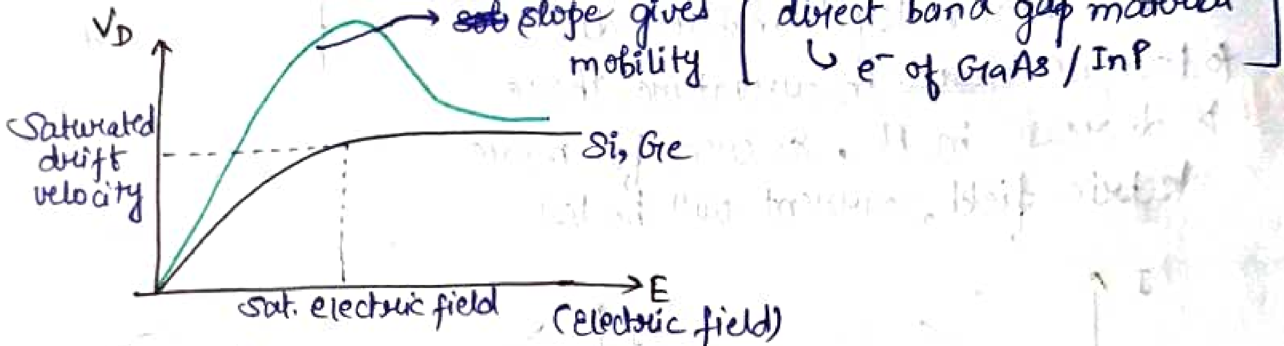
As^+ ↑ ionized impurity

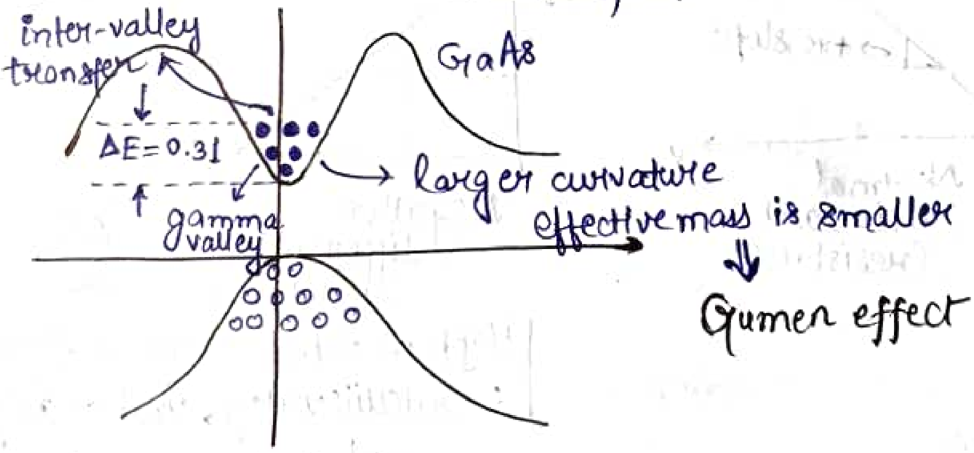
→ $\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L}$

↳ net mobility









Two Valley Model Theory:

As you increase electric field, e^- will go to other ~~sattelite~~ satellite valleys, whose curvature is small, effect mass (m^*) is larger, mobility is less.

As there are no satellite valleys in V.B., this phenomenon is displayed only by electrons.

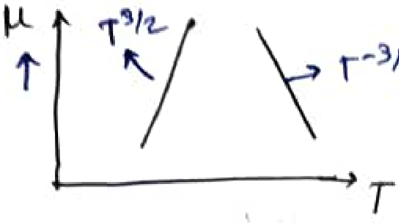
27-02-2024

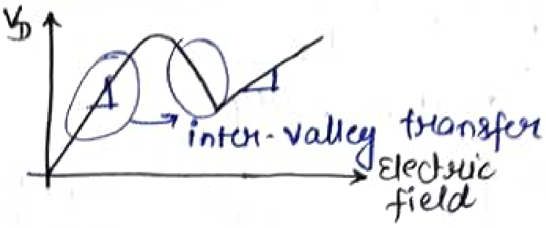
Drift: $V_D = \underbrace{\mu}_{\text{mobility}} \cdot E$, So devices made with GaAs are much faster than Si b/c $\mu_{GaAs} > \mu_{Si}$.

Scattering:

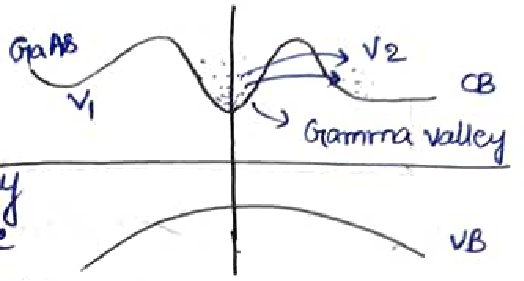
- Lattice scattering : $\mu_L \propto T^{-3/2}$
- Impurity scattering : $\mu_I \propto \frac{T^{3/2}}{N}$

Resultant mobility : $\boxed{\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I}}$.

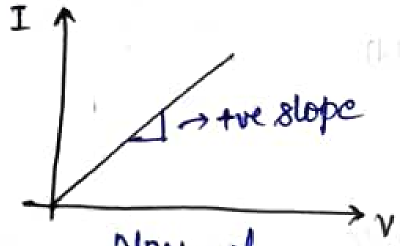




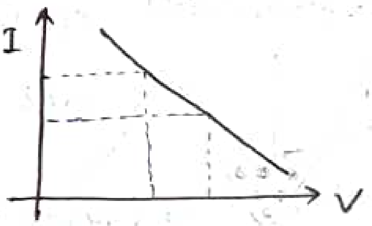
→ $m^* \propto \frac{1}{\text{curvature}}$, $\mu \propto \frac{1}{m^*}$



When e^- moves from Gamma valley to V_2 (inter-valley transfer), due to decrease ~~incre~~ in curvature, there is decrease in μ, so even for more electric field, current will be less.



Normal conductors (resistors).



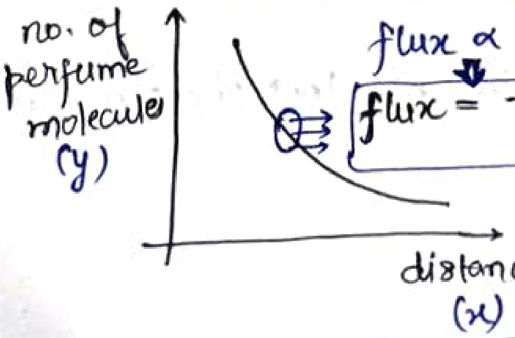
Negative differential resistance $= \frac{\Delta V}{\Delta I}$

[Happens when e^- move from valley to satellite valley, under high E (GaAs)]

↳ Gunn Effect

Diffusion

↳ Particles would move from regions of higher concentration to regions of lower concentration, until a uniform concentration is established.

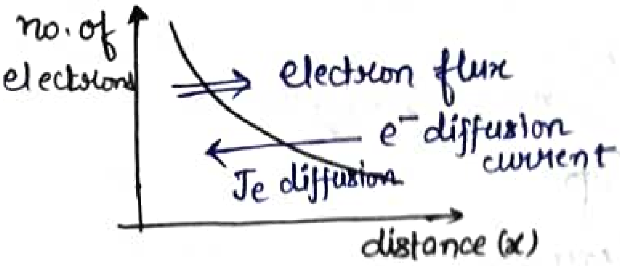


flux $\propto dy/dx$

$\Rightarrow \boxed{\text{flux} = -D\frac{dy}{dx}}$, D : Diffusivity or diffusion coefficient. [cm^2/s]

[If there is concⁿ gradient, diffusion will occur to relax/eliminate the gradient.]

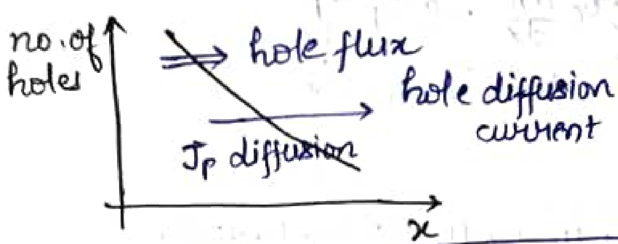
Diffusion Current



→ e^- will move to setup uniform concentration.

$$J_{e,diffusion} = -D_e \frac{dn}{dx} \times \text{charge}$$: Diffusion current density

$$\Rightarrow \boxed{J_{e,diffusion} = D_e \cdot \frac{dn}{dx} \cdot q}$$ (for e^-, charge $= -q$)



$$\boxed{J_{P,\,diffusion} = -D_P \frac{dP}{dx} \cdot q}$$

Total current. $= J_{e,diff} + J_{h,diff} + J_{e,drift} + J_{h,drift}$

[Drift is a forced phenomenon while diffusion is a random phenomenon.]

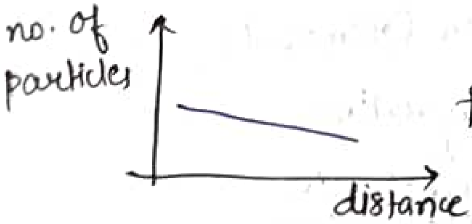
$$\therefore \boxed{J = \underbrace{q[n\mu_e + p\mu_h]E}_{\text{Drift current}} + q\left[D_e \frac{dn}{dx} - D_p \frac{dP}{dx}\right]}$$

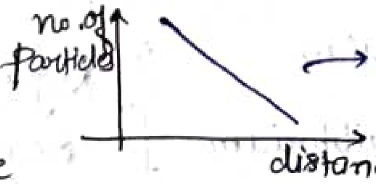
28-02-2024

→ $\frac{dP}{dx}, \frac{dn}{dx}$: concentration gradient

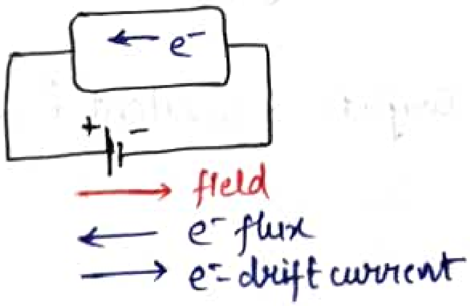
Fick's Law

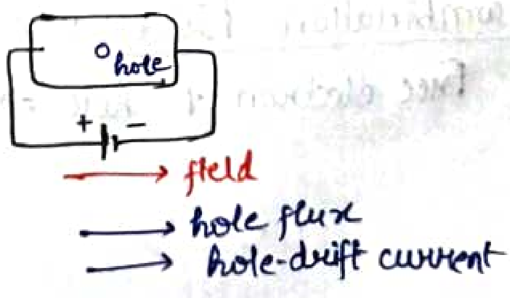
flux ∝ concentration gradient





→ large gradient
⇓
Large ~~flux~~ flux





→ Drift Vs Diffusion

Drift ↓ forced phenomenon (μ: mobility)

Diffusion ↓ random phenomenon (D: diffusivity)

→ $\boxed{\frac{D}{\mu} = \frac{KT}{q}}$: Einstein relationship

KT : thermal energy
$\approx$ 26 mV @ 300K

$\frac{KT}{q}$: thermal voltage [q → only magnitude]

→ $J_{total} = J_{drift} + J_{diffusion}$

$$= \underbrace{q[n\mu_e + p\mu_n]E}_{\text{drift current}} + \underbrace{qD_e\frac{dn}{dx} - qD_p\frac{dp}{dx}}_{\text{diffusion current}}$$

$J_{drift} = q[n\mu_e + p\mu_n]E$

⇒ $\boxed{J = \sigma E}$, $\boxed{\rho = \frac{1}{\sigma}}$, $\boxed{\sigma = q(n\mu_e + p\mu_n)}$: Conductivity

Thermal Equilibrium

1. Temperature is constant.
2. No electric field.
3. No photon falling
4. No pressure.

At thermal equilibrium, $\boxed{n_o p_o = n_i^2}$

Non-equilibrium

$\boxed{n \cdot p \neq n_i^2}$

$n \cdot p > n_i^2$: carrier generation

$n \cdot p < n_i^2$: carrier depletion (removal)

Non-equilibrium
↓
Thermal equilibrium
} Regeneration & Recombination (destroying)

Recombination Process :

Free electron + hole ⇒ Complete a covalent bond

Non-Equilibrium Condition :

Semiconductors, under : [external stimulus]

① Electric field
② Pressure
③ Photon absorption

$$n \cdot p \neq n_i^2$$

Excess carriers :

$$n_0 , \ p_0$$

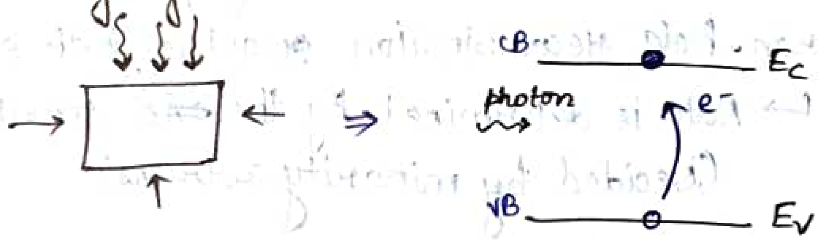
Semiconductors under non-equilibrium would like to come to the equilibrium condition by :

① Recombination of mobile carriers.

② Generation of mobile carriers.

$n \cdot p > n_i^2$: Generation
$n \cdot p < n_i^2$: Depletion

Eg. Generation by light



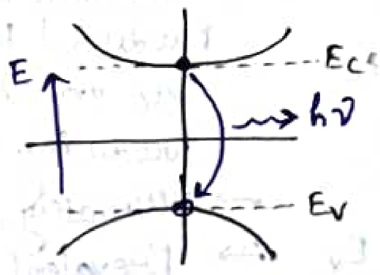
↳ Photogeneration

Eg. Generation by thermal excitation.
Eg. Generation by electric field.

Recombination Process

① Band-band recombination / Radiative recombination / Direct recombination

↳ Direct bandgap (possible only in direct bandgap material).
↳ Called as radiative, due to generation of photon.

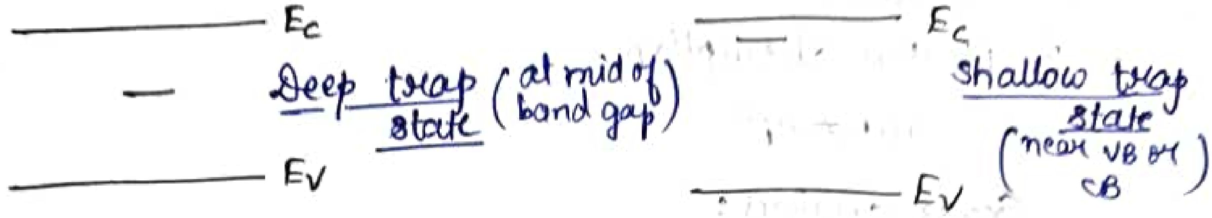


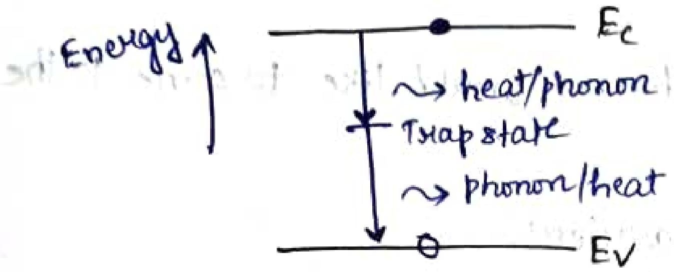
→ e^- in CB directly combines with hole in VB resulting in production of photon.

23-02-2024

② Trap Assisted Recombination / Shockley Reed Hall [SRH]

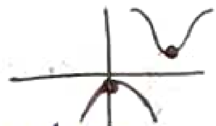
↳ Practically, there may be energy levels in b/w E_c and E_v, called as trap states. [Impurities/ Defect state / Trap level state]





→ Electron, instead of jumping directly from E_c to E_v, jump first to trap state, then to E_v.
↳ This produces heat, not photons.

↳ Indirect recombination.
↳ Non-radiative.
↳ Produces Photons (lattice vibration).
↳ Schockley-Reed-Hall recombination
↳ Possible in indirect-bandgap material.

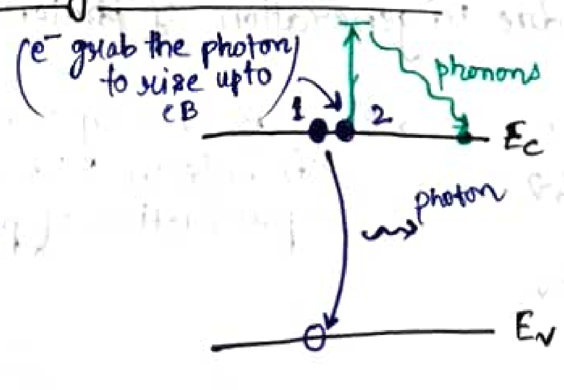


Electron-hole recombination requires both e^- and hole.
↳ Rate is determined by the ~~one~~ carrier smaller in number (Decided by minority carriers)

Recombination Rate,

$\boxed{R = \beta np}$ ⇝ no. of carriers recombined per unit volume per unit time.
↳ (cm^3/s).
↳ depends both on n and p (minority carriers).

③ Auger Recombination



→ 2^{nd} electron captures the photon produced before it can come out; gets excited, then deexcited, producing heat (phonons).
→ Ultimately, no photon is produced
→ Prevalent in direct band-gap material.

Rate of recombination,

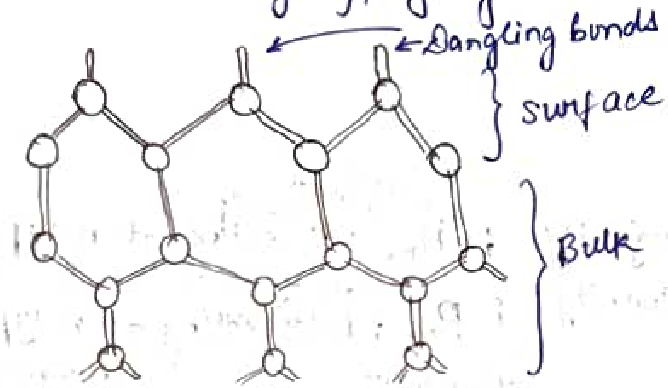
$$\boxed{R = \beta n^2 p} \quad \text{or} \quad \boxed{\beta n p^2} \quad (\text{in}/cm^3/s)$$

↳ Does not depend on minority carriers.

④ Surface Recombination

↳ Recombination that happens ~~at~~ near the surface of device/material.

- Dangling bonds : Unstable bond due to cutting the surface.
- Surface passivation : Passivation (completing the dangling bonds) by applying some material, usually silicon dioxide.



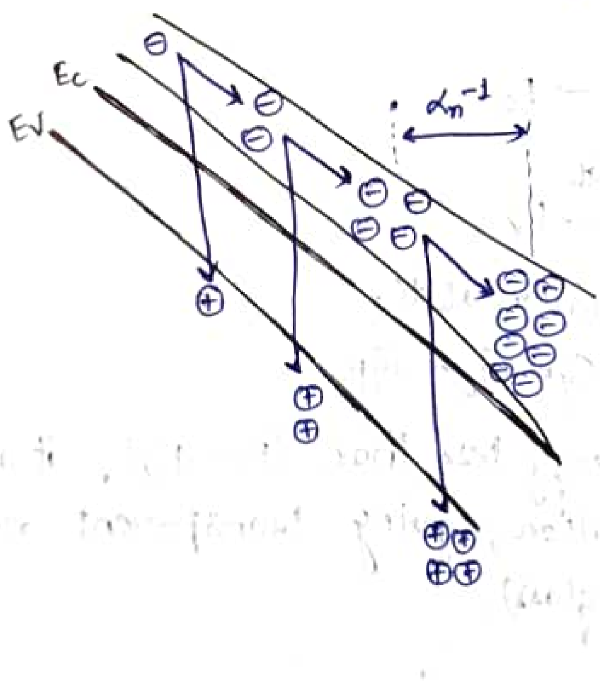
→ when a material is cut, some bonds are broken and they tend to absorb the e⁻s generated in the bulk to complete octet rather than combining with a hole.

Impact Ionization

↳ Generating carriers by applying electric field.

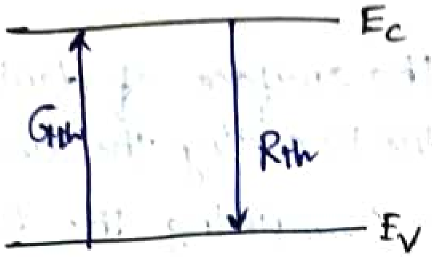
↳ Electrons under high electric field has a large speed, collide with the lattice producing more electrons.

↳ Not a good method, as it may damage the device.



→ Rate of recombination $\propto$ Concentration of excess minority carriers

<u>Direct bandgap material:</u>



G_{th} : Rate of generation at thermal eqm

R_{th} : Rate of recombination at thermal eqm

$$G_{th} = R_{th}$$

$$R = \beta . n . p$$

<u>n-type sc:</u>

$\boxed{\text{n-type}}$ electrons ⇝ majority ; n_{n_0} : e^- sitting at n-type sc at thermal eqm (carrier, material, no. of)

holes ⇝ minority ; p_{n_0} : holes sitting at n-type sc at thermal eqm (no. of, thermal eqm)

<u>p-type sc:</u>

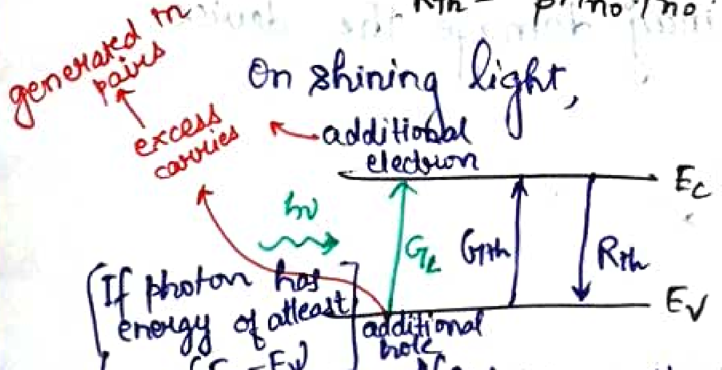
$\boxed{\text{p-type}}$ holes ⇝ majority ; p_{p_0}

electrons ⇝ minority ; n_{p_0}

Under equilibrium,

$$R_{th} = \beta n_{n_0} p_{n_0}$$

On shining light,



New generation rate,

$$G = G_L + G_{th}$$

\# If photon has energy less than $(E_c - E_V)$, it will simply pass without any excitation, giving transparent nature of materials (e.g., glass).

$R = \beta n_n \cdot p_n$, n_n : new electron concentration
p_n : new hole concentration.

$$n_n = n_{n0} + \Delta n$$
$$p_n = p_{n0} + \Delta p$$
$\Delta n = \Delta p$ (excess carriers are generated in pairs)

→ we would keep track of those carriers which are smaller in number, minority carriers (holes in p-type SC).

$$\frac{dp_n}{dt} = G - R$$
$$= G_{th} + G_L - R$$

Steady state : No change in concentration of carriers.
↳ $\frac{dp_n}{dt} = 0$.

