Analog Electronics

Review of Semiconductors

1. Examples of semiconductors are

Silicon (Si), Germonium (Ge), Gallium Arsenide (GaAs)

Si, Ge → Single crystalline; GaAs → Poly crystalline.

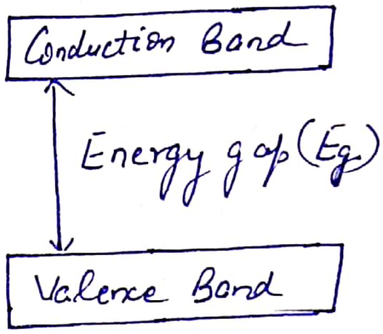
Q:- Why Si & Ge are generally preferred compared to GaAs?

Ans:- At Temperature, T = 0 K

E_{g0} of Ge = 0.785 eV

E_{g0} of Si = 1.21 eV

E_{g0} of GaAs = 1.58 eV

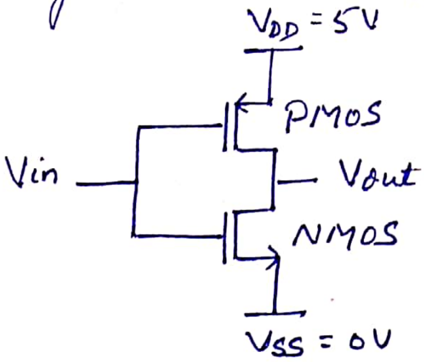


General energy band diagram

Since the energy gap (E_g) for Si & Ge is less compared to GaAs, therefore we expect more conduction in case of Si & Ge than GaAs.

Q:- Why GaAs is preferred in CMOS Technology?

Ans:



CMOS Inverter

Vin	PMOS	NMOS	VOUT
0	ON	OFF	V_{DD}
1	OFF	ON	V_{SS}

Mobility → Movement of majority carriers.

→ The mobility (μ) in case of GaAs > Si & Ge.

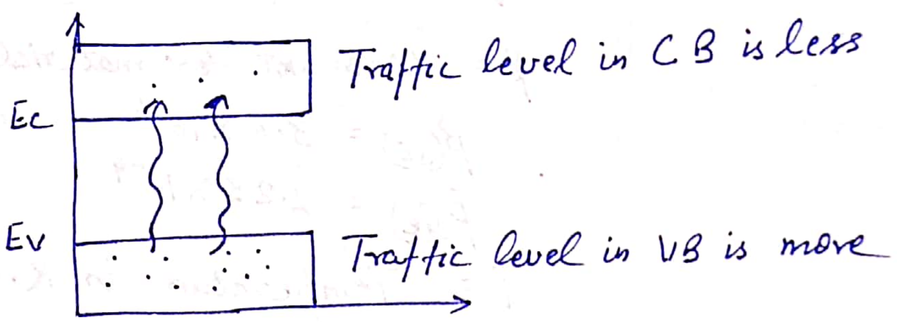
→ The temperature tolerant capability is more in GaAs (since energy gap is more).

→ Typical values of temperature for which the device can withstand :-

a) Ge → 100°C
b) Si → 200°C
c) GaAs > 200°C.

2. The mobility of electrons (μ_e) is greater than the mobility of holes (μ_h).

~~Reso.~~ Reason :-



When the device conducts, things are in motion, so the effective mass of hole is always greater than the effective mass of electron.
Therefore, traffic level is more in Ge, Si compared to GaAs. Hence mobility of Ge, Si < GaAs.

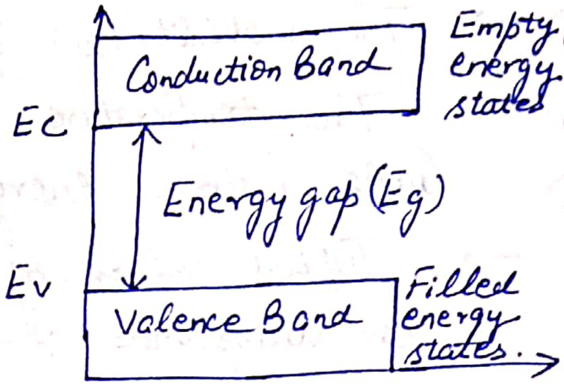
3. Ions :- Ions are indirect atoms which are immobile in nature.

There are two types of ~~iom~~ ions —

a) Positive ions → When the atom looses an $\bar{e}$, the atom is characterised as +ve ion.

b) Negative ions → When the atom gains an $\bar{e}$, the atom is characterised as −ve ion.

4. Energy band diagram:



$E_c \rightarrow$ Lowest energy level in conduction band

$E_v \rightarrow$ Highest energy level in valence band

$E_g \rightarrow$ Forbidden gap.

Energy gap Vs Temperature :

$$E_g\,(\text{Temp. in K}) = E_{g_0} - \beta T$$

where E_{g_0} = Energy gap at 0K $\left\{ \begin{array}{l} Ge \rightarrow 0.785\,eV \\ Si \rightarrow 1.21\,eV \end{array} \right\}$

β = constant for material ~~$Ge \rightarrow \beta(Ge) = 3.6\times10^{-4}$~~

$\beta(Si) = 3.6 \times 10^{-4}$ ~~$\beta(Si) =$~~

$\beta(Ge) = 2.23 \times 10^{-4}$

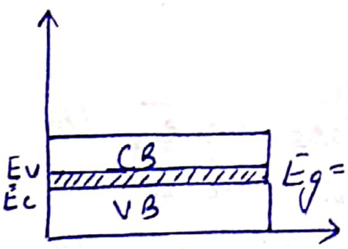
T = Temperature in K.