At steady state,
$$\frac{dp_n}{dt} = 0.$$

$\Rightarrow G_L = R - G_{th} = U$: net recombination rate

$G_L \Rightarrow R \rightarrow R$
No $G_L \Rightarrow R \rightarrow R_{th}$

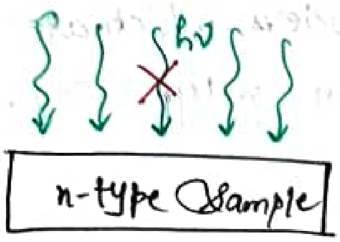
$$U = R - G_{th}$$
$$= \beta n_n p_n - \beta n_{n0} p_{n0}$$
$$= \beta [n_{n0} + \Delta n][p_{n0} + \Delta p] - \beta n_{n0} p_{n0}$$
$$= \beta [\cancel{n_{n0} p_{n0}} + n_{n0}\Delta p + \Delta n\, p_{n0} + \Delta n \Delta p - \cancel{\beta n_{n0} p_{n0}}]$$
$$= \beta [n_{n0} \Delta p + p_{n0} \Delta p + \Delta p \Delta p] \quad [\because \Delta n = \Delta p]$$
$$\Rightarrow U = \beta [n_{n0} + p_{n0} + \Delta p] \Delta p$$

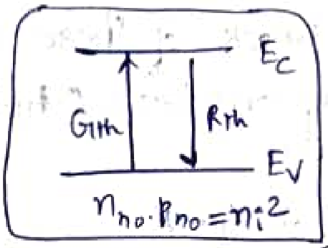
As $n_{n0} \gg p_{n0}, \Delta p$: Low-level injection
[when $n_{n0} \sim \Delta p$: High-level injection]

$$\Rightarrow U = \beta n_{n0} \Delta p$$
$$= \beta n_{n0} [p_n - p_{n0}]$$

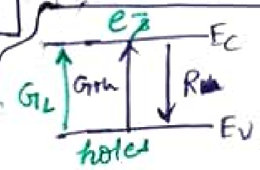
$\Rightarrow U = \dfrac{P_n - P_{no}}{1/\beta n_{no}} = \dfrac{P_n - P_{no}}{\tau_p}$, τ_p: minority carrier lifetime of holes (or excess minority carrier lifetime)

Physical Meaning of τ_p:





Books
→ Ben G. Streetman
or
→ S.M. Sze



$U = \dfrac{P_n - P_{no}}{\tau_P} = G_L$

$P_n = P_{no} + \underbrace{\tau_P G_L}_{\Delta P}$

$\Delta n + n_{no} \rightarrow$ electrons $\rightarrow n_{no}$
$\Delta p + P_{no} \rightarrow$ holes $\rightarrow P_{no}$

On switching off the light, electrons and holes would try to have ~~to~~ their original no., i.e., P_{no} and n_{no}.

Lifetime (τ_p): Time it would take electrons and holes to have n_{no} and P_{no} of them after switching off light.

$G_L = R - G_{th} = U = \dfrac{P_n - P_{no}}{\tau_P}$ (at steady state) → net recombination rate

$P_n = P_{no} + (\tau_P G_L) \rightarrow$ steady state hole concentration

or, $P_n = P_{no} + \Delta p$

01-03-2024

At $t=0$, light is turned off.

$G_L = 0$.

[$\Delta n, \Delta p$ decreases to zero due to recombination of holes and electrons.]

when $G_L = 0$,

$$\frac{dP_n}{dt} = G_{th} - R = -U = -\left[\frac{P_n - P_{no}}{\tau_P}\right]$$

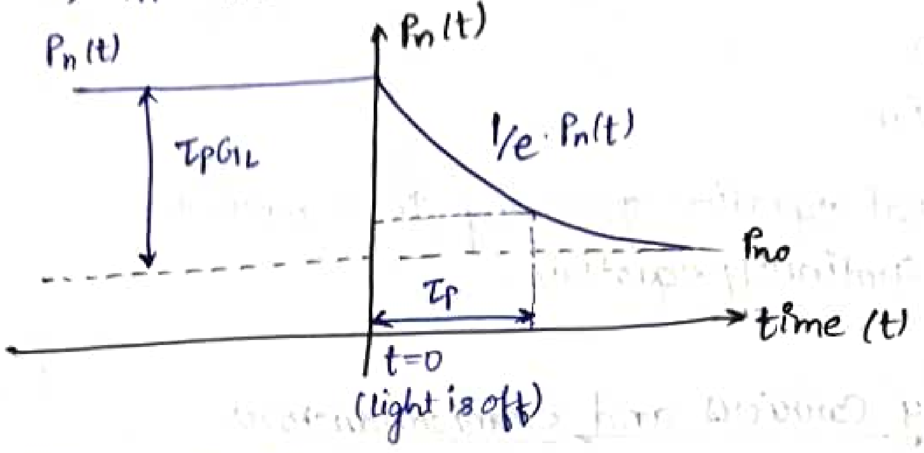
$$\Rightarrow \frac{dP_n}{dt} = -\left[\frac{P_n - P_{no}}{\tau_P}\right]$$

There's a decay in the carrier concentration.

At $t=0$ (time at which laser is turned off),

$$P_n = P_{n0} + \tau_p G_L$$

At $t \to \infty$, $P_n = P_{n0}$



Take $P_n - P_{n0} = y$

$$\Rightarrow dP_n = dy$$

$$\therefore \frac{dy}{dt} = -\frac{y}{\tau_p}$$

$$\Rightarrow \frac{dy}{y} = -\frac{dt}{\tau_p}$$

$$\Rightarrow \log y = -\frac{t}{\tau_p} + K$$

$$\Rightarrow \log[P_n - P_{n0}] = -\frac{t}{\tau_p} + K$$

At $t=0$, $P_n = P_{n0} + \tau_p G_L$.

$$\Rightarrow K = \log[G_L \tau_p]$$

$$\therefore \log(P_n - P_{n0}) = -\frac{t}{\tau_p} + \log(G_L \tau_p)$$

$$\Rightarrow P_n - P_{n0} = e^{-t/\tau_p} \cdot G_L \tau_p$$

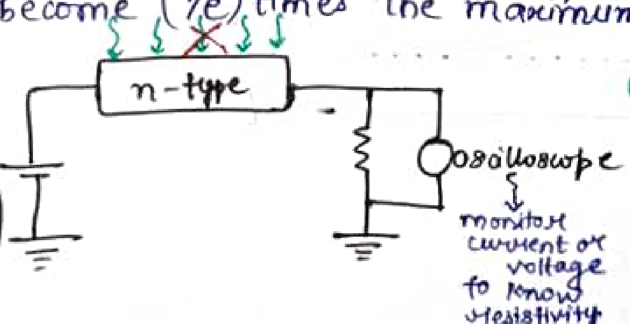
~~Pno Pno + G~~

Depends on type of the semiconductor $\therefore$ $\boxed{P_n(t) = P_{n0} + G_L \tau_p e^{-t/\tau_p}}$

→ exponential decay

Minority carrier lifetime: Time taken by minority carriers to become (1/e) times the maximum number of them, P_n.

Experimental Setup: (Lifetime measurement using Photoconductivity method)



On turning on light, conductivity ↑ Resistivity ↓

On turning off light, conductivity ↓ Resistivity ↑

→ Transportation mechanisms for charges:

1. Drift [applied electric field]
2. Diffusion [concentration gradient]
3. Generation
4. Recombination.

↳ Mathematical equation governing these methods: continuity equation.

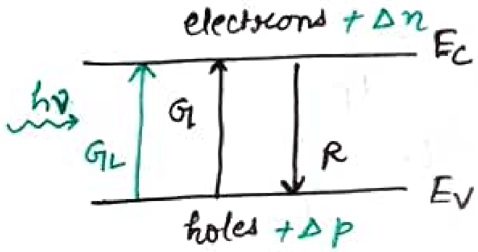
04-03-2024

* Excess Minority Carriers and Semiconductors under Non-Equilibrium Conditions

$n_0 p_0 = n_i^2$

$G_{th} = R_{th}$

$G_0 = R_0$



Non-equilibrium:

$n \cdot p \neq n_i^2$

$n = n_0 + \Delta n$

$p = p_0 + \Delta p$

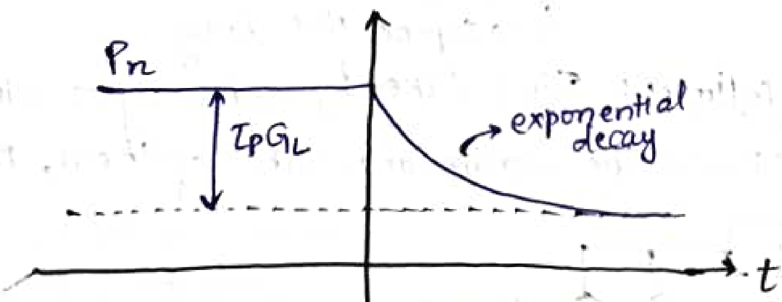
n-type: electrons → majority
holes → minority

Rate of recombination,

$$U = \frac{P_n - P_{n0}}{\tau_p} = G_L$$

$$P_n = P_{n0} + \underbrace{\tau_p G_L}_{\Delta p}$$

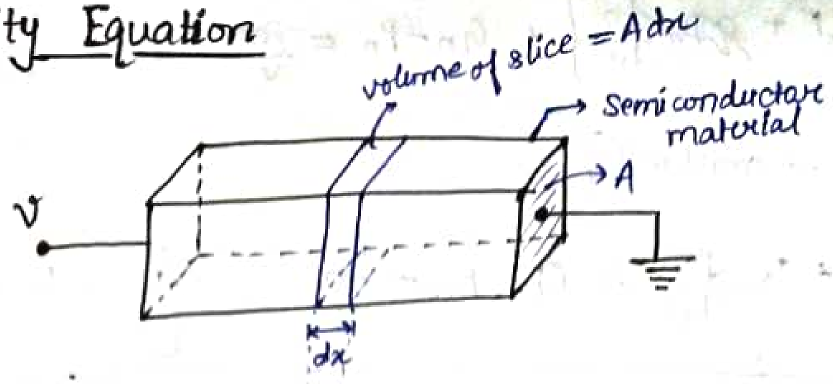
additional holes produced

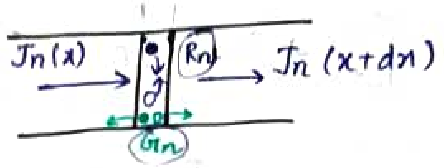


$$\boxed{P_n(t) = P_{n0} + \tau_p G_L e^{-\frac{t}{\tau_p}}}$$

0 at $t \to \infty$

Continuity Equation





R_n : rate of recombination
G_n : rate of generation

[Electrons are entering and leaving due to diffusion and drift]

Net rate of change of electron concentration in a volume of Adx,

[Electrons increasing: e^-s entering, e^- generated
Electrons decreasing: e^-s leaving, e^- recombined]

$$\frac{\partial n}{\partial t} Adx = \left[\frac{J_n(x)}{-q} A + G_n Adx\right] - \frac{J_n(x+dx)}{-q} A - R_n Adx$$

$$= \underbrace{\left[\frac{J_n(x)}{-q} - \frac{J_n(x+dx)}{-q}\right]}_{e^- \text{ due to drift + diffusion}} A + [G_n - R_n] Adx.$$

$$= -\frac{1}{q}\left[J_n(x) - J_n(x+dx)\right] A + [G_n - R_n] Adx$$

$$\left[= -\frac{1}{q}\left[\underbrace{qn\mu E}_{\text{drift current}} + \underbrace{q D_n \frac{dn}{dx}}_{\text{diffusion current}}\right] \right]$$

[Assuming 'dx' to be very small,
$$J_n(x+dx) \approx J_n(x) + \frac{\partial J_n(x)}{\partial x} . dx$$]

$$= -\frac{1}{q}\left[\cancel{J_n(x)} - \left[\cancel{J_n(x)} + \frac{\partial J_n(x)}{\partial x} dx\right]\right] A + [G_n - R_n] Adx$$

$$\Rightarrow \frac{\partial n}{\partial t} Adx = \frac{1}{q} \cdot \frac{d}{dx}\underbrace{[J_n(x)]}_{\text{(drift + diffusion)}} Adx + [G_n - R_n] Adx$$

$$\Rightarrow \frac{1}{q} \cdot \frac{d}{dx}\left[q n \overset{\text{mobility of } e^- \text{(const.)}}{\mu_n E} + q \overset{\text{diffusivity of } e^- \text{(const.)}}{D_n} \frac{dn}{dx}\right] + G_n - R_n = \frac{\partial n}{\partial t}$$

$[\mu_n, D_n \rightarrow \text{constants}]$

$$\Rightarrow \mu_n\left[\frac{d}{dx}(n \cdot E)\right] + D_n \frac{d^2 n}{dx^2} + G_n - R_n = \frac{\partial n}{\partial t}$$

[E can be space-dependent]

$$\Rightarrow \boxed{\mu_n \cdot n_p \frac{dE}{dx} + \mu_n \cdot E \frac{dn_p}{dx} + D_n \frac{d^2 n_p}{dx^2} + G_n - \left[\frac{n_p - n_{p_0}}{\tau_n}\right] = \frac{\partial n_p}{\partial t}}$$

(for p-type material)

...①

[For holes: $R = \frac{p_n - p_{no}}{\tau_p}$ (n-type)

For e⁻s: $R = \frac{n_p - n_{p_0}}{\tau_n}$ (p-type)]

For holes:

$$\boxed{\frac{\partial p_n}{\partial t} = \underbrace{-p_n \cdot \mu_p \frac{\partial E}{\partial x} - \mu_p E \frac{\partial p_n}{\partial x}}_{\text{Drift}} + \underbrace{D_p \frac{\partial^2 p_n}{\partial x^2}}_{\text{Diffusion}} + \underbrace{G_p}_{\text{Generation}} - \underbrace{\left[\frac{p_n - p_{no}}{\tau_p}\right]}_{\text{Recombination}}}$$

(for n-type material)

...②

Considering only one-dimension,

$$\frac{dp_n}{dt} = -p_n \mu_p \frac{dE}{dx} - \mu_p E \frac{dp_n}{dx} + D_p \frac{d^2 p_n}{dx^2} + G_p - \left[\frac{p_n - p_{no}}{\tau_p}\right]$$

Poisson's Equation

↳ gives expression for electric field, E, due to dipole.

$$\frac{dE}{dx} = \frac{\rho}{\epsilon}$$ ...③

, ρ: charge density b/c of ionized impurities

\# Solving ①, ②, ③ would give current due to electric field.

For $E = 0$, $G_n = 0$, infinite lifetime,

$$D_n \frac{d^2 n_p}{dx^2} = \frac{dn_p}{dt}.$$

07-03-2024

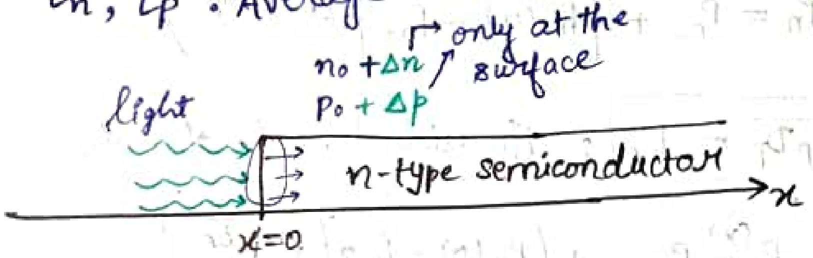
Conditions:

① Steady state : time-dependance = 0
② Electric field, E = 0.
③ Infinite lifetime : $\frac{1}{\tau_p} = 0 \Rightarrow$ Recombination term $= 0$.

Diffusion length: Average distance travelled by carriers before recombining.

↳ For electron : L_n
↳ For hole : L_p.

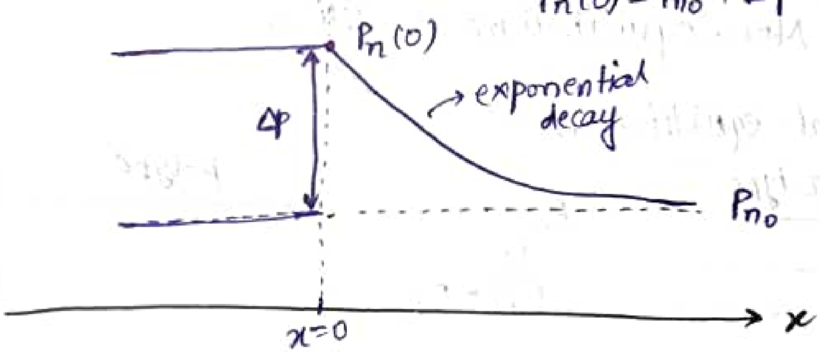
Lifetime: τ_n, τ_p : Average time the carrier survives before recombining.



we are assuming that the light absorption happens only at $x=0$.

$x=0$: large concentration of e^-s and holes $\xrightarrow{\text{diffuse}}$ $x>0$: less concⁿ of e^-s and holes

$P_n(0) = P_{n0} + \Delta P$



$P_n(0)$: hole concen at $x=0$
P_{n_0} : hole concen ~~before light turned on~~ (at ∞ x)

At steady state,

[finite only at x=0, & we're interested in x>0]

$$\frac{\partial P_n}{\partial t} = \cancel{P_n \mu_p \frac{\partial E}{\partial x}}^{\,0} + \cancel{\mu_p E \frac{\partial P_n}{\partial x}}^{\,0} + D_p \frac{\partial^2 P_n}{\partial x^2} + \cancel{G_p}^{\,0} - \left[\frac{P_n - P_{n0}}{\tau_p}\right]$$

[we're not applying $\vec{E}$.]

$$\Rightarrow D_p \frac{\partial^2 P_n(x)}{\partial x^2} - \left[\frac{P_n(x) - P_{n0}}{\tau_p}\right] = 0$$

$$\Rightarrow \frac{\partial^2 P_n}{\partial x^2} = \frac{P_n - P_{n0}}{\tau_p D_p}$$ → Possible solution : ~~e^x~~ e^{-x} ✓ ~~sin~~ ~~cos~~

But as concⁿ ↓ with x, only valid solution is e^{-x}.

$\therefore \quad \dfrac{d^2y}{dx^2} = \dfrac{y}{\tau_p D_p}$ $\quad\Big|\quad P_n - P_{n_0} = y$

$\Rightarrow \dfrac{d^2P_n}{dx^2} = \dfrac{d^2y}{dx^2}$

$\Rightarrow y = K_1 e^{\frac{-x}{\sqrt{\tau_p D_p}}} + K_2$

Boundary conditions:

At $x=0$, $P_n = P_n(0)$

At $x \to \infty$, $P_n = P_{n_0}$

$P_n - P_{n_0} = K_2$

$P_n(0) - P_{n_0} = K_1$

$$\therefore \quad P_n = P_{n_0} + \left[P_n(0) - P_{n_0}\right]\left(e^{\frac{-x}{\sqrt{\tau_p D_p}}}\right)$$

$\boxed{\sqrt{\tau_p D_p} = L_p}$: diffusion length of holes

$$\Rightarrow \boxed{P_n(x) = P_{n_0} + \left[P_n(0) - P_{n_0}\right] e^{-\frac{x}{L_p}}}$$

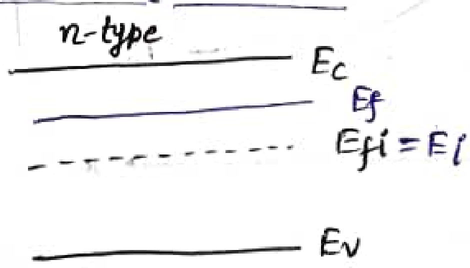
$\boxed{\sqrt{\tau_n D_p} = L_n}$: diffusion length of electrons.

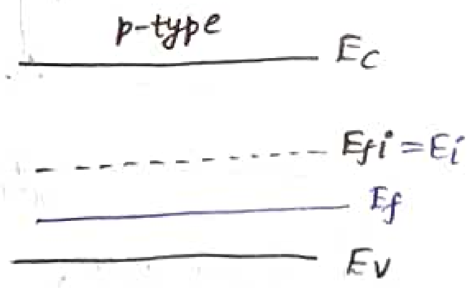
12-03-2024

$n_0 p_0 = n_i^2$: Equilibrium

$n_0 p_0 \neq n_i^2$: Non-equilibrium condition

Under thermal-equilibrium:





Non-equilibrium condition:

↳ Concept of fermi-level (E_f) is not valid anymore.

↳ Quasi-Fermi energy level $\rightleftarrows$ electrons / holes

IMREF level (FERMI spelt backwards)

Excess carriers:

$n_0 \to n_0 + \Delta n$

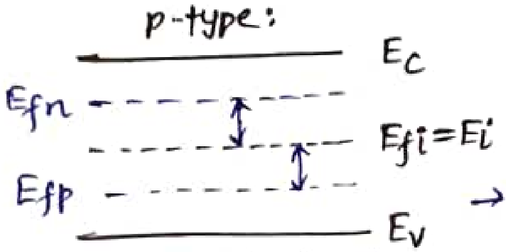
$p_0 \to p_0 + \Delta n$

$$n_0 = n_i \exp\left(\frac{E_f - E_{fi}}{KT}\right) \longrightarrow n_0 + \Delta n = n_i \exp\left(\frac{E_{fn} - E_{fi}}{KT}\right)$$

$$p_0 = n_i \exp\left(\frac{E_{fi} - E_f}{KT}\right) \longrightarrow p_0 + \Delta p = n_i \exp\left[\frac{E_{fi} - E_{fp}}{KT}\right]$$

E_{fn} : Quasi-Fermi level for electrons
E_{fp} : Quasi-Fermi level for holes

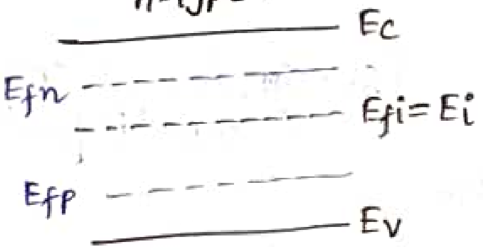
p-type:



→ Both E_{fn} & E_{fp} will be present.

$n_0 p_0 \neq n_i^2$

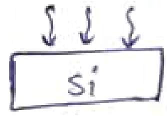
n-type:



Q) Assume that $10^{13}/cm^3$ EHPs are generated optically every microsecond in a Si sample with $n_0 = 10^{14}/cm^3$. The life-time of electron and hole concentration is $2\mu s$. Also plot the Quasi-Fermi levels for electron and hole for the sample. $[n_i = 1.5 \times 10^{10}/cm^3]$

Calculate the equilibrium and steady-state electron and hole concentration

Soln:



$10^{-6}s \longrightarrow 10^{13}/cm^3$

$1s \longrightarrow 10^{19}/cm^3/s \quad [=G]$

At equilibrium,

$n_0 = 10^{14}/cm^3$

$n_i = 1.5 \times 10^{10}/cm^3$

$\therefore p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{14}}$

$= 2.25 \times 10^6 /cm^3$

After giving light,

$G = 10^{19}/cm^3/s$

$\tau = 2 \times 10^{-6} s$

$P_n = P_{n_0} + G \cdot \tau \qquad$ [n-type]

$= 2.25 \times 10^6 + \underbrace{10^{19} \times 2 \times 10^{-6}}_{\Delta P}$

$= 2.25\times10^{6} + 2\times10^{13}$

$\approx 2\times10^{13}/cm^3$

$n_n = n_{n_0} + G\,\tau_n \quad [n_o = 10^{14}/cm^3]$

$= 10^{14} + 10^{19}\times2\times10^{-6}$

$= 1.2\times10^{14}/cm^3.$

$P_n \gg p_0$ [minority carrier]

$n_n \approx n_0$

Using $n_o + \delta n = n_i \exp\left[\frac{E_{fn}-E_{fi}}{KT}\right]$

$\Rightarrow E_{fn} - E_{fi} = \ln\left(\frac{n_o+\delta n}{n_i}\right)\times KT$ [$\delta n = \delta p$, because they're generated in pair]

$= \ln\left(\frac{1.2\times10^{14}}{1.5\times10^{10}}\right)\times 26m$

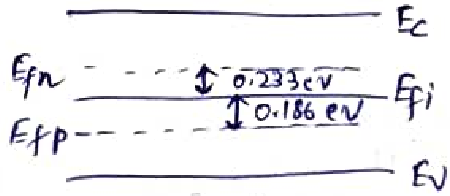
$= 0.233\,eV$

and, $p_0 + \delta p = n_i \exp\left(\frac{E_{fi}-E_{fp}}{KT}\right)$

$\Rightarrow E_{fi} - E_{fp} = \ln\left(\frac{2\times10^{13}}{1.5\times10^{10}}\right)\times 26m$

$= 7.195\times 26m$

$= 0.186\,eV$



Q) Consider an n-type Silicon sample with a doping conⁿ $N_D = 10^{16}/cm^3$. If it is luminated such that EHPs at a rate of $10^{18}/cm^3$ per second are generated, calculate the majority and minority carrier concentrations at steady state. Assuming the life-time to be 1 microsecond, plot the decay of the excess carriers with time once the light source is turned off.
Also plot the Quasi-Fermi levels for electron and hole for the sample. $[n_i = 1.5\times10^{10}/cm^3]$.

Soln:

$\tau = 1\times10^{-6}s$ (Lifetime)

photons

$\boxed{\text{n-type}}$

$\Delta n = 10^{12}/cm^3$

$\Delta p = 10^{12}/cm^3$

$n_0 = 10^{16}/cm^3$

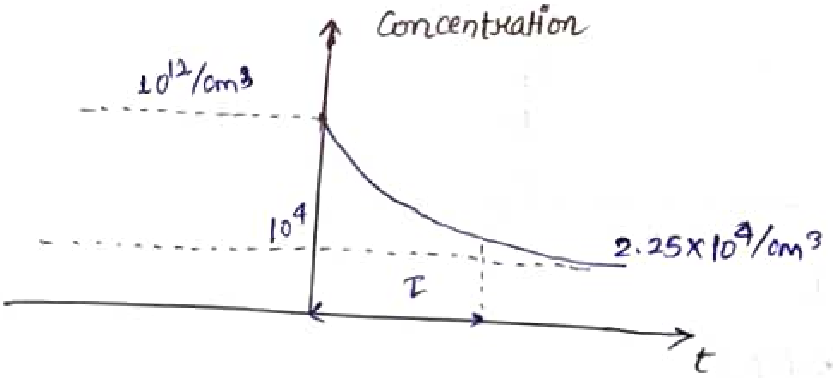
$n_i = 1.5\times10^{10}/cm^3$

$\therefore p_0 = \frac{n_i^2}{n_0} = 2.25\times10^4/cm^3$

$G.\tau_n = 10^{18}/cm^3/s \times 1\times10^{-6}s$
$= 10^{12}/cm^3$

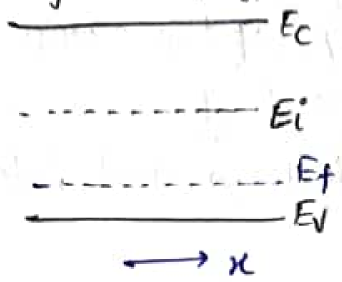
$\therefore P_n = 2.25\times10^4 + 10^{12}$
$\approx 10^{12}/cm^3$

$n_n = 10^{16}+10^{12} = 1.0001\times10^{16}/cm^3$
$\approx 10^{16}/cm^3$

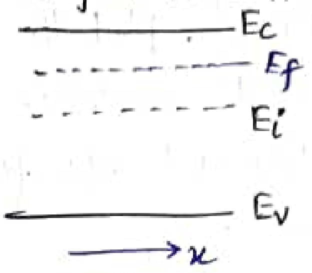


P-N JUNCTION

Independent p-type:



Independent n-type:



After joining p-type and n-type materials:

Only one Fermi energy-level. (for the entire material)

$\Downarrow$

Invariance of the Fermi-level

$$\boxed{\frac{dE_f}{dx} = 0}$$

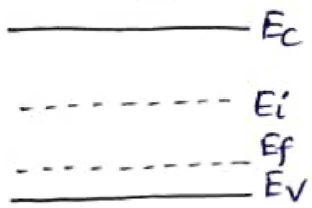
19-03-2024

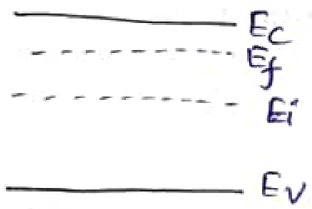
Summary

Types of semiconductors:

↳ Direct ($GaAs$), Indirect (Si)

Doping: p-type (holes), n-type (electrons)





Density of states (DOS):

$$n(E) = DOS(E) \times f(E)$$
$$p(E) = DOS(E) \times [1 - f(E)]$$

Transport:

Mobility (μ) → Drift: applied electric field

Diffusion coefficient (D) → Diffusion: difference of concentration

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}}$$ ... Einstein equation

Carrier Scattering:

→ Lattice scattering → μ_L (Mobility)

→ Impurity scattering → μ_I $\boxed{\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I}}$

Equilibrium: $n_0 p_0 = n_i^2$

Non-equilibrium: $n_0 p_0 \neq n_i^2$

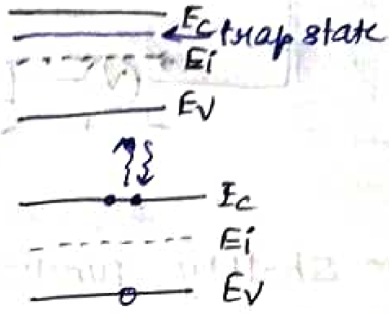
Recombination / Generation:

→ Direct recombination

→ Indirect recombination

→ Trapassisted recombination [SRH]

→ Auger recombination



Carrier Lifetime & Diffusion length:

τ_n, τ_p | L_n, L_p

$L_n = \sqrt{D_n \tau_n}$

$L_p = \sqrt{D_p \tau_p}$

→ Most of the indirect sc have larger lifetime. (depends on the material)

Excess minority carriers:

$R = \beta . n . p$

$= \frac{P_n - P_{n0}}{\tau_p} = \frac{\Delta p}{\tau_p}$

Compensated semiconductors: Both impurities are present.

Completely compensated sc: Equal no. of both impurities.

Continuity equation: Drift, diffusion, generation, recombination.

↳ Differential eqn in time and space.

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}$$

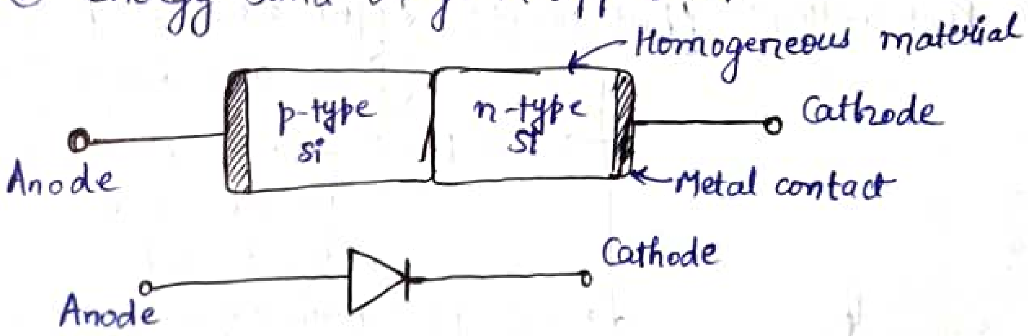
P-N Junction

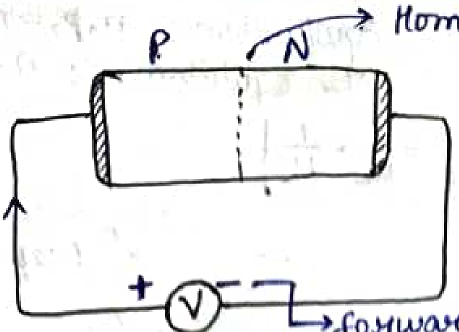
→ Two modes of operation:

1. Forward bias
2. Reverse bias.

→ Different ways to understand P-N junction:

1. Particle approach
2. Energy band diagram approach.





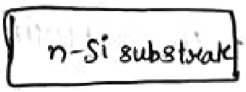
20-03-2024

~~Scho~~ Shotkky Junction : Junction b/w the metal contacts and Semi-conductor.

Homo junction : Junction made of same band-gap (same material, here Si).

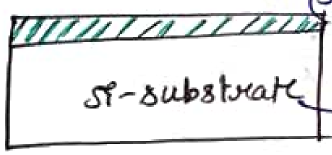
Hetero junction : Junction made of material of different band-gap.

PN Junction Fabrication

- 

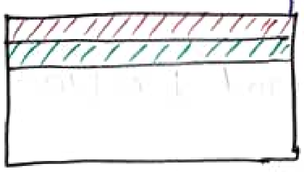
  Start with n-doped substrate

- Deposit a masking film.



→ CVD (Chemical Vapor Deposition) : A technique to deposit the film.

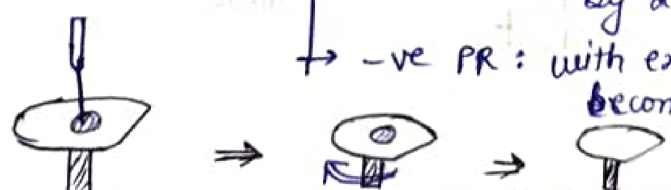
- Spin coat Photo Resist



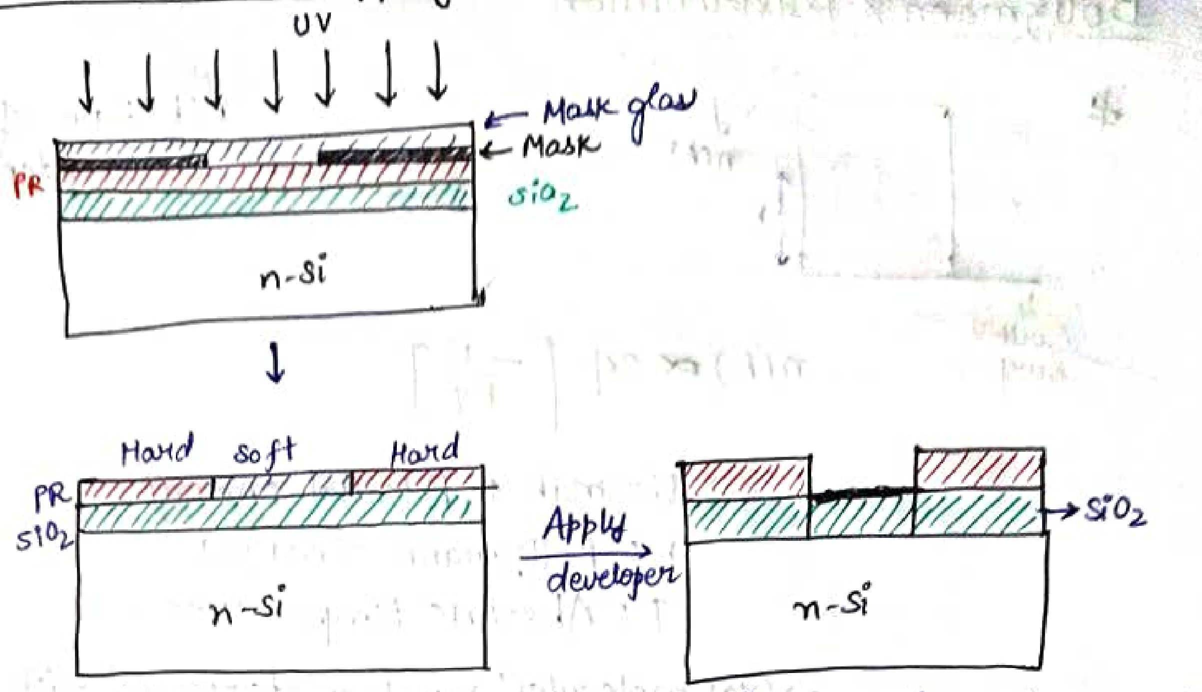
Photocoating : Photoresist : Light-sensitive polymer (Properties change on exposure to UV light)

→ +ve PR : with exposure to UV light, the PR can be easily removed by developer.

→ -ve PR : with exposure to UV light, it becomes hard.

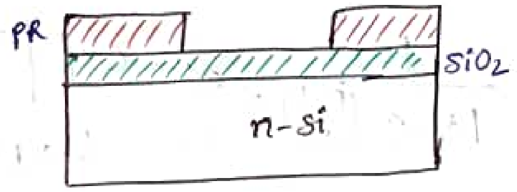


- **Photo Resist Removal (stripping)**



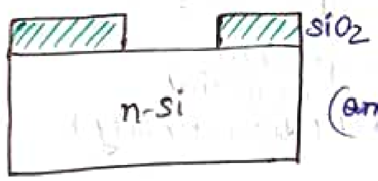
(Developer has eaten away the photoresist)

- **Etching (oxide Removal)**



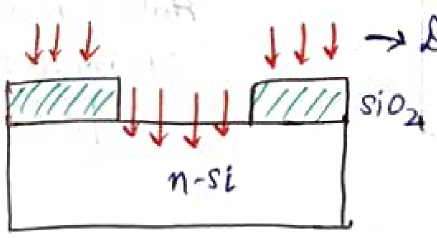
(window opening)

- **Stripping**



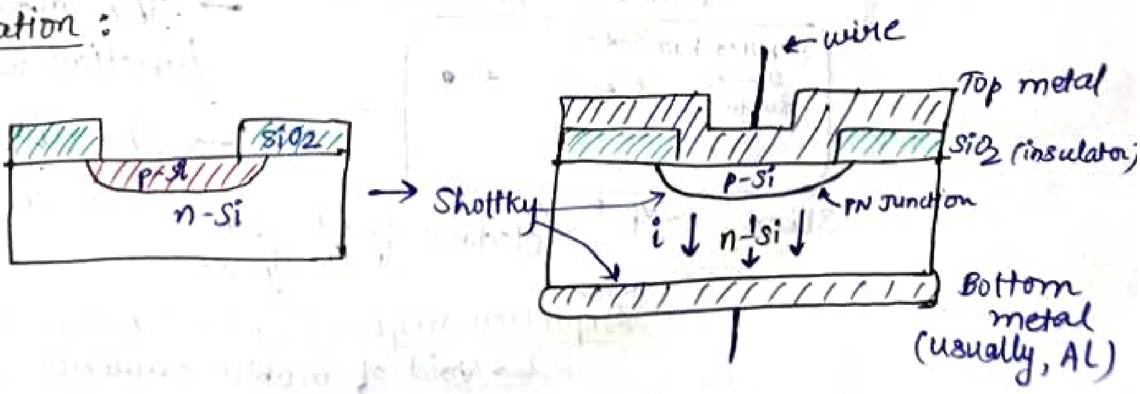
(only column V impurities present)

- **Diffusion or Ion implantation**



→ Dopant gas or accelerated impurity atoms (p-type) (column III impurities)

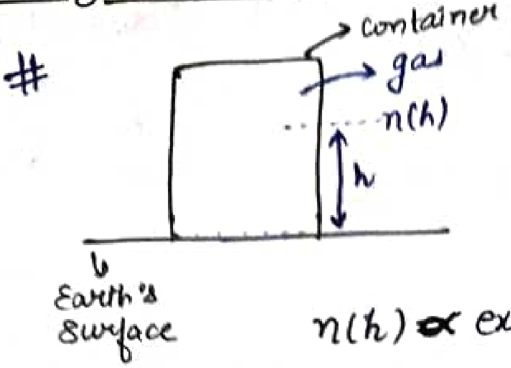
- **Metallization :**



21-03-2024

Boltzmann's Distribution

#



$n(h)$: no. of gas molecules (density) at height 'h'

$$n(h) \propto \exp\left[-\frac{U}{KT}\right]$$

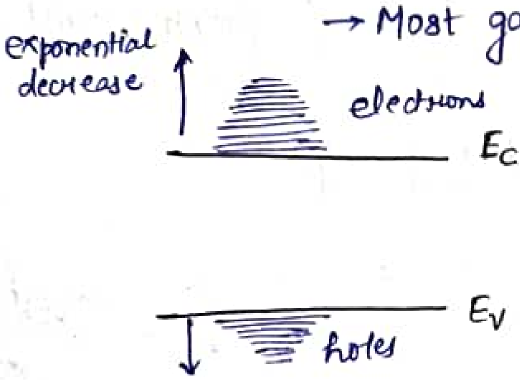
$U = mgh$: Potential energy

K : Boltzmann constant

T : Absolute temperature.

→ Gas molecules' number decreases with height.

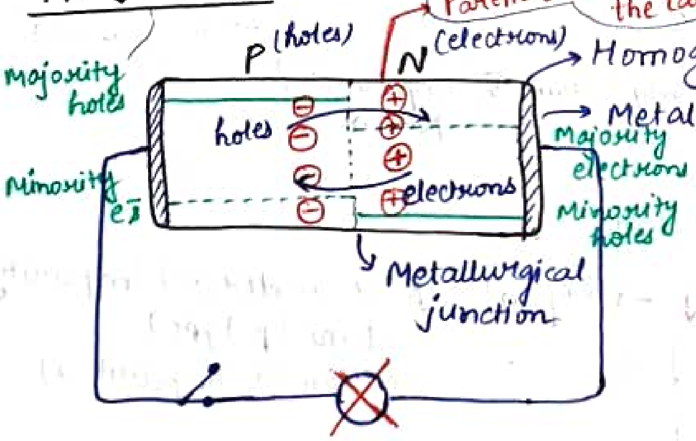
→ Most gas molecules reside at the ground.



$$\frac{1}{1+e^{\left(\frac{E-E_f}{KT}\right)}} \approx \exp\left[-\frac{(E-E_f)}{KT}\right]$$

↳ Boltzmann distribution

PN Junction :

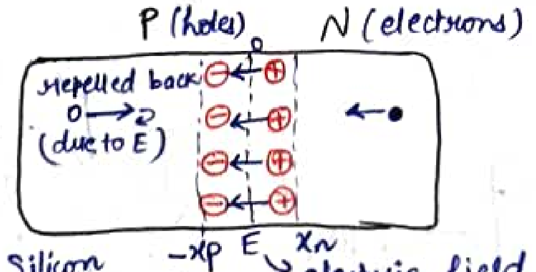


Due to concentration gradient,

Holes : P → N

Electrons : N → P

[Diffusion]



↳ electric field due to dipoles

Depletion region / space-charge region

↳ void of mobile carriers

→ The electric field at the junction slows down diffusion

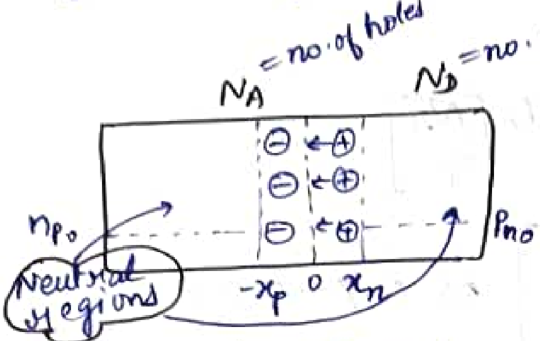
→ The diffusion at the junction is a self-limiting process.

Rules to be obeyed in a p-n junction under equilibrium :

① Charge neutrality across the depletion region.

[Every -ve charge must terminate with a +ve charge ⇒ To maintain E.]

②



→ Remains ~ constant after p-n junction formation

N_A, N_D: Doping densities

$-x_p, x_n$: dimension of depletion region

Regions outside depletion region

For $N_A = 2N_D$

$\Rightarrow \boxed{x_p = \frac{x_n}{2}}$

→ Larger the doping density, smaller the depletion region width.

Individual widths of the depletion region will be decided by the doping densities.

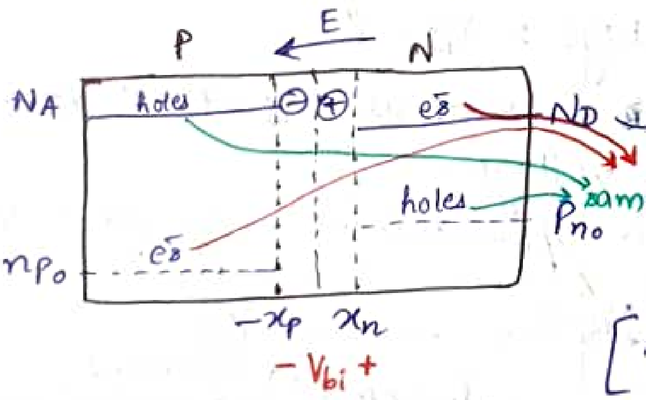
③ Law of mass action holds for neutral regions.

$N_A \cdot n_{p_0} = n_i^2$ [Recombination rate = generation rate]

$N_D \cdot p_{n_0} = n_i^2$

(22-03-2024)

→ $x_n + x_p$ = depletion width
↳ depends on doping density.



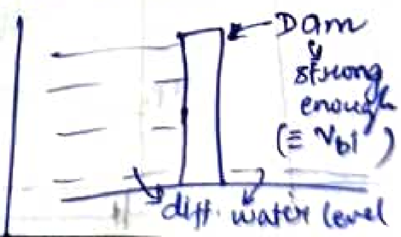
⇒ flat lines ⇒ no current flow

same particle but at different energy level.
⇓
Their ratio obeys Boltzmann distribution

[V_{bi} : built-in voltage]

Energy = qV_{bi}

→ The same particles at different energy levels on P & N sides obey Boltzmann distribution.



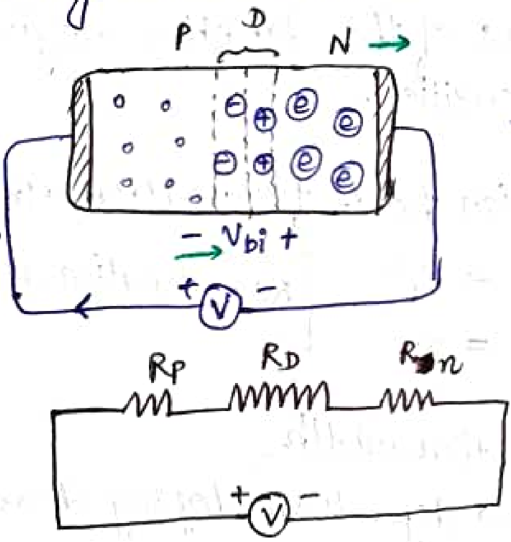
$$\boxed{\begin{aligned} \frac{p_{n0}}{N_A} &= \exp\left[\frac{-q V_{bi}}{KT}\right] \\ \frac{n_{p0}}{N_D} &= \exp\left[\frac{-q V_{bi}}{KT}\right] \end{aligned}}$$ (Boltzmann's Equation)

$$V_{bi} = \frac{KT}{q} \ln\left[\frac{N_A}{p_{n0}}\right] = \frac{KT}{q} \ln\left[\frac{N_D}{n_{p0}}\right]$$

$$\Rightarrow \boxed{V_{bi} = \frac{KT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right]} \approx 0.7 - 0.8\ V \quad (\text{for Si})$$

→ PN Junction without any applied voltage is of no use.

Apply a voltage across the PN Junction.



→ Neutral P & N regions have lot of carriers, hence less resistivity

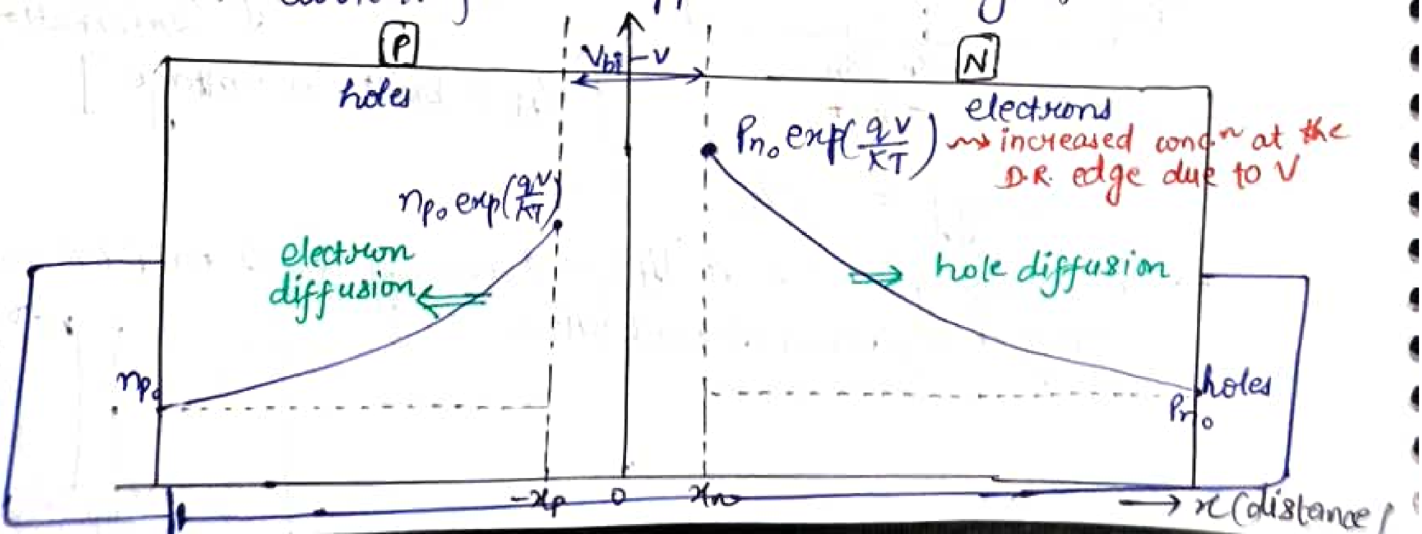
→ Diffusion region has large resistivity.

[Forward Biasing]

Effective voltage : $V_{bi} - V$

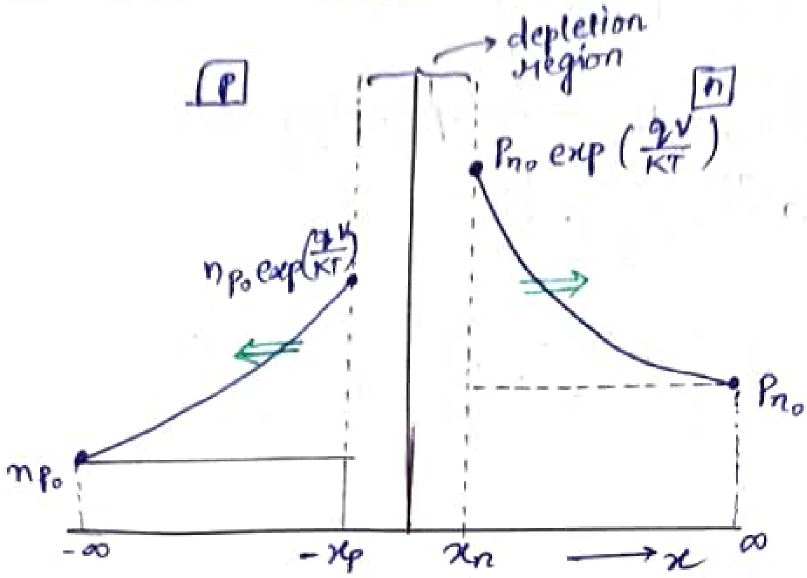
→ Diffusion starts as soon as V_{bi} starts decreasing due to applied voltage.

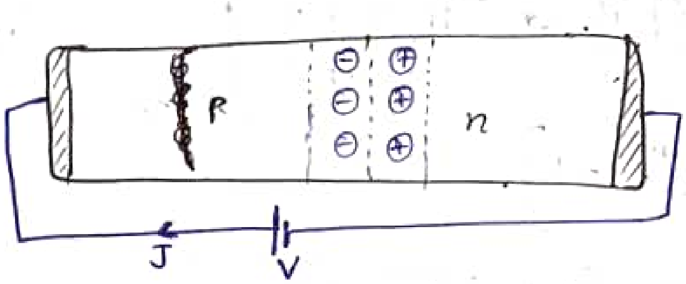
→ Current flow is appriatiable only after $V > V_{bi}$.



26-03-2024

$J = J_{hole} + J_{electron}$





$$J_p = -q \frac{dP_n}{dx} \cdot D_p$$

$$\cancelto{0}{\frac{dP_n}{dt}} = \cancelto{0}{-P_n \mu \frac{\partial E}{\partial x}} - \cancelto{0}{\mu_p E \frac{\partial P_n}{\partial x}} + D_p \frac{d^2 P_n}{dx^2} + \cancelto{0}{G_p} - \frac{P_n - P_{n_0}}{\tau_p}$$

$$\Rightarrow D_p \frac{d^2 P_n(x)}{dx^2} - \frac{P_n(x) - P_{n_0}}{\tau_p} = 0$$

[continuity eq^n in neutral regions]

[E=0 in neutral region; E is present only in depletion region]

Boundary conditions:

At x_n, $P_n(x_n) = P_{n_0} \exp\left(\frac{qV}{KT}\right)$

At ∞, $P_n(\infty) = P_{n_0}$.

Take $y = P_n(x) - P_{n_0}$.

$$\Rightarrow \frac{d^2 y}{dx^2} = \frac{d^2 P_n(x)}{dx^2}$$

$\therefore D_p \frac{d^2 y}{dx^2} - \frac{y}{\tau_p} = 0 \rightarrow$ Possible solution : sin, cos exponential

$$\Rightarrow y = A \exp\left[\frac{-x}{\sqrt{\tau_p D_p}}\right]$$

$$\Rightarrow y = A \exp\left[\frac{-x}{L_p}\right]$$

$$\Rightarrow P_n(x) - P_{no} = A.\exp\left[\frac{-x}{L_p}\right]$$

At $x = x_n$, $P_n(x_n) = P_{no}.\exp\left[\frac{qV}{KT}\right]$

$$\Rightarrow P_{no}\exp\left[\frac{qV}{KT}\right] - P_{no} = A.\exp\left[-\frac{x_n}{L_p}\right]$$

$$\Rightarrow A = P_{no}\left[e^{\frac{qV}{KT}} - 1\right].e^{\frac{x_n}{L_p}}$$

$$\therefore P_n(x) = P_{no} + P_{no}\left[\exp\left(\frac{qV}{KT}\right) - 1\right].\exp\left[\frac{x_n - x}{L_p}\right]$$

Now,

$$J_p = -q\frac{dP_n(x)}{dx}.D_p$$

$$= -q.D_p.P_{no}\left[\exp\left(\frac{qV}{KT}\right) - 1\right].e^{\frac{x_n - x}{L_p}}.\left(\frac{-1}{L_p}\right)\Bigg|_{x = x_n}$$ [calculating J_p at x_n]

$$= -q\frac{D_p}{L_p}.P_{no}\left[\exp\left(\frac{qV}{KT}\right) - 1\right].$$

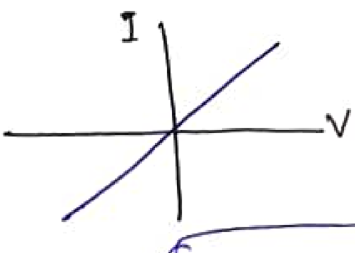
Similarly, $J_n = -q\frac{D_n}{L_n}\,n_{po}\left[\exp\left(\frac{qV}{KT}\right) - 1\right].$

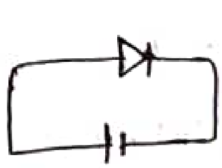
$$\therefore I = \left[-\frac{qD_p}{L_p}.P_{no}\left[\exp\left(\frac{qV}{KT}\right) - 1\right] - \frac{qD_n}{L_n}n_{po}\left[\exp\left(\frac{qV}{KT}\right) - 1\right]\right].A$$

$$= \left\{qA\left[\frac{D_p.P_{no}}{L_p} + \frac{D_n n_{po}}{L_n}\right]\right\} \times \left[\exp\left(\frac{qV}{KT}\right) - 1\right]$$

$$\Rightarrow I = I_o\left\{\exp\left(\frac{qV}{KT}\right) - 1\right\}$$ ... so Diode Equation

I_o : reverse saturation current

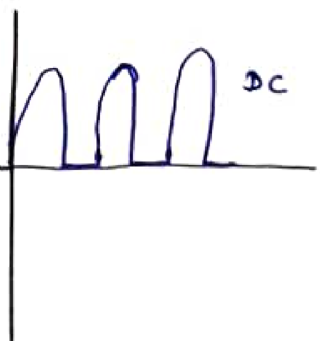




$$\boxed{I_o = qA\left(\frac{D_p P_{no}}{L_p} + \frac{D_n n_{po}}{L_n}\right)}$$

$$\therefore \boxed{I = I_o\left[e^{\frac{V}{V_T}} - 1\right]}, \quad V_T = \frac{KT}{q}$$

$= -I_o$ (for small negative V)



$$\boxed{\frac{KT}{q} = V_T = 0.0256\text{ V}} \approx 26\text{mV}$$

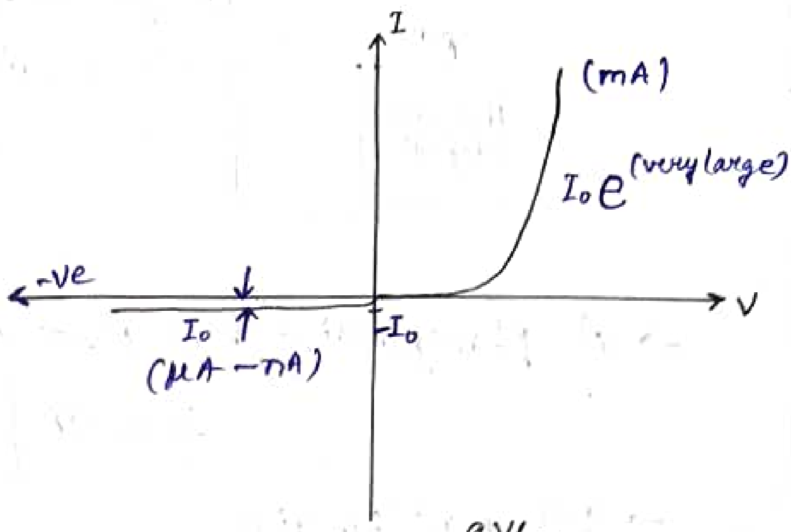
Thermal voltage

For large V, say $V = 10V_T$,

$$I = I_0\left[e^{\frac{10V_T}{V_T}} - 1\right]$$
$$\doteq I_0\left[e^{10} - 1\right]$$
$$\approx I_0 e^{10}$$

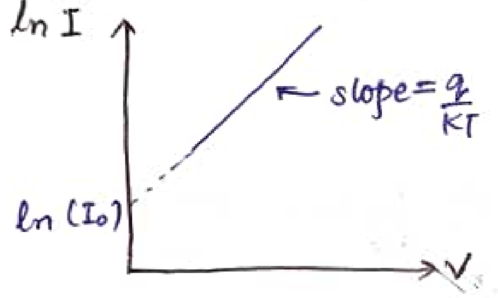
For small V, say $V = -10V_T$,

$$I = I_0\left[e^{-\frac{10V_T}{V_T}} - 1\right]$$
$$= I_0\left[e^{-10} - 1\right]$$
$$\approx -I_0$$



$$I_0 \approx I_0 e^{qV/KT}$$

→ $\ln(I) = \ln(I_0) + q\frac{V_A}{KT}$



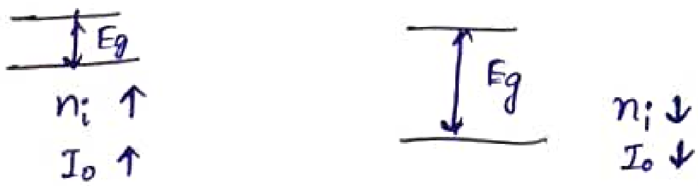
$$I_0 = qA\left[\frac{D_n}{L_n}\cdot n_{p_0} + \frac{D_p}{L_p}\cdot p_{n_0}\right] = qA\left[\frac{D_n}{L_n}\,\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\cdot\frac{n_i^2}{N_D}\right]$$

$$\therefore\; I = qA\,n_i^2\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right]\left(e^{\frac{qV}{KT}} - 1\right).$$

→ $I_0 \propto n_i^2$

n_i : Intrinsic carrier concentration.

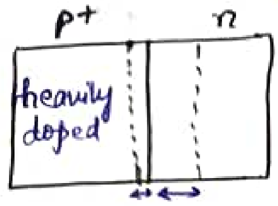
$$n_i = \sqrt{N_C N_V}\;\exp\left[-\frac{E_g}{2KT}\right]$$



→ n_i increases exponentially with temperature.
↳ Depends on bandgap Eg.

→ Lightly doped side of the p-n junction will have a larger no. of minority carriers and thus larger current component.

→ $p^{\oplus}$ or $n^{\oplus}$: heavily doped [Degenerate]



→ width of depletion depends on doping density

Doping density ↑ ⇒ width of depletion region ↓

⇒ Contribute to current ↓

→ A $p^{+}n$ junction has $N_A \gg N_D$,

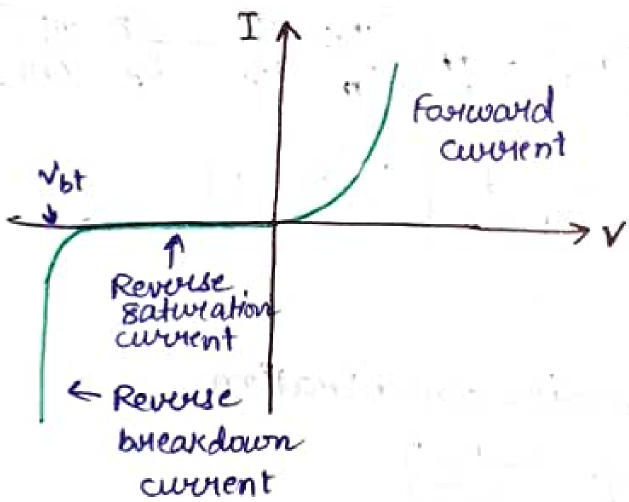
$$I_0 \approx qA\left[\frac{D_P}{L_P} \cdot P_{no}\right] = qA\left[\frac{D_P}{L_P} \cdot \frac{n_i^2}{N_D}\right]$$

→ For p-n^{+} junction,

$$I_0 \approx qA\left[\frac{D_n}{L_N} \cdot n_{po}\right] = qA\left[\frac{D_n}{L_N} \cdot \frac{n_i^2}{N_A}\right]$$

$\underset{(const)}{J} = J_p \downarrow + J_n \uparrow$

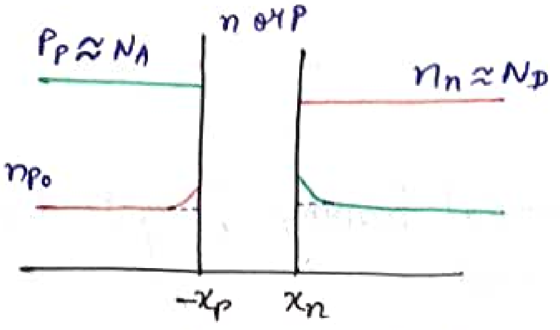
Deviations from the ideal diode behaviour :



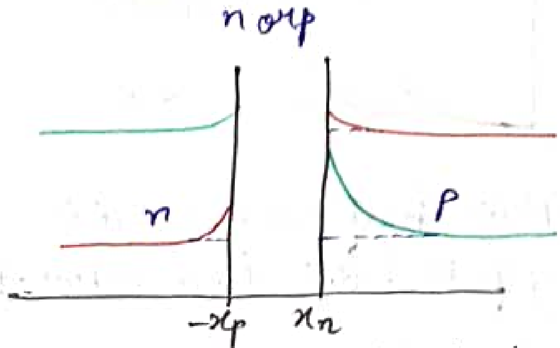
Ideal : $I = I_0\left(e^{\frac{qV}{KT}} - 1\right)$

Other deviations:

$$I = I_0 \left(e^{\frac{qV}{nKT}} - 1\right), \quad n: \text{ideality factor.}$$

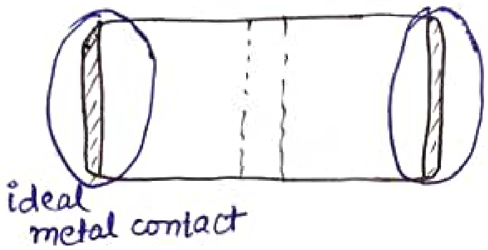


(a) Low-level injection



(b) High-level injection.

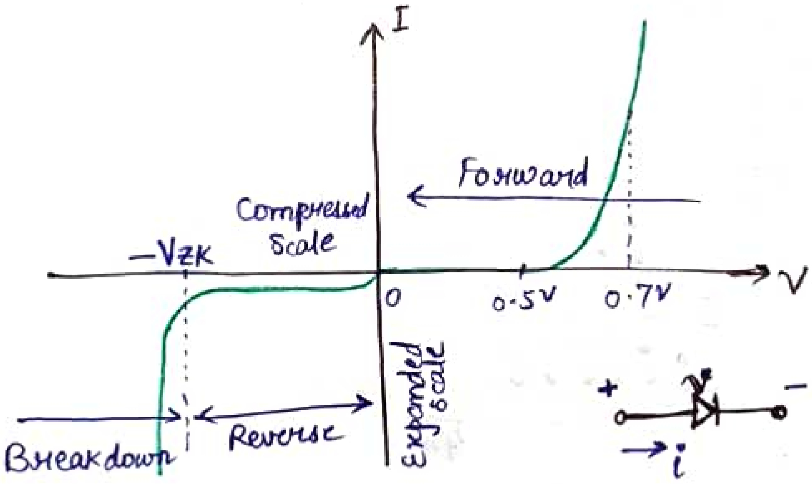
#



- No free carriers in depletion region.
- Abrupt transition at $x = x_p$ & $x = x_n$.
- Zero E for $x_n < x < -x_p$.
- complete dopant ionization

→ Depletion Approximation

Temperature dependence of I-V characteristics:



→ Si based rectifiers are better than Ge based ones.

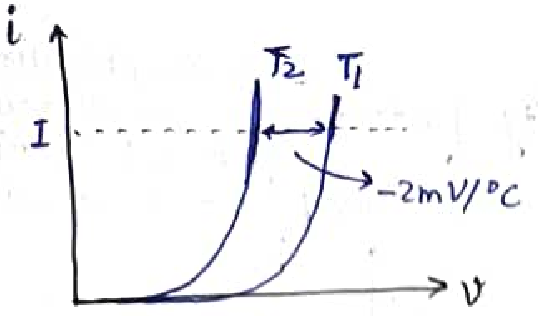
$E_g(Si) > E_g(Ge)$

$\Rightarrow n_i$ of Si $< n_i$ of Ge

$\Rightarrow I_o(Ge) > I_o(Si)$

$n_i \propto E_g, T$

28-03-2024



$T_2 > T_1$

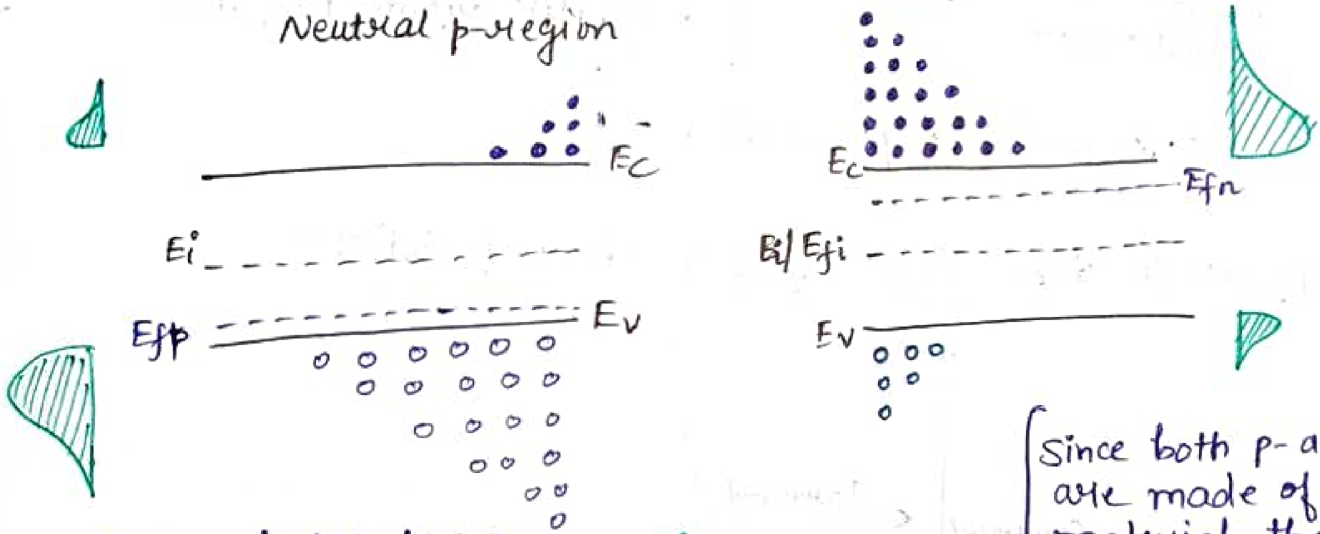
→ Make half-wave rectifier of material having largest band gap to have low saturation current, I_0.

Band-Diagram Analysis of P-N

p-type

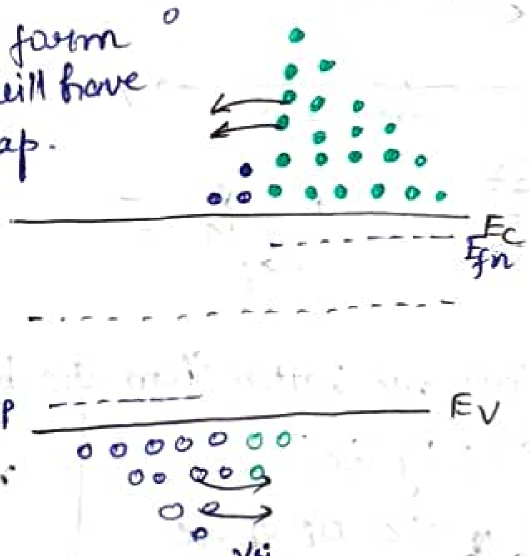
n-type

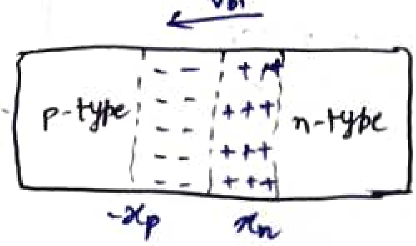
Neutral p-region



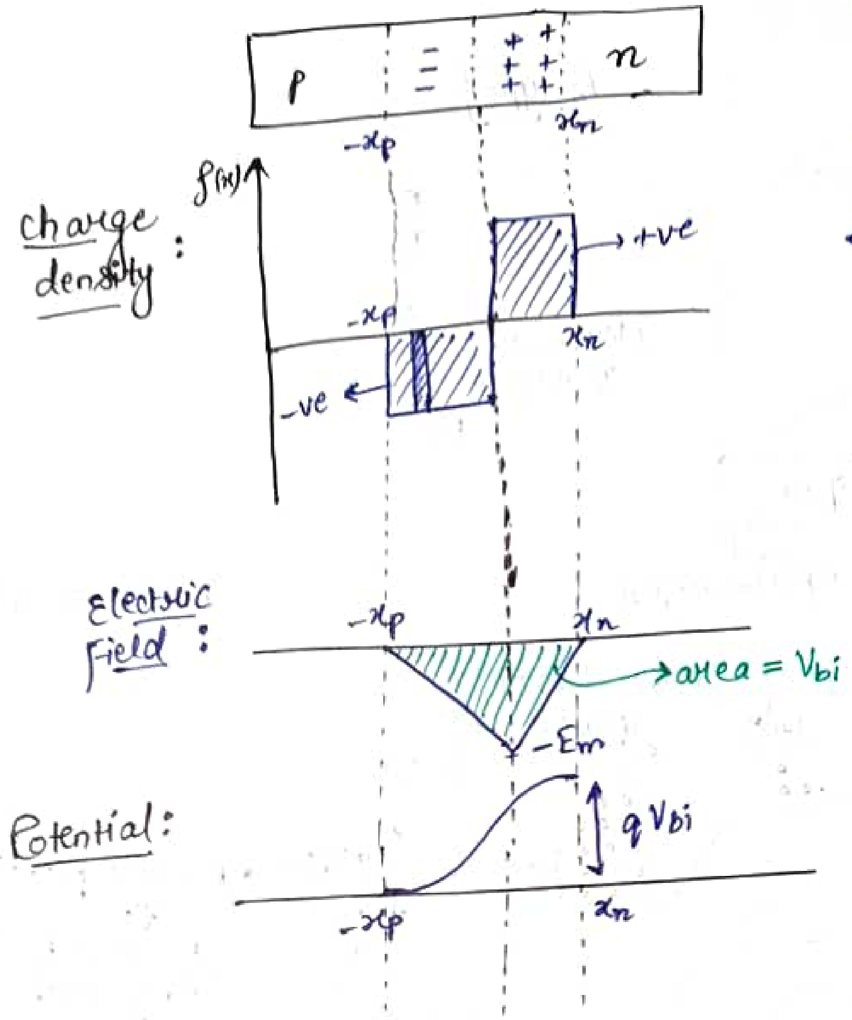
[Since both p- and n-types are made of same material, they have same band gap.]

→ Combing both to form junction, both will have same bandgap.





V_{bi} : built-in potential / barrier potential



→ **Electric field :**

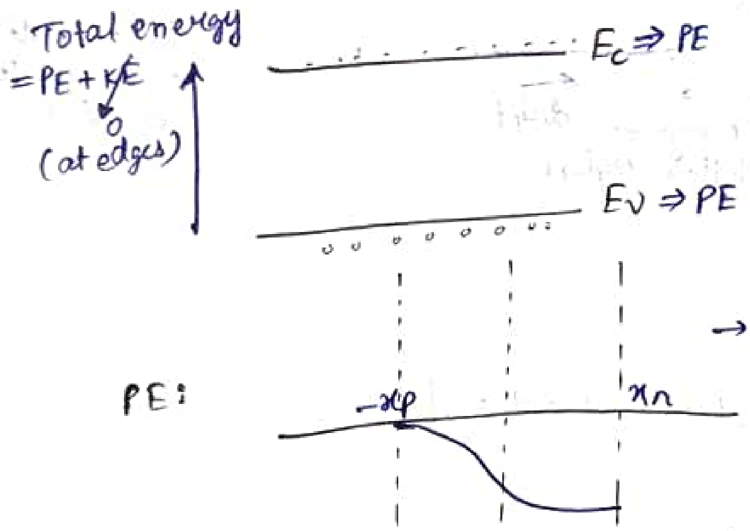
$$\frac{dE}{dx} = \frac{\rho(x)}{\epsilon}, \quad E: \text{Electric field}$$

$$\Rightarrow E = \int_{-x_p}^{x_n} \frac{\rho(x)}{\epsilon}\, dx.$$

→ **Electric Potential:**

$$E = -\frac{dV(x)}{dx}, \quad V(x): \text{Potential}$$

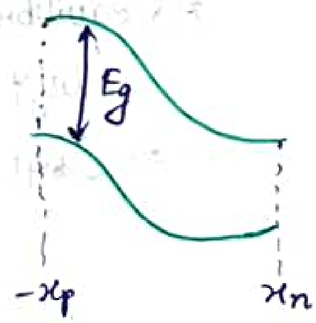
$$\Rightarrow \quad V(x) = -\int_{-x_p}^{x_n} E\, dx$$

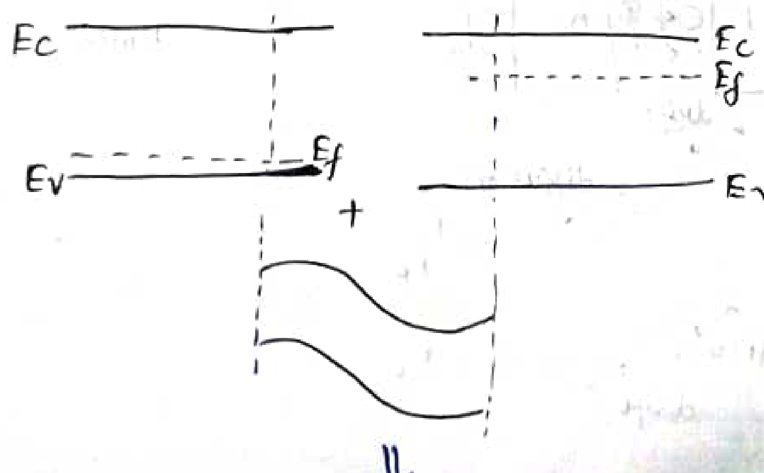


→ **Potential energy**

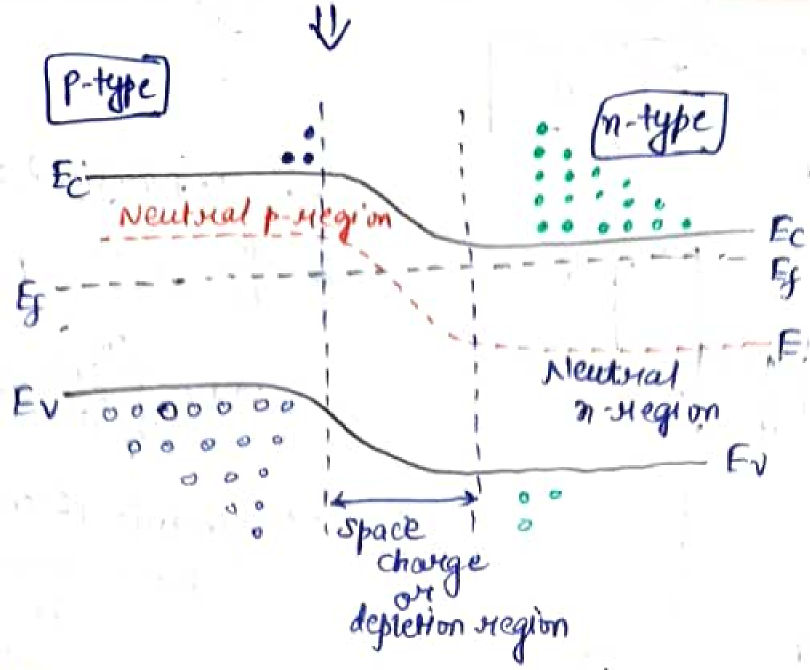
PE = $-q \times$ Potential

→ For both e^-s and holes



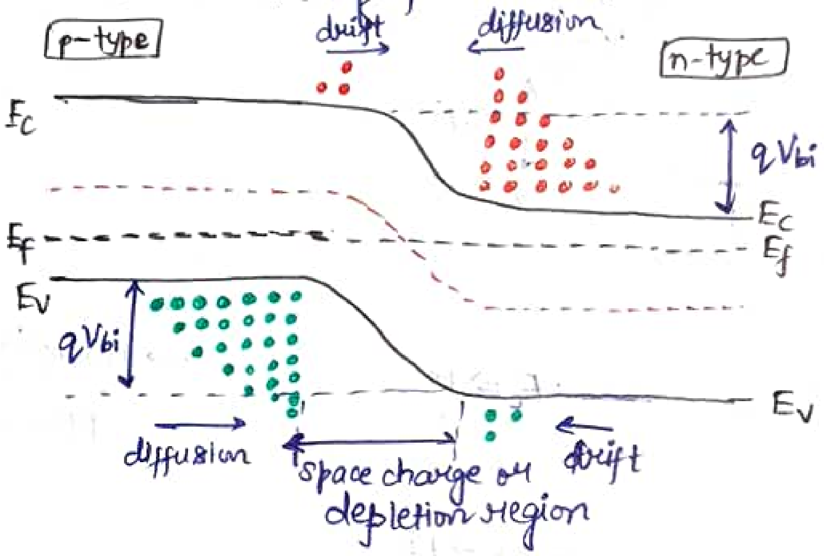


⇓



03-04-2024

$\frac{dE_f}{dx} = 0$ (Invariance of fermi-level)

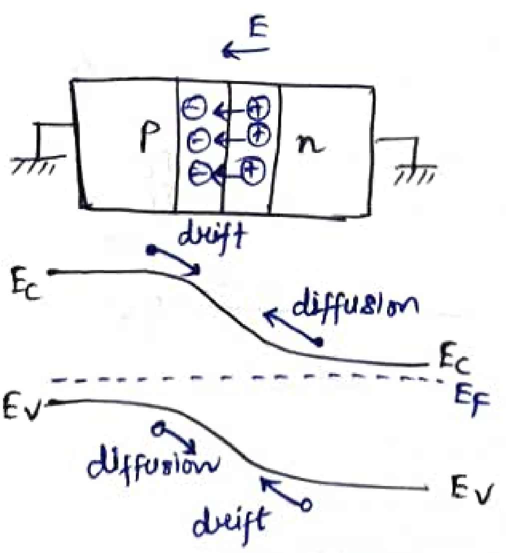


qV_{bi} → Barrier potential
⇓
For e⁻ or hole to go to the other side, have to ~~cross this~~ overcome this barrier.

At equilibrium,

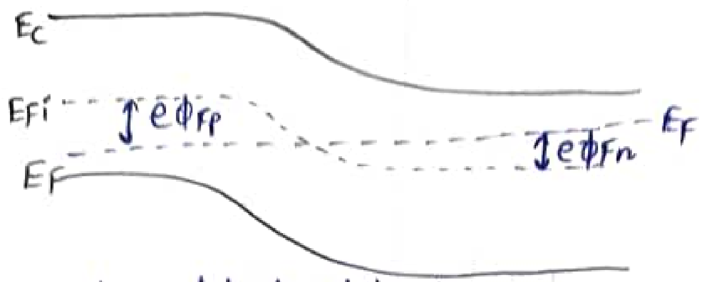
drift = diffusion

$\Rightarrow J_{drift} = J_{diff}$ [Net current = 0]



Electrons → sink
Holes → float
} Natural tendency

Built-in Potential



$$V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$$

$$n_o = N_C \exp\left(\frac{-(E_C - E_F)}{KT}\right)$$

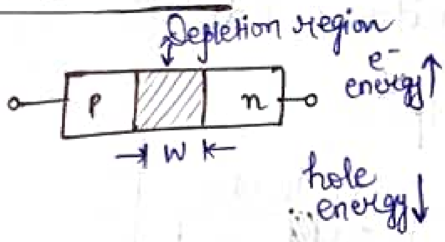
$$n_o = n_i \exp\left(\frac{E_F - E_{Fi}}{KT}\right)$$

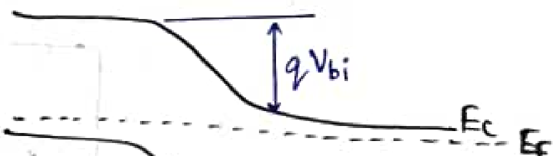
Potential ϕ_{Fn} in n-region:

$$e\phi_{Fn} = E_{Fi} - E_F$$

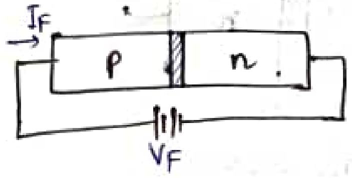
$$\boxed{V_{bi} = \frac{KT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)}$$

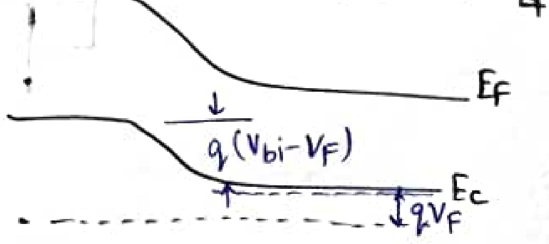
Forward and Reverse Bias



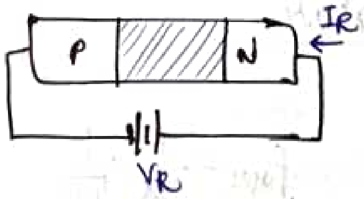


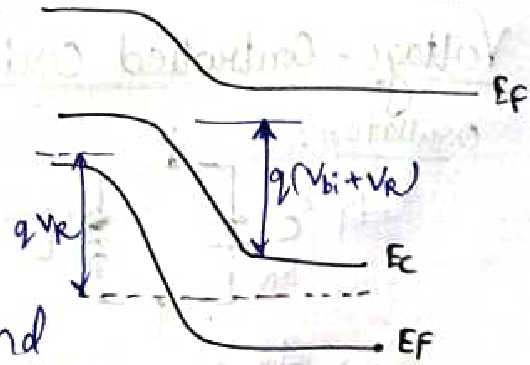
Forward bias:
↳ Decreases the barrier for carrier flow





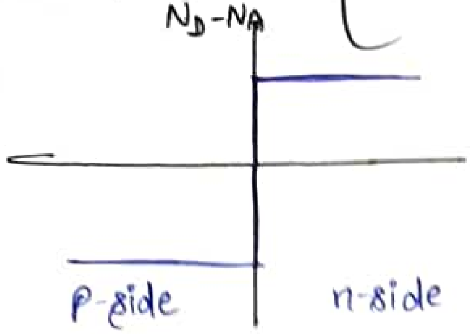
Reverse Bias
↳ Increases the barrier for current flow



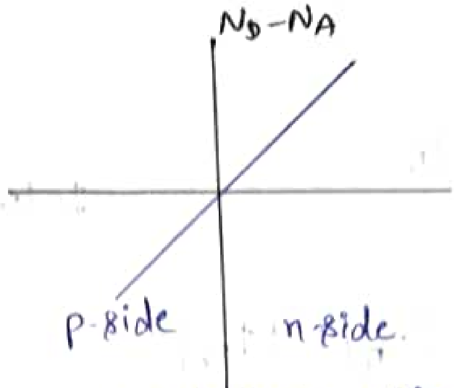


→ Reverse current is small negative and limited by supply of thermally generated. So, as temp. increases, reverse saturation current also increases.

Abrupt and Graded Junction

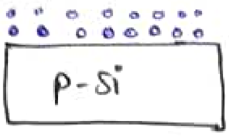


↳ by epitaxial growth



↳ diffusion or ion implantation

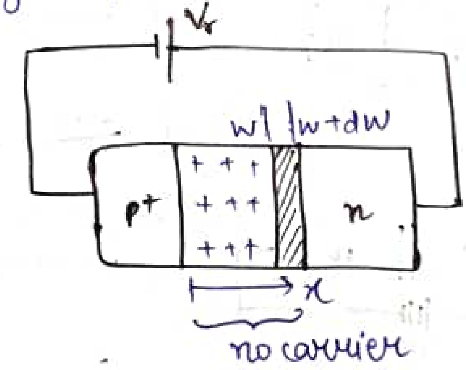
Epitaxial growth : layer-by-layer growth

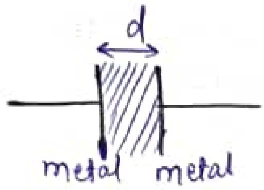


Capacitance of p-n junction

↳ Junction capacitance (transition region capacitance, depletion layer capacitance) → RB

↳ Charge storage capacitance (diffusion capacitance) → FB





$C = \epsilon_0 \epsilon_r \frac{A}{d}$

Voltage-Controlled Oscillator.

Oscillator :

$f_{res.} = \frac{1}{2\pi} \frac{1}{\sqrt{LC}}$

→ As we change the voltage applied, the capacitance of the diode changes.

→ Diode can act as capacitor, rectifier and switch.

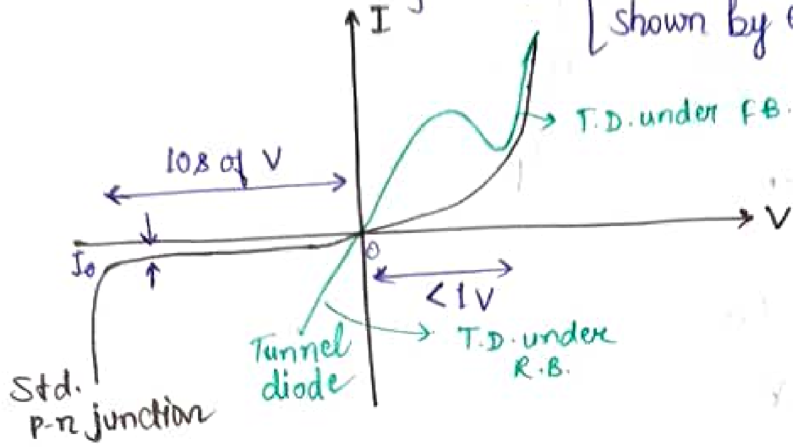
Tunnel Diode

(09-04-2023)

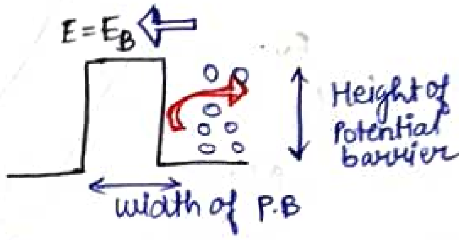
↳ Also called as Esaki diode.

↳ New phenomenon in narrow germanium p-n junctions.

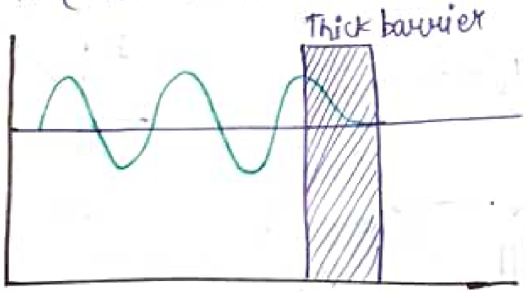
↳ Works on the principle of "Quantum tunneling".
[shown by electrons, holes, photons and some other particle]

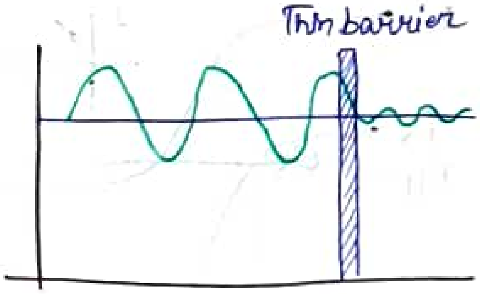


→ As barrier height or width decreases, electron's probability to cross the tunnel increases.

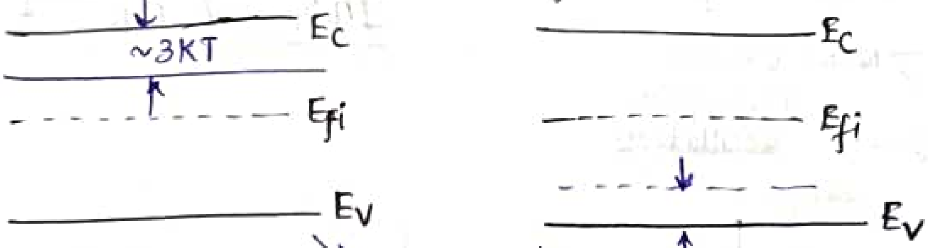


→ This is due to wave nature of the electron.





Non-degenerate vs. Degenerate doping.



For heavy / degenerate doping (p^+/N^+) → on both P & N-sides.

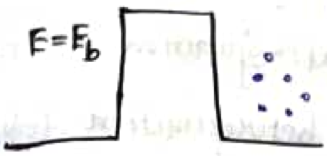
Concept of Tunneling:

↳ Quantum-mechanical phenomenon

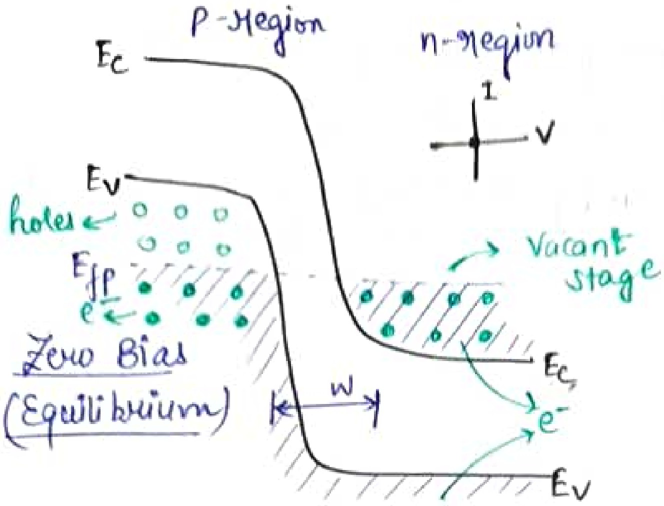
Probability of tunneling → by wave nature of e^-

↳ Probability that e^- can tunnel through barrier and appear to the other side.

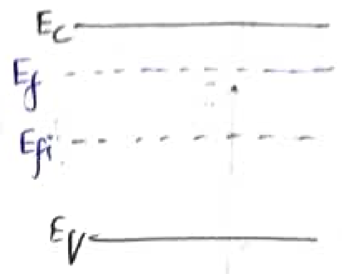
↳ depends on width, height of barrier.

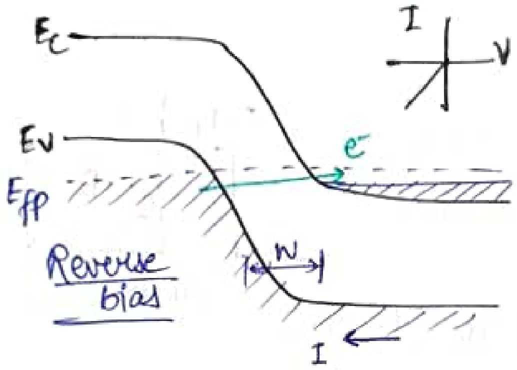


→ Electron can exist on both side provided tunnel is thin.



Zero Bias (Equilibrium)

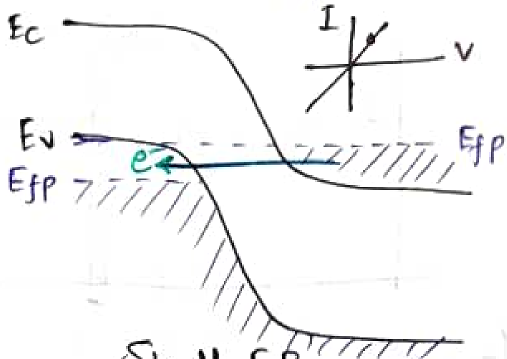




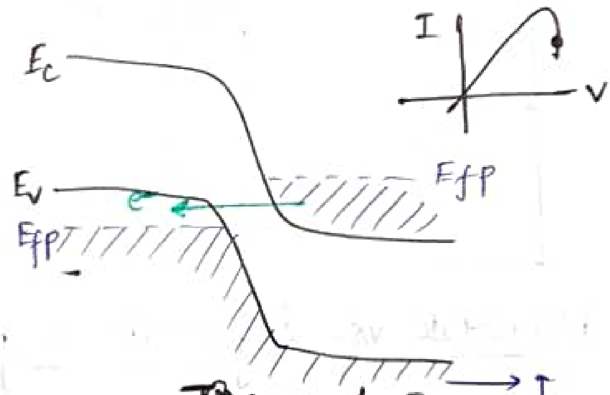
Reverse bias

RB: Height ↑
Width (W) ↓
Potential barrier ↓

−ve diff. Resistance,
diff. $R = \frac{\Delta V}{\Delta I}$.

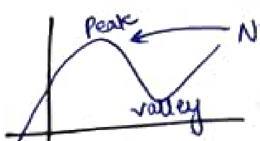


Small F.B.



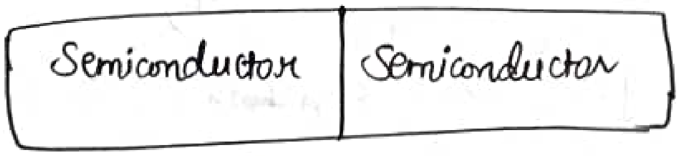
Increased F.B.

#



NDR: used in microwave oscillators

→



Same bandgap: Homojunction
Heavily doped: Tunnel diode
Different bandgap: Heterojunction (same/diff. lattice constant)

| p-Si | p-Ge | → Isotype heterojunction (same type doping)

| p-Si | n-Ge | → Anisotype heterojunction (different type doping)

→ Rectifying property:

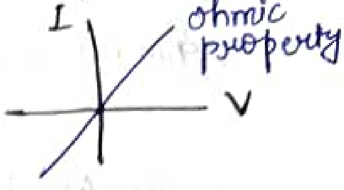
↳ p-n junction

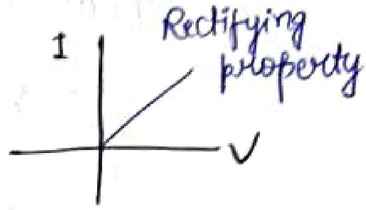
↳ allows current to flow in one direction only.

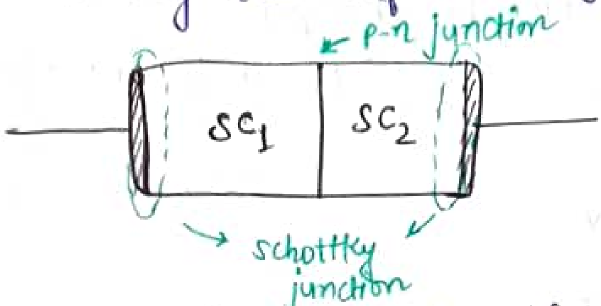
→ Ohmic property:

↳ schottky junction

↳ ideally needed (for schottky junction)



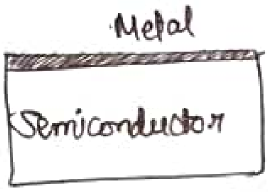


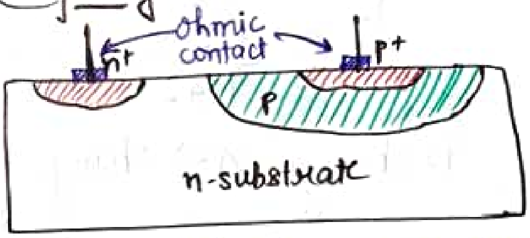


→ Schottky can have property either of :

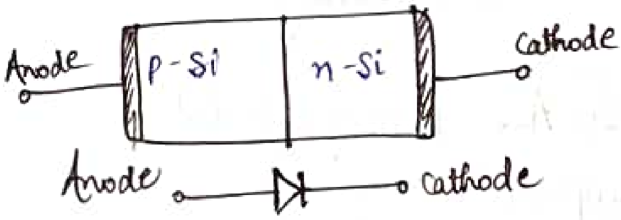
- rectifying property
- ohmic property.

Construction of Schottky Property



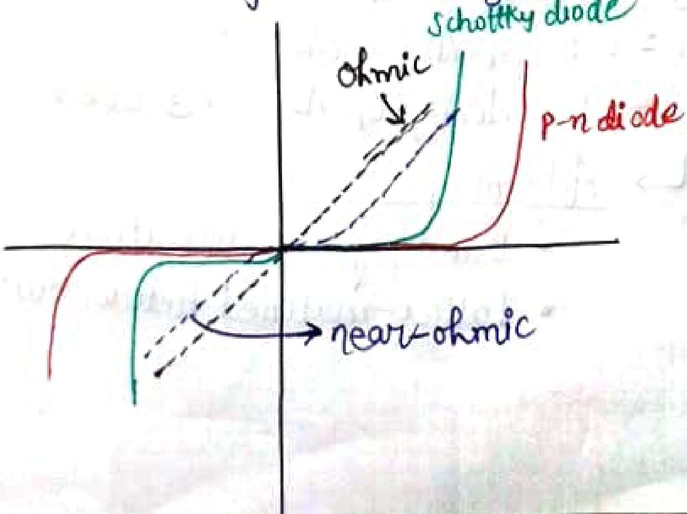


metal — p^+ — p — n — n^+ — metal



Schottky diode : Metal + SC junction < ohmic / schottky

P-n diode : SC + SC junction only

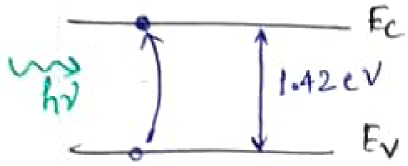


Compound Semiconductor

Element: Si, Ge (IV)

Binary compound: GaAs, InP, GaP, ~~GaP~~ GaSb, AlAs (III-V)
CdTe, ZnSe (II-VI)

GaAs: 1.42 eV → cannot be changed
↳ Not useful for optoelectronic devices
↙
(interpolation of e^-, holes and photons)



$$E(eV) = \frac{1.24}{\lambda(\mu m)}$$

→ Element SC have indirect bandgap, so radiative recombination is not possible.

λ emitted from GaAs:

$$\lambda = \frac{1.24}{1.42}\,\mu m = 0.87\,\mu m$$

To change λ ⇒ change bandgap
⇓
Use compound SC

<u>Ternary / Quaternary SC</u>: λ tunability

<u>Alloyed SC</u>:

$Al_x Ga_{1-x} As$ / GaAs ← starting material (100% 100%)

x: alloy composition

$Al_{0.3} Ga_{0.7} As$ → replaced 30% of Ga with Al

↳ By changing % of Al, bandgap can be changed.

x = 0: GaAs / GaAs → 1.42 eV

x = 1: AlAs / GaAs → 3.01 eV

↳ <u>Advantages</u>:

- Bandgap modification
- Lattice-matched heterostructures.

Compound Semiconductors : Ternary and Quaternary

↳ choice of semiconductor for any Optoelectronic.
↳ Application would depend on the bandgap wavelength.
↳ The no. of useful semiconductors are limited.

→ If E_g or λ has to be changed, we use

Ternary materials: → Replace x% of Ga with Al

$$Al_x Ga_{1-x} As / GaAs$$

$$\lambda = \frac{1.24}{E(eV)} \mu m$$

eg. $Al_{0.3} Ga_{0.7} As / GaAs$ [x: alloy composition]

Quaternary materials:

$$In_{1-x} Ga_x As_y P_{1-y} / InP$$

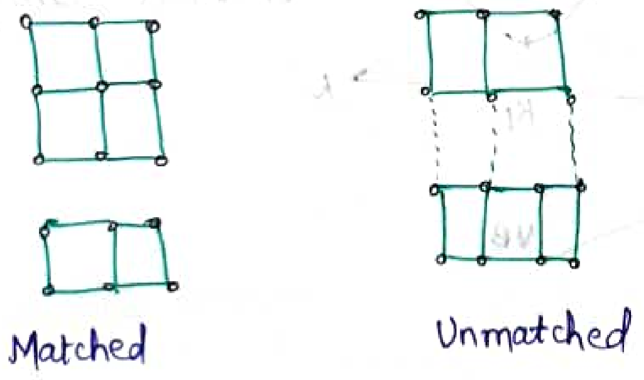
$$In_x Ga_{1-x} As_{1-y} P_y / GaAs$$

↳ Bandgap modification
↳ Formation of lattice matched heterostructure.

$Al_x Ga_{1-x} As/GaAs$ emitting at 780 nm is the most commonly used material for LASER diodes in printers, CD, barcode readers.

↳ Wavelength tuning

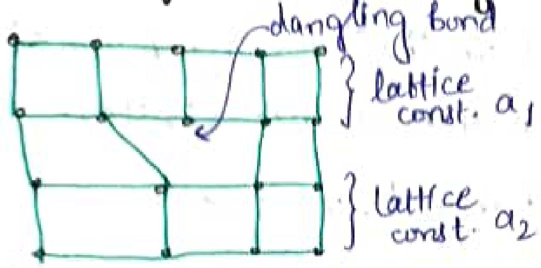
Formation of lattice matched heterostructures:



(11-04-2024)

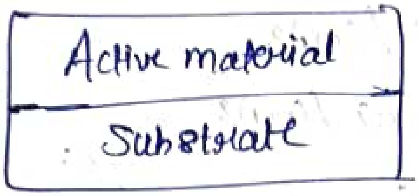
→ Lattice matching depends on the lattice constants.

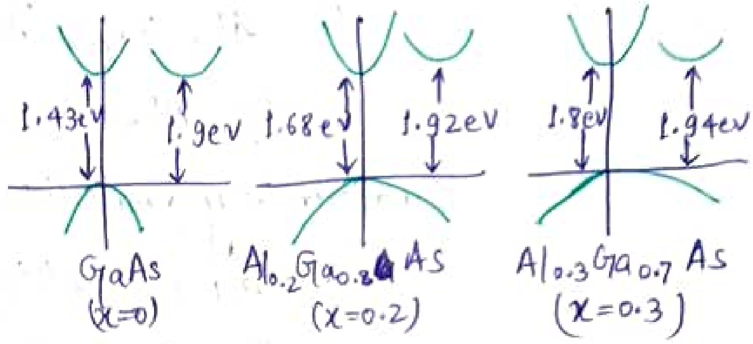
Importance of Lattice Matching:



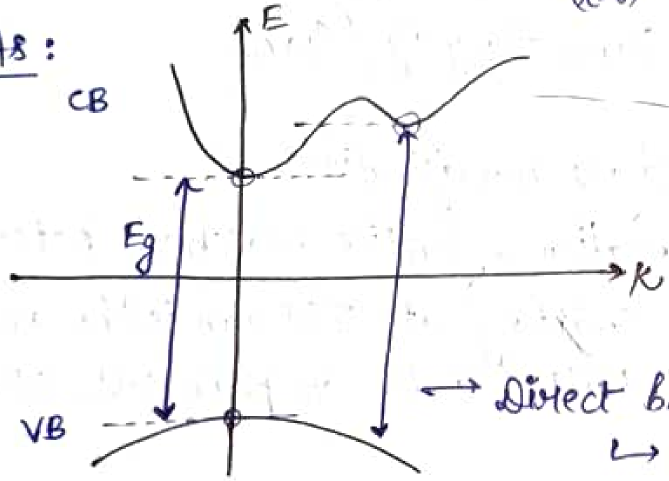
→ Dangling bonds capture moving e^- and form bond.
↳ Bad for optoelectronic SC material.

→





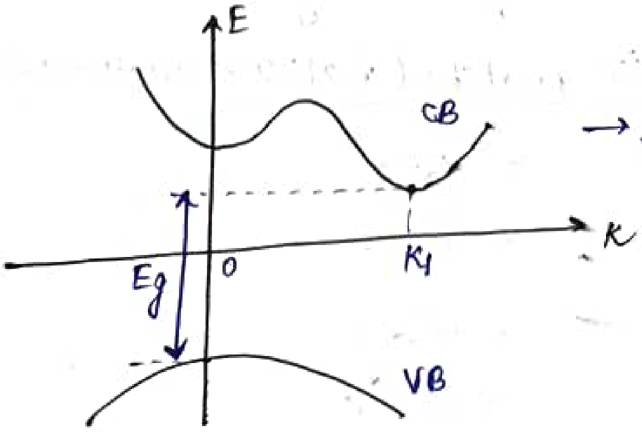
GaAs:



Bandgap/Energy gap (E_g): Energy difference b/w bottommost point of CB and topmost point of VB.

→ Direct bandgap
↳ same K values for bottommost point of CB & topmost point of VB.

Si:



→ Indirect bandgap

$Al_xGa_{1-x}As$

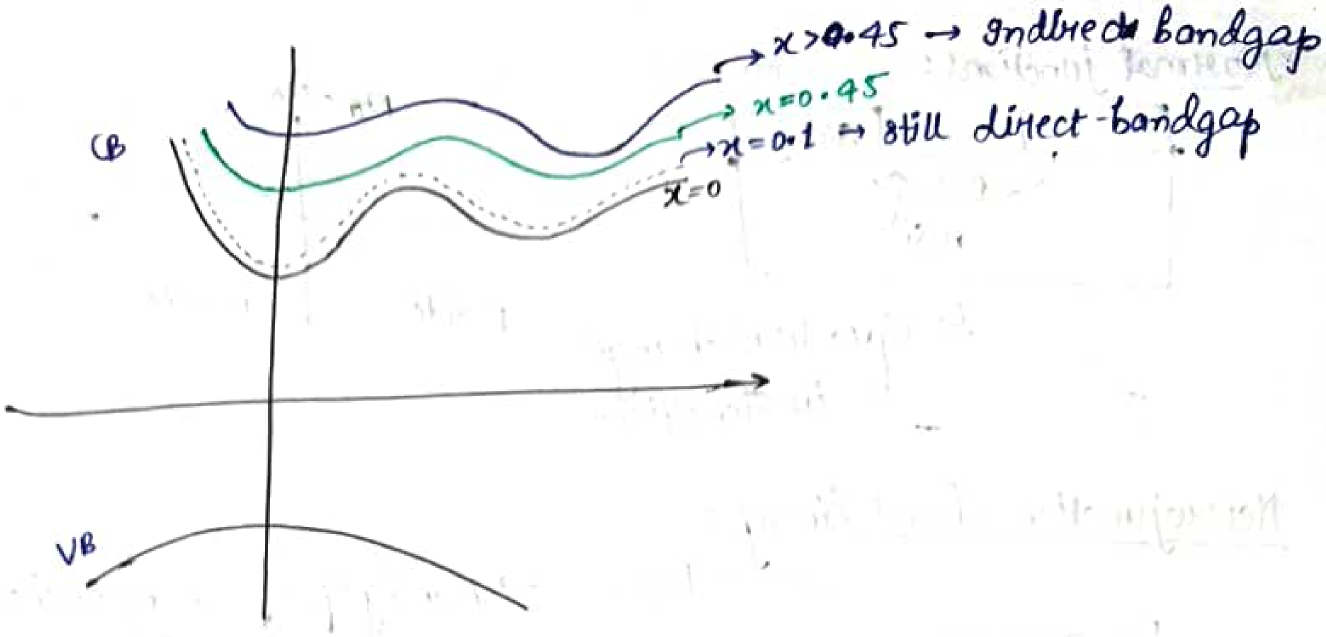
when $x=0$, GaAs

$x=0.1$, $Al_{0.1}Ga_{0.9}As$

$x=0.45$, $Al_{0.45}Ga_{0.55}As$

$x<0.45$ → direct bandgap

$x>0.45$ → indirect Bandgap



→ For optoelectronic devices, look for:
1. Lattice constant
2. Direct vs. Indirect bandgap → [$0 < x < 0.45$ for $Al_x Ga_{1-x} As$]

Doping	Alloying
• Adjacent group	• Same group
• Changes conductivity	• Changes bandgap
• Small no. of atoms replaced	• Large no. of atoms replaced.
• No lattice rearrangement.	• Lattice rearrangement.

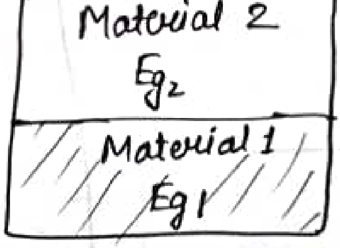
II B	III A	IV A	V A	VI A
	^{5}B	^{6}C	^{7}N	^{8}O
	^{13}Al	^{14}Si	^{15}P	^{16}S
^{30}Zn	^{31}Ga	^{32}Ge	^{33}As	^{34}Se
^{48}Cd	^{49}In	^{50}Sn	^{51}Sb	^{52}Te

Heterojunction

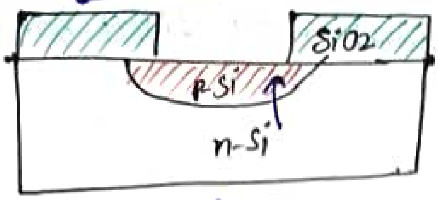
↳ Junction formed b/w dissimilar materials having different bandgaps (different lattice constants).

↳ They are grown by epitaxial techniques. [Growing material over the other]

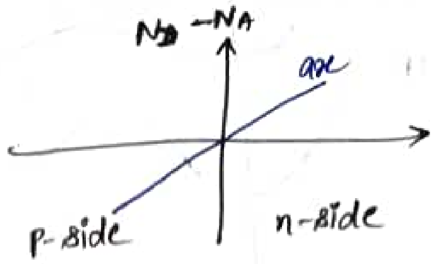
↳ Junctions formed are abrupt/step.



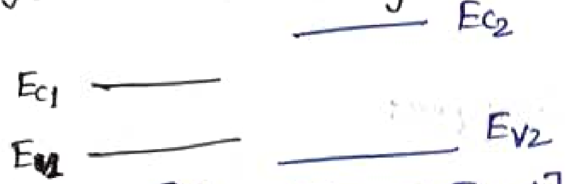
Normal junctions:



↳ Gradual change in densities.

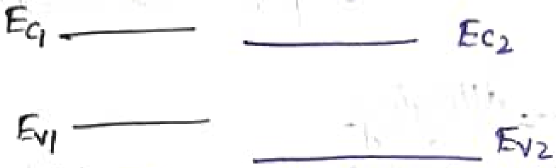


Heterojunction Band lineup:



→ Bandgap of one material lies completely within others'.

[Straddling or Type-I alignment]



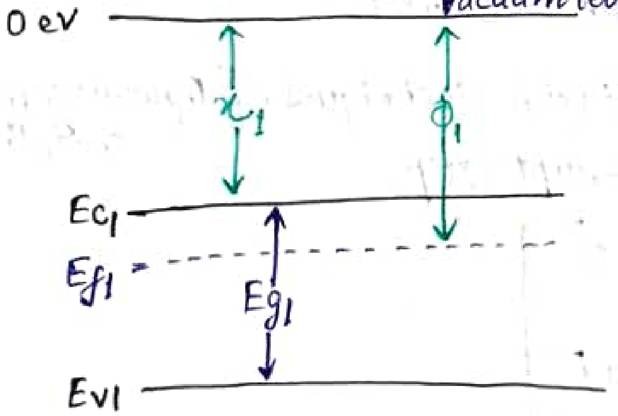
[Staggered or Type-II alignment]

[Broken or Type-III alignment (GaSb-InAs)]

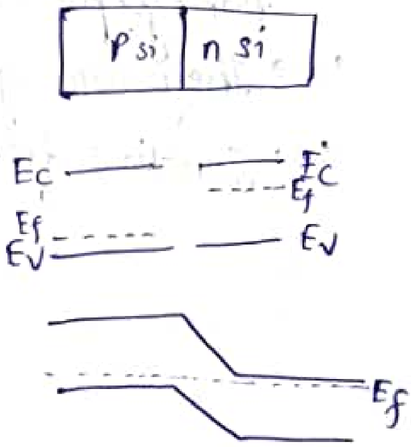
12-04-2024

Heterojunction Band diagram:

vacuum level → ref. → (needed b/c bandgaps are different)



#



Parameters:

ϕ : Work function → energy required to take e^- from E_{f1} to vacuum level

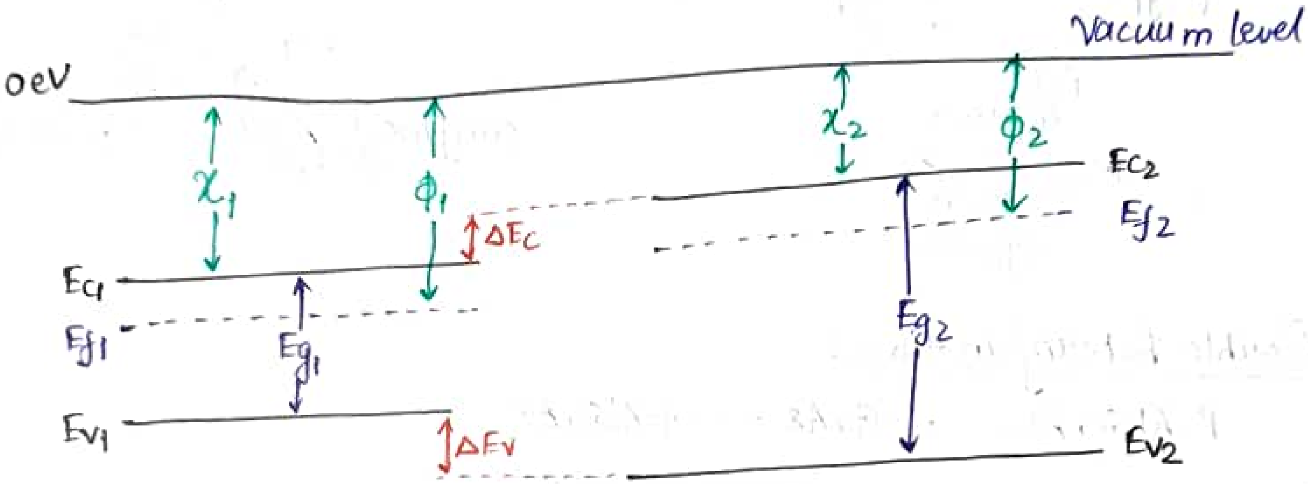
χ : Electron affinity → energy required to take e^- from E_{c1} to v.l. (to make it free)

E_g : band gap

E_c : ~~val~~ conduction band

E_v : Valence band

E_f : fermi-level

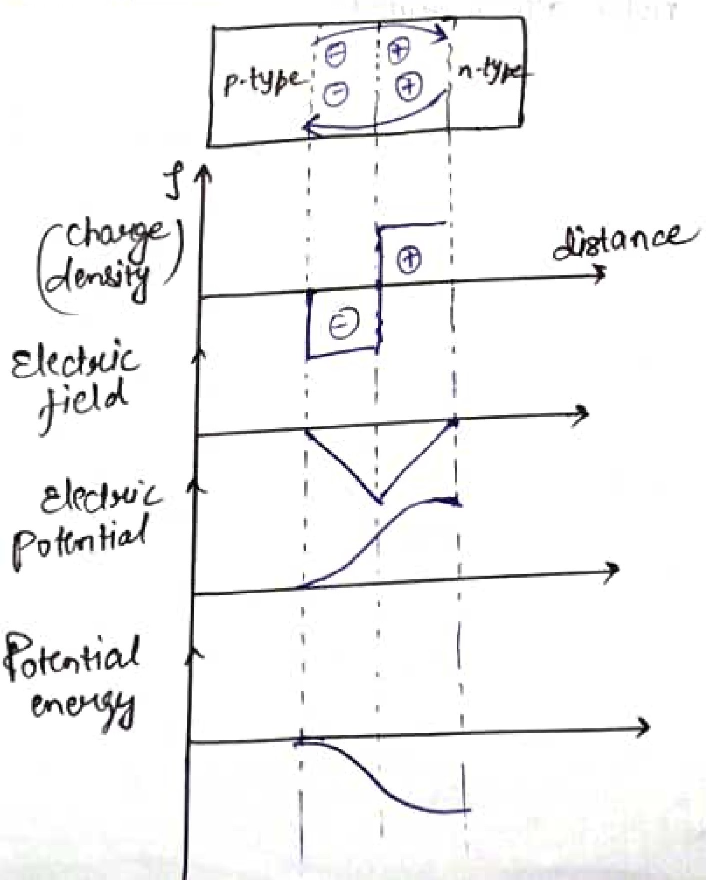


ΔE_c : CB off-set

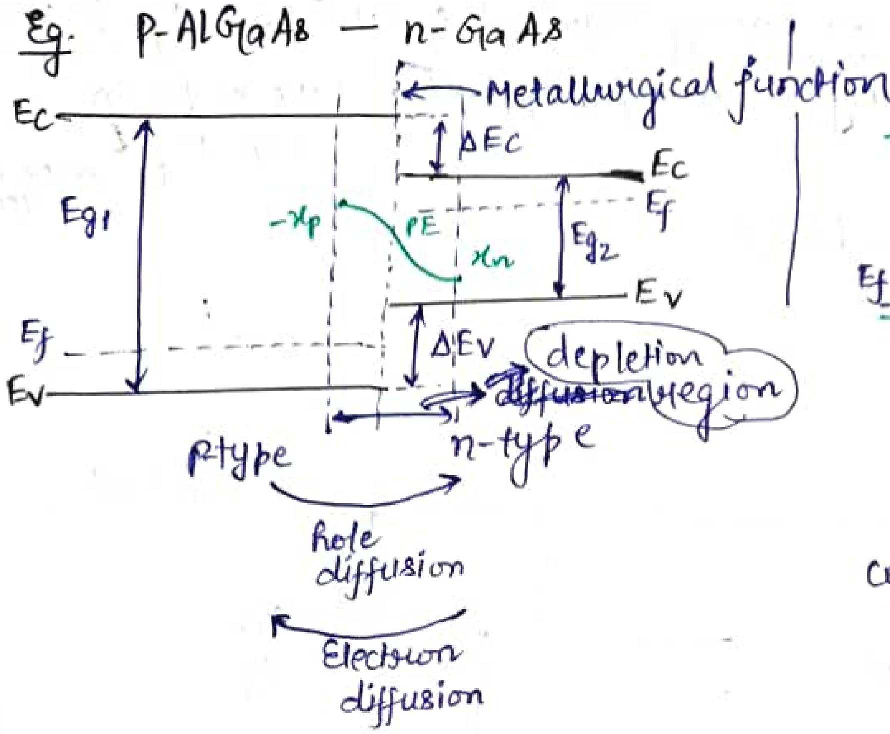
ΔE_v : VB off set

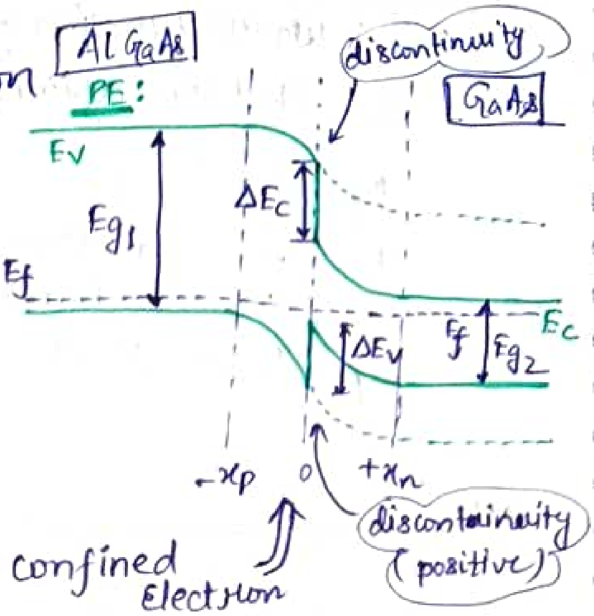
$\Delta E_g = E_{g2} - E_{g1}$: Band ~~Energy~~-gap off-set

Homo ~~Hetero~~junction:



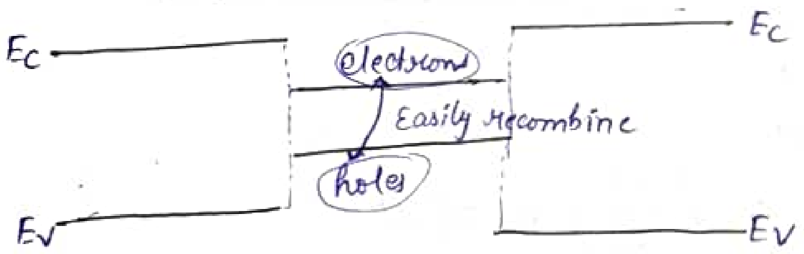
Eg. P-AlGaAs — n-GaAs





Double heterojunction:

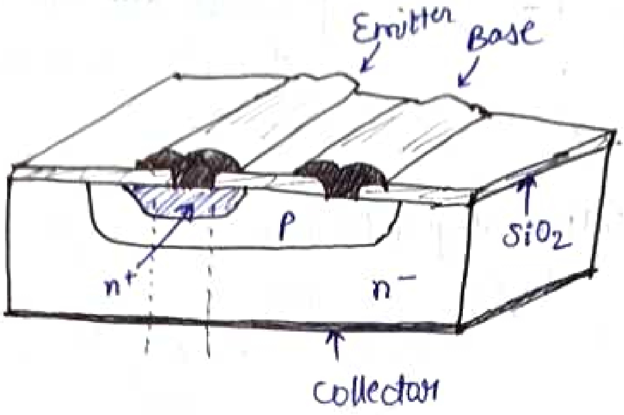
P-AlGaAs — n-GaAs — n-AlGaAs

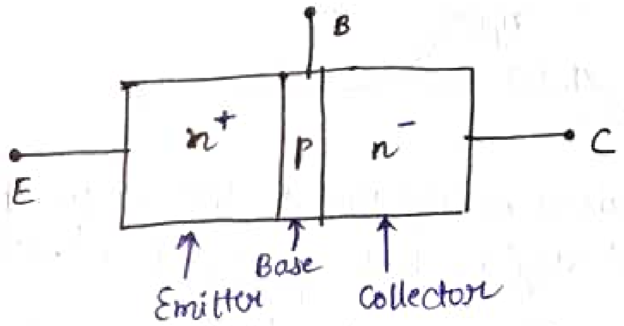


Both electrons and holes are confined.

15-04-2024

Bipolar Junction Transistor (BJT)

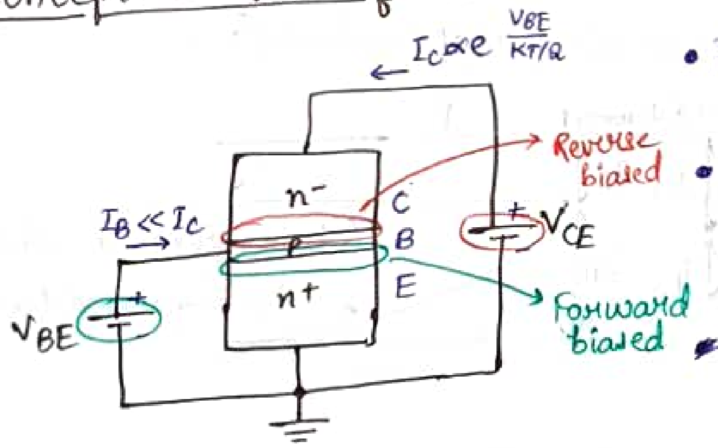




Emitter → heavily doped
Base → Moderately doped
Collector → lightly doped

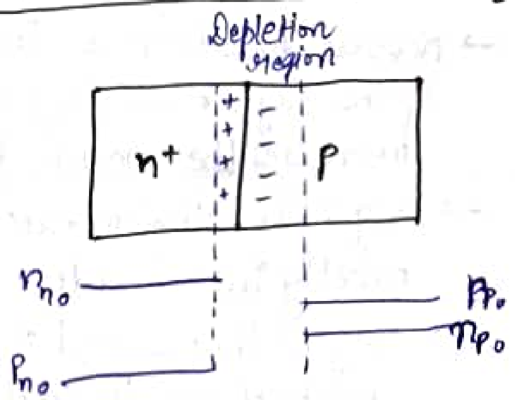
Base → very thin
Collector → very large (largest area)

Conceptual view of a BJT



- Device acts as a voltage-controlled current source — V_{BE} controls I_C
- The B-E junction is forward biased and the B-E junction is reverse-biased.

n^+p Junction under Equilibrium:



$I_C = \beta I_B$

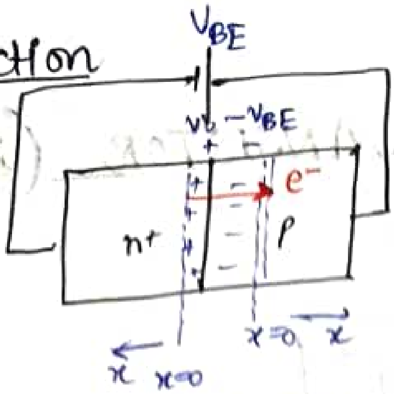
$n_{n0} \approx N_D$ (donor conc)

$p_{p0} \approx N_A$ (acceptor conc^n)

$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{n_i^2}{N_A}$$

$$p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{n_i^2}{N_D}$$

n^+p Junction under Forward Bias:

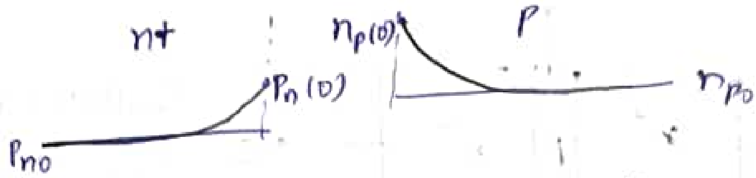


→ Depletion region narrows; diffusion processes are no longer balanced by electrostatic force.

At the edge of depletion region $(x=0)$, concn. of minority carriers:

$$n_p(0) = \frac{N_D}{e^{V_D/V_T}} \cdot e^{V_{BE}/V_T} = n_{p0}\, e^{V_{BE}/V_T} \approx \frac{n_i^2}{N_A} e^{V_{BE}/V_T}$$

→

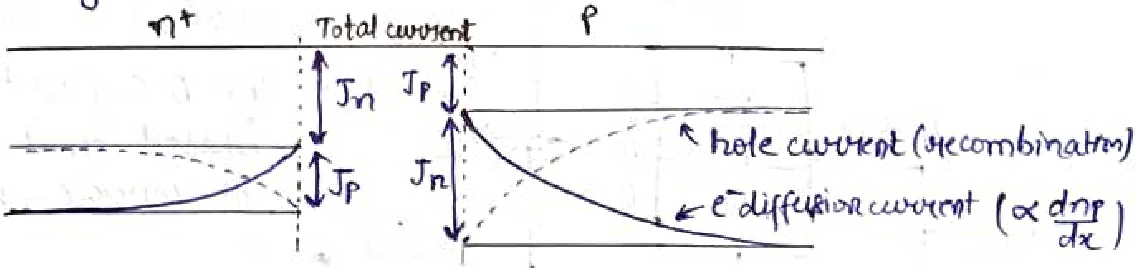


↳ The carriers would like to diffuse further into the neutral regions, but quickly fall victim to recombination.

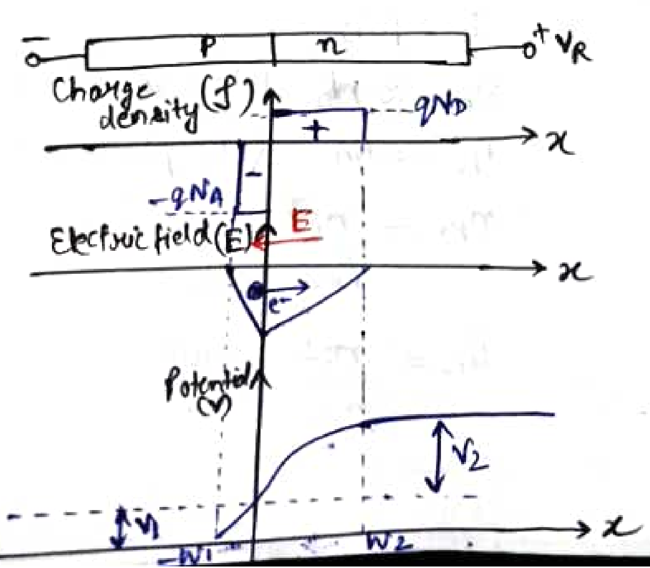
→ In each region, there are two types of currents:

(i) Diffusion of injected minority carriers due to non-zero $\frac{dn_p}{dx}$ (or $\frac{dp_n}{dx}$).

(ii) Minority carrier currents for recombination.



pn^- Junction under Reverse Bias:

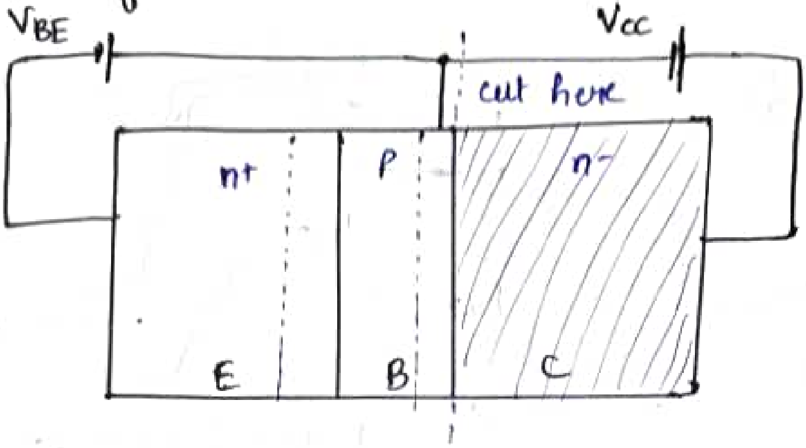


→ Reverse bias increases the width of the depletion region and increases the electric field

→ Depletion region extends mostly into n^- side.

→ Any e^- that would 'somehow' make it into the depletion region will be swept through, into the n-region, due to electric field.

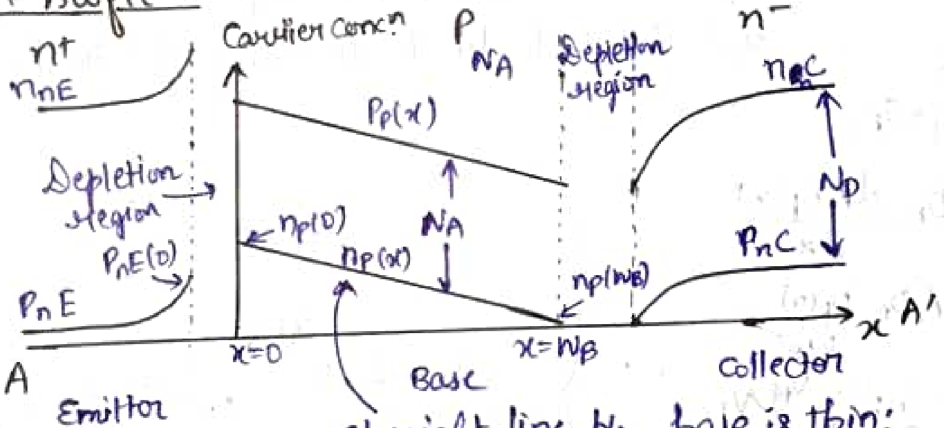
Main Idea of BJT :



→ Make the p-region of pn⁺junction very thin.
→ Attach an n⁻region that would collect and sweep across most of the electrons before there is a significant amount of recombination.

16-04-2024

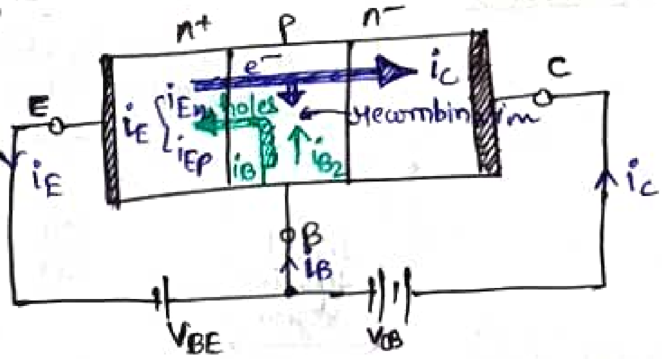
Carrier Profiles :



straight line b/c base is thin; negligible recombination ("short base" e⁻ profile)

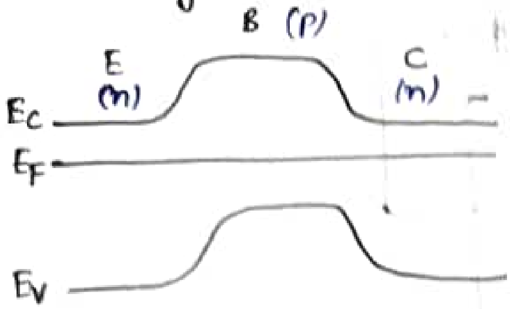
→ Assymetricity in doping results in amplification. ↓ due to n^+p.

Current flow in BJT :

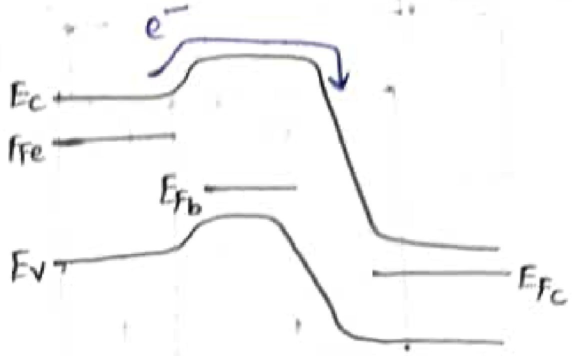


→ Primary current is due to e⁻s captured by collector.
→ Two (undesired) base current components :
ⓘ Hole injection into emitter (→0 for infinite emitter doping)
ⓘⓘ Recombination in base (→0 for base with width →0)

Band diagrams



Zero bias



Forward active
↳ EB junction is FB.
↳ CB junction is RB.

→ $I_E = I_B + I_C$

$I_C = \beta I_B$

$I_B = I_{B_1} + I_{B_2}$, I_{B_1} : current due to hole injection (into emitter)
I_{B_2} : current due to recombination (in the base)

$$\beta = \frac{I_C}{I_{B_1} + I_{B_2}}$$

$$J_n = q D_n \frac{d\, n_p(x)}{dx}$$

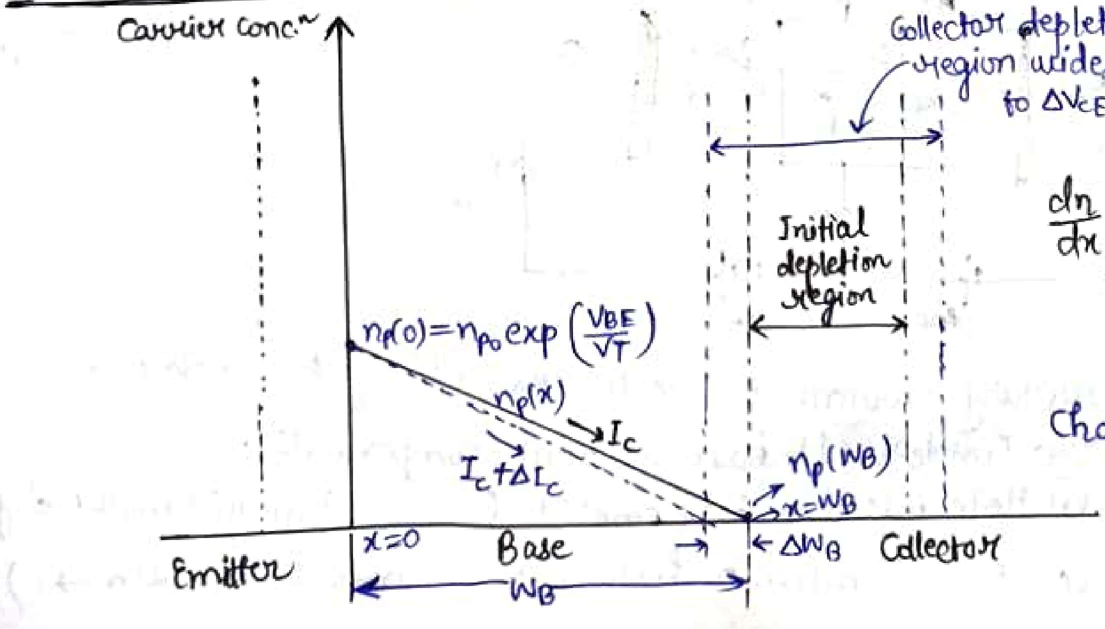
$$I_C \approx q A D_n \frac{n_p(0)}{W_B}$$

$$n_p(0) \approx \frac{n_i^2}{N_A} e^{V_{BE}/V_T}$$

$$I_C \approx \frac{q A D_n n_i^2}{W_B N_A} e^{V_{BE}/V_T}$$

$I_C \approx I_S e^{V_{BE}/V_T}$, $I_S = \dfrac{q A D_n n_i^2}{W_B N_A}$

Base Width Modulation (BWM)



$$\frac{dn}{dx} = \frac{n_{p0} \exp\left(\frac{qV_{BE}}{KT}\right)}{-W_B}$$

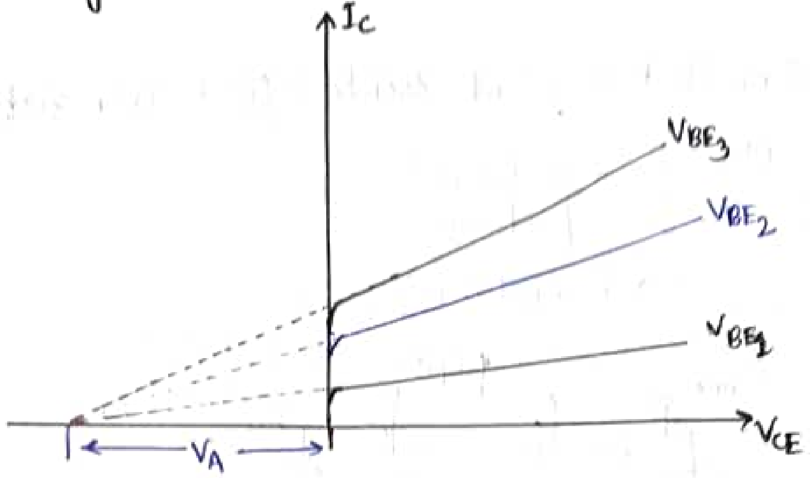
$$= \frac{-n_{p0} \exp\left[\frac{qV_{BE}}{KT}\right]}{W_B}$$

$$\text{Charge} = Aq\frac{dn}{dx}$$

$$I_{B_2} = \frac{\text{charge}}{\tau_n}$$

$$= \frac{Aq\, n_{p0} \exp\left(\frac{qV_{BE}}{KT}\right)}{W_B \tau_n}$$

Early Voltage

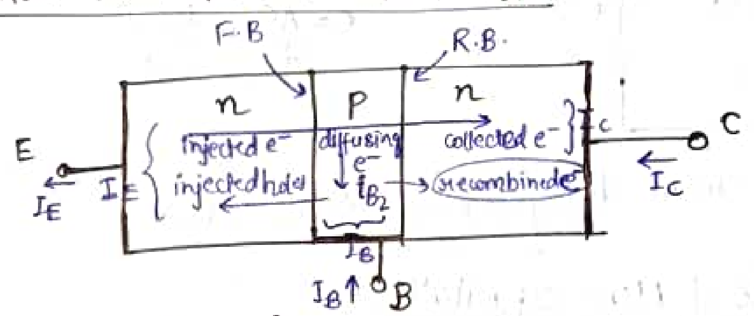


Punch through Effect:
Increase V_{CC} and I_C so much that depletion region widens.

$$V_A = \frac{I_C}{\frac{\partial I_C}{\partial V_{CE}}} = \frac{W_B}{\frac{dW_B}{dV_{CE}}} = \text{constant} \rightarrow \text{Indep. of } I_C$$

$$\therefore \boxed{I_C \approx I_S\, e^{\frac{V_{BE}}{V_T}} \left(1 + \frac{V_{CE}}{V_A}\right)}$$

→ Terminal currents in active mode:



Emitter current: $i_E = I_{En} + I_{Ep}$ → hole injection from B to E
I_{En}: e^- injection from E to B

Collector current: $i_C = i_{Cn} + i_{CBo}$
i_{Cn}: e^- drift
i_{CBo}: CBJ reverse saturation current with emitter open

Base current: $i_B = i_{B_1} + i_{B_2}$
i_{B_1}: hole injection from B to E
i_{B_2}: recombination in base region

→ Most of the injected electrons reach the edge CBJ ~~ate~~ before being recombined if the base is narrow.

Emitter injection efficiency, $\gamma = \dfrac{i_{En}}{i_{En} + i_{Ep}}$

Base transport factor, $\alpha_T = \dfrac{i_{Cn}}{i_{En}}$

Common-base current gain, $\alpha = \dfrac{i_{Cn}}{i_E} = \gamma\, \alpha_T < 1$

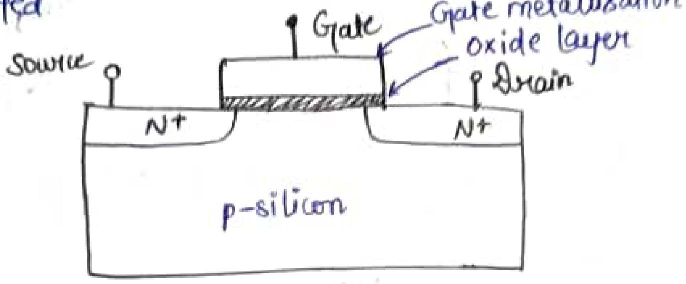
MOSFET

↳ Metal Oxide Semiconductor Field ~~Oxide~~ Effect Transistor

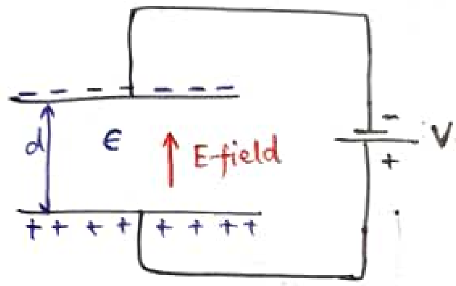
↳ Enhancement MOSFET → channel is enhanced

↳ Depletion MOSFET → channel is depleted

(both: n-channel, p-channel)



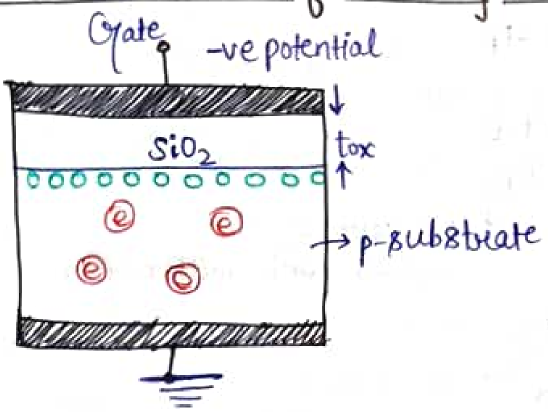
Parallel-plate capacitor:



$$C = \frac{A\epsilon}{d} = \frac{K\epsilon_0 A}{d}$$

→ Capacitance can be changed by: d, A, $K(\epsilon_r)$.

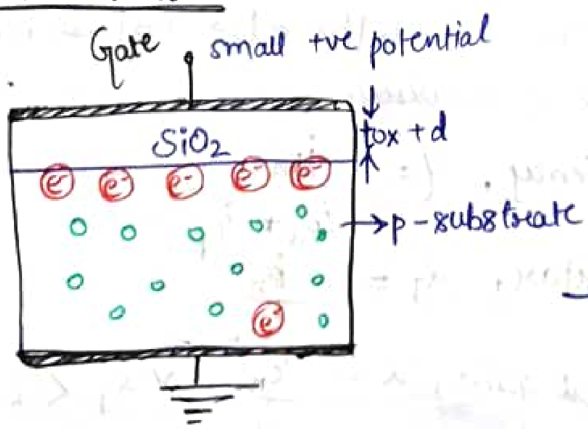
Accumulation mode of MOS capacitor:



$$C = \frac{\epsilon_0 \epsilon_r A}{t_{ox}}$$

→ Holes get accumulated just below the oxide layer.

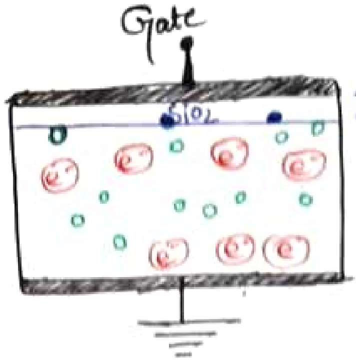
Depletion mode:



$$C = \frac{\epsilon_0 \epsilon_r A}{t_{ox} + d}$$

→ Holes are driven away resulting in the formation of a depletion region below oxide layer.

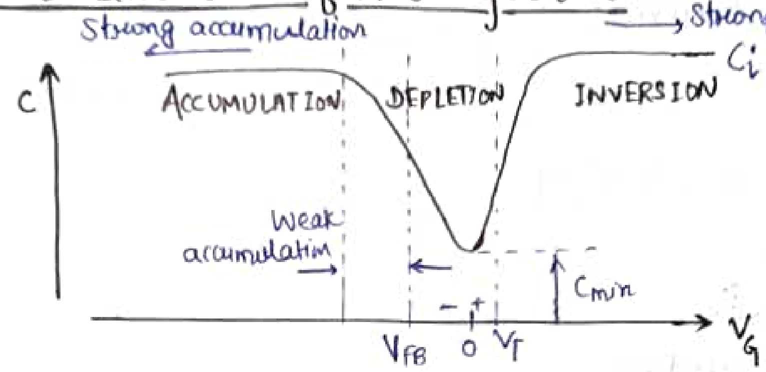
Inversion mode:



$$C = \frac{\epsilon_0 \epsilon_r A}{t_{ox}}$$

→ Electrons (minority carriers) are attracted just below oxide layer which now inverts the region below oxide layer.

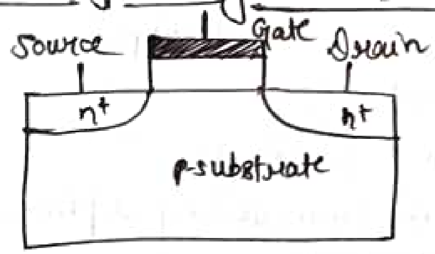
CV characteristics of MOS capacitor:



23-04-2024

→ By scaling devices:
- → Faster speed
- → More no. of devices
- → Reduce power consumption
- → Reducing the size.

Need for High-K and low-K dielectric materials:



→ Scaling of MOSFET causes decrease in thickness of oxide layer, leading to increase in leakage current (Gate leakage) → (Even when MOSFET is OFF)

↳ Use high-K dielectric, e.g., HfO_2 (Hafnium oxide).

→ As source and gate wires come closer, a capacitance of $C = \frac{\epsilon_0 \epsilon_r A}{d}$, (d: dist. b/w wires) forms b/w them.

↳ This capacitance causes RC delay.

↳ To minimize the capacitance, use low-K dielectric material.

→ Use copper interconnect to connect one MOSFET to the other.

Optoelectronic Devices

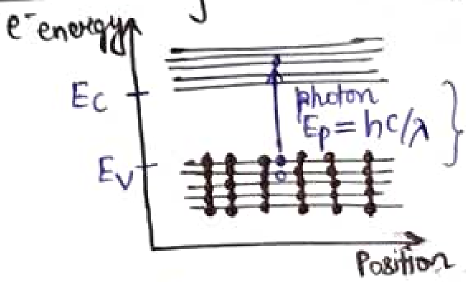
- ↳ Devices with interplay b/w electrons, holes and photons.
- ↳ Also called photonic devices.

Absorbs photons (light) creating e^- and h
- solar cells
- Photoconductors
- Photodiodes or photodetectors

e & h recombines to generate photon (light)
- LED
- LASER diodes

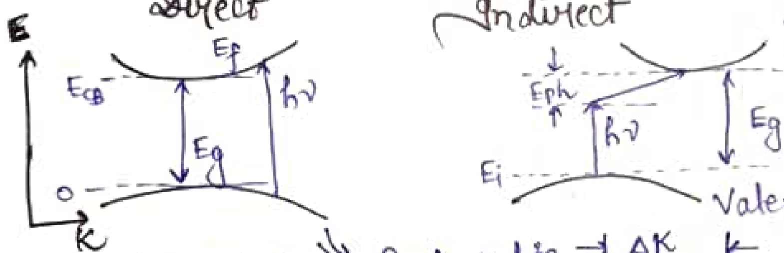
Optical Absorption and Emission

- Energy conservation
- Momentum conservation



Materials based on structure:

Direct, Indirect



Direct: $K = K_i = K_f$ ↳ Preferred in optoelectronic devices

Indirect: → ΔK

$E_f - E_i = h\nu + E_{ph}$ (Phonon absorption)

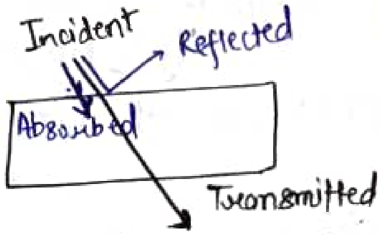
$E_f - E_i = h\nu - E_{ph}$ (Phonon emission)

$K_f = K_i + K_{ph}$

Absorption coefficient (α): Tells how good a material can absorb photon $[\equiv cm^{-1}]$
↳ Larger for direct bandgap

↓

Inverse of α (α^{-1}): Tells average distance travelled by a phonon before getting absorbed.

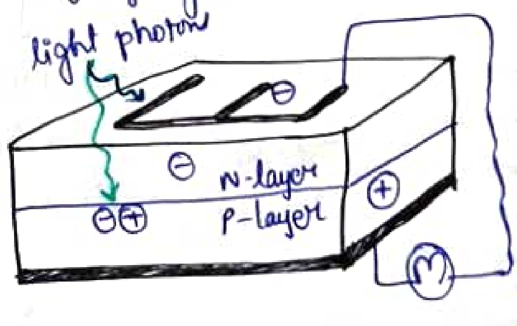


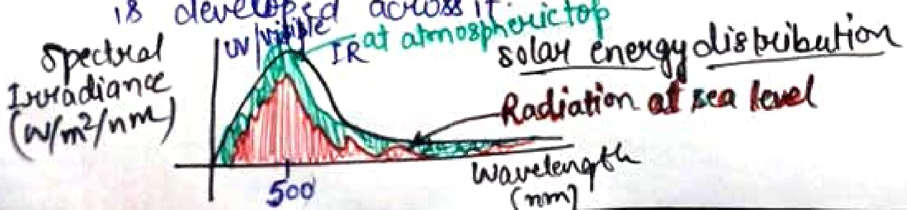
$\boxed{n = \sqrt{\epsilon}}$, ϵ: dielectric constant

$$\text{Refractive index } (n) = \frac{\text{velocity of light in vacuum}}{\text{velocity of light in medium}}$$

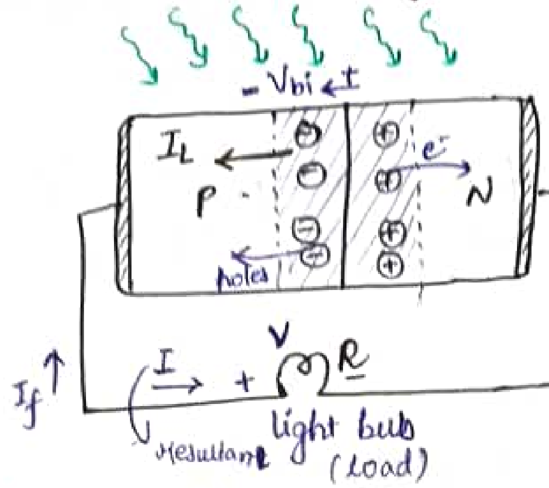
Solar cell (Photovoltaic cell)

- ↳ we want no reflection and transmission
- ↳ when light is shined on it, a potential diff. is developed across it.



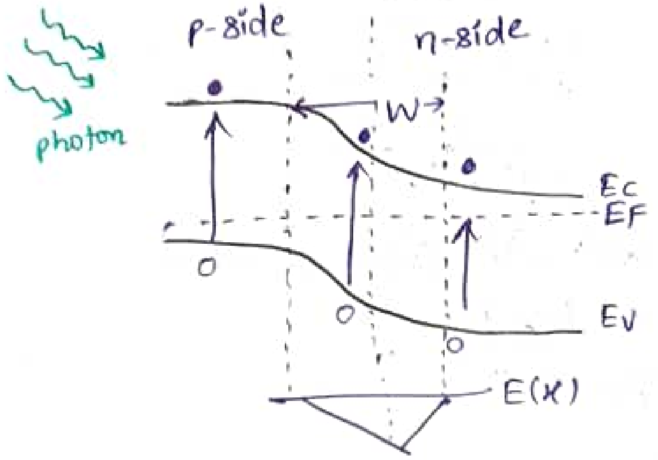


Photons with Energy greater than E_g striking P-N Junction:



→ Only electrons and holes present in the depletion region are swept by the strong electric field and collected at the P- and N-electrode
⇓
Photogeneration

→ Incoming photon with energy greater than the bond energy break the ~~bond~~ covalent bond, resulting in electron-hole pair generation.



→ Only photons falling on the depletion region results in photocurrent.

→ Solar cell is an unbiased, illuminated p-n junction.

Carriers generated: Photo-generated carriers
current generated: Photo-current (I_{ph}/ I_L)

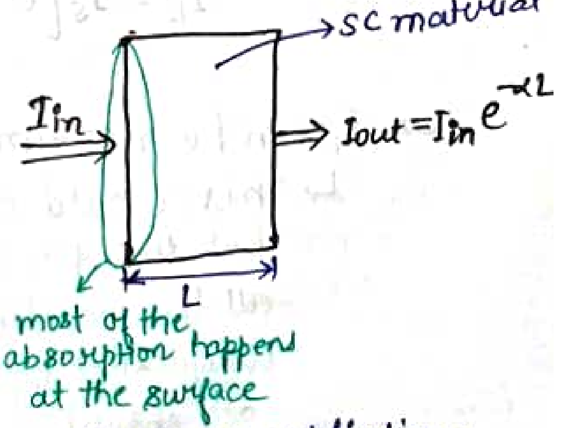
→ Direct vs. indirect bandgap solar cell

	(GaAs)	(Si)
① Efficiency/ Performance :	↑	↓
② cost :	↑ ⇓ For space-application	↓ ⇓ For power-generation

→ The photocurrent, I_L, produces a voltage-drop, V, across the resistor, R.
↳ This V, then, forward-bias the junction, producing forward-bias current, I_f.

→ Absorption coefficient (α) ↳ cm^{-1}

$\frac{1}{\alpha}$ = skin depth



→ For space application: skin depth ↓, α ↑ (GaAs > Si)

$$I_f = I_s\left[e^{\frac{qV}{KT}} - 1\right]$$

Resultant current,

$$I = I_L - I_f = I_L - I_s\left[e^{qV/KT} - 1\right]$$

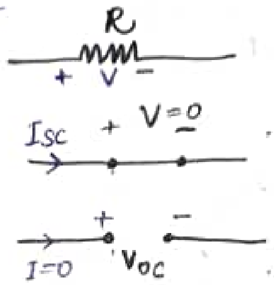
$\rightarrow$ I is opposite to I_f

$\rightarrow$ V is opposing V_{bi}.

$\hookrightarrow$ Current generated by the solar-cell

Solar-cell : Power-generating device

$P = V\,I$



Resistance : (Load)

Shorted : $V=0$

Open : $I=0$

Max^m current generated by solar-cell (when shorted)

$\hookrightarrow$ Short circuit current $\rightarrow I_{sc}\uparrow$

$\rightarrow$ Open-circuit voltage $\rightarrow V_{oc}$ $\uparrow$

$\hookrightarrow$ For power-generating device, we would want to maximise I_{sc} and V_{oc}.

Shorted load : $V=0$

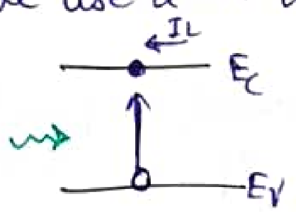
$I = I_L$ = photo-generated current

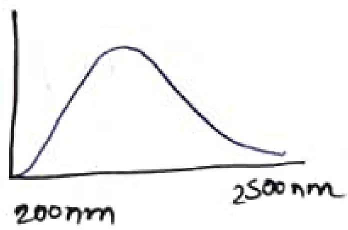
Open-load : $I=0$

$$I_L = I_s\left[e^{\frac{qV_{oc}}{KT}} - 1\right]$$

$\rightarrow$ I_L can be maximised if we use a SC with the smallest gap.

$\hookrightarrow$ This would ensure that the photons of all the wavelengths (originating from Sun) get absorbed.





$$I_L = I_s\left[e^{\frac{qV_{oc}}{KT}} - 1\right]$$

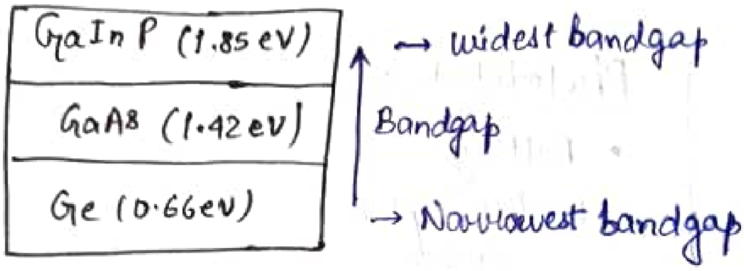
$$\Rightarrow V_{oc} = \frac{KT}{q}\ln\left[1 + \frac{I_L}{I_s}\right]\uparrow \Rightarrow \text{Bandgap}\uparrow$$

$$I_s \propto n_i^2 \propto \frac{1}{\text{bandgap}}$$

→ To maximise V_{oc}, we should use a SC whose bandgap is the largest.

Multi-junction Solar cells

↳ Multiple materials are cascaded.

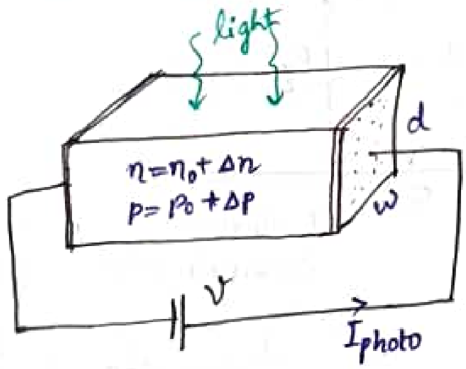


Moth-Eye Structure

↳ Bio-inspired

24-04-2024

Photoconductors



→ when light is shined, e-h pairs will be generated, reducing the resistivity.

Photoconductivity:

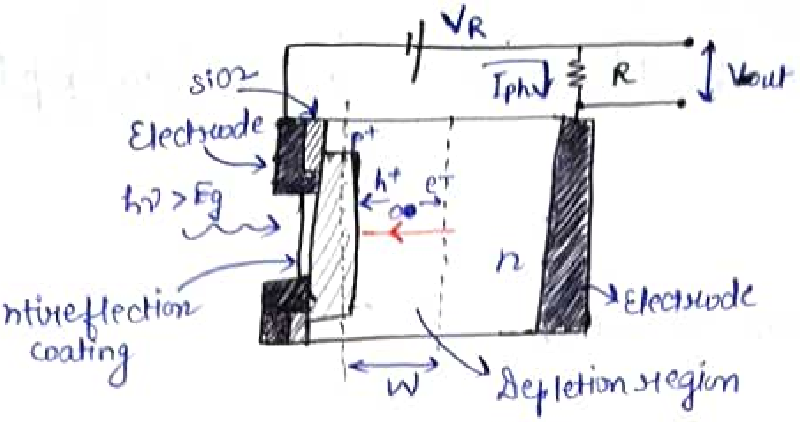
$$\Delta\sigma = \frac{e\eta\lambda I\,(\mu_e + \mu_h)}{hcd}$$

Photodetector (or photodiodes)

↳ convert light energy to an electrical signal.

↳ Light is absorbed and EHPs are created leading to photocurrent.

↳ Even with no light absorption, a current flows called as Dark current.



→ wider depletion region (due to reverse bias) to capture maxm photon.

→ Sensor

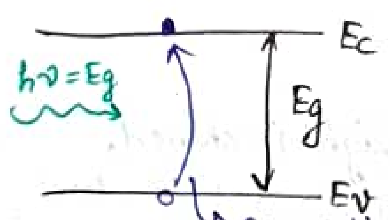
→ Fast response

Solar cell	Photodetector
• Unbiased	• Battery
• Narrow depletion region	• wider depletion region
	• Particular λ $[\lambda = 1550\ nm]$

$$\text{Quantum efficiency } (\eta) = \frac{\text{Rate of generation of useful EHP}}{\text{No. of incident photons per unit time}} = \frac{I_{ph}/e}{P_o/h\nu}$$

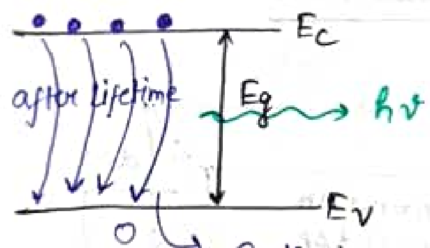
$$\text{Responsivity } (R) = \frac{\text{Photocurrent}}{\text{Incident optical power}} = \frac{I_{ph}}{P_o}$$

↳ characterizes the performance of photodetector.



↳ generation/absorption

↳ in solar cell, photodetector

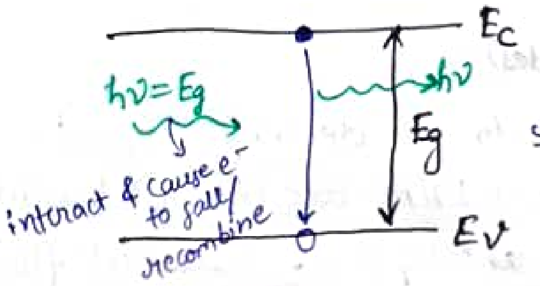


↳ Radiative recombination (for direct bandgap)

⇒ Spontaneous emission (in random dirn)

↳ in LED

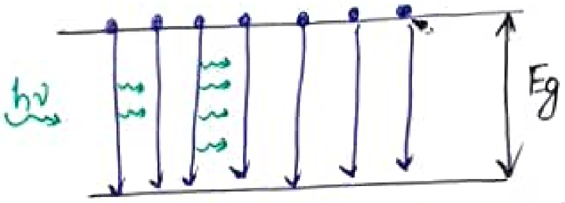
LASER : Light Amplification by Stimulated Emission of Radiation



⇒ Stimulated Emission

⇓

Incoming photon & generated photon are in the same phase/dirn & of same energy $[\lambda, \nu]$.



→ constant light

~~Non~~ Coherent light source: All photons have same direction, same polarisation and same energy.

LED / LASER : ~~Non-coherent~~.

LED → Non-coherent

LASER → coherent