Q: Calculate the energy gap value for Si & Ge at Room Temperature (T = 27°C).

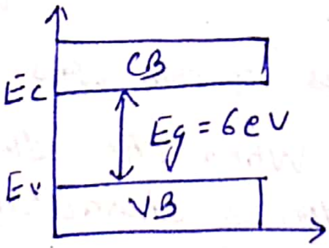
Sol^n:
Si $\rightarrow$ 1.12 eV
Ge $\rightarrow$ 0.72 eV

$\rightarrow$ As Temp increases, energy gap value decreases.

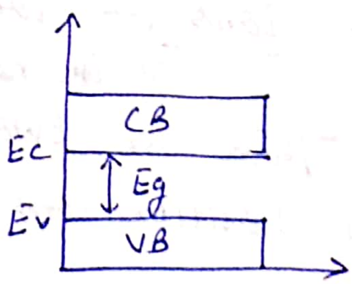
5. Classification of Materials (Based on Energy Band Theory) :-



Conductor



Insulator



Semi conductor

~~$E_g(Si) = 0.785$~~

$E_g(Ge) = 0.785\,eV$

$(Si) = 1.21\,eV$

$(GaAs) = 1.58\,eV$.

Q:- Why carbon is not behaving like a semiconductor (4)

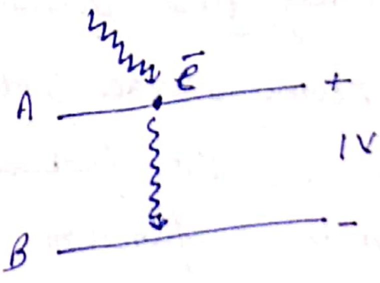
Ans:- Energy gap of Carbon = 2 eV. As the energy gap value for carbon is more than the typical value of semiconductor, therefore ~~it~~ it behaves like a perfect insulator.

6. Differences b/w conductors, insulators & semiconductors.

Property	Conductors.	Insulators.	Semiconductors.
1) Resistivity	Less ($10^{-8}\,\Omega cm$)	Highest ($10^{12}\,\Omega cm$)	$10^{-4}\,\Omega cm$ to $10^{3}\,\Omega cm$
2) Type of Bonding	Metallic	Ionic & covalent	Covalent
3) Energy gap.	0 eV	6 eV	Ge = 0.785 eV Si = 1.21 eV GaAs = 1.58 eV
4) Temp. coeff. of resistance	+ve	Nil	-ve
5) Charge carriers.	$\bar{e}$	Nil	$\bar{e}$ & holes.

7. Unit of eV →

$$1\,eV = 1.6\times10^{-19}\,(\text{Charge}) \times 1V$$
$$= 1.6\times10^{-19}\,J$$



The amount of energy required for an $\bar{e}$ to fall through a voltage difference of 1V.

8. **Doping** :→ Process of adding any impurity in the semi-conductor thus improving its conductivity is called doping.

Two types of semiconductors → a) Intrinsic (Pure).
b) Extrinsic (Impure).

a) **Intrinsic semiconductor** → $n = p = n_i$

where n = concⁿ of $\bar{e}/cm^3$
p = concⁿ of holes/cm^3
n_i = intrinsic concentration/cm^3.

b) **Extrinsic semiconductor** →

Intrinsic s/c + Dopant = Extrinsic s/c.

Dopants are of two types

i) Pentavalent impurity → Here majority carriers are $\bar{e}$ & minority carriers are holes.

for example: Arsenic, Antimony, Bismuth, Phosphorus.

ii) Trivalent impurity → Here majority carriers are holes & minority carriers are $\bar{e}$.

for example: Gallium, Boron, Aluminium, Indium.

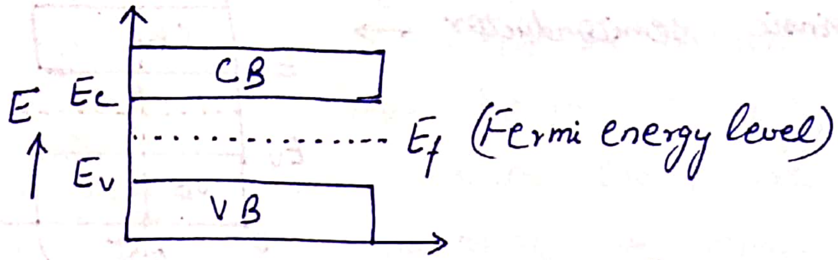
9. **Energy band diagram in a semiconductor** :-

Fermi Dirac probability function:- In the energy band diagram, the probability that the energy level of $\bar{e}$ is given by a function called as fermi function is defined as

$$F(E) = \frac{1}{1 + e^{(E - E_f)/KT}}$$

where
E = Energy of $\bar{e}$
E_f = Fermi energy
K = Boltzmann constant
T = Temperature.

At $T = 0K$



$F(E) = 1$ for $E < E_f$

$= 0$ for $E > E_f$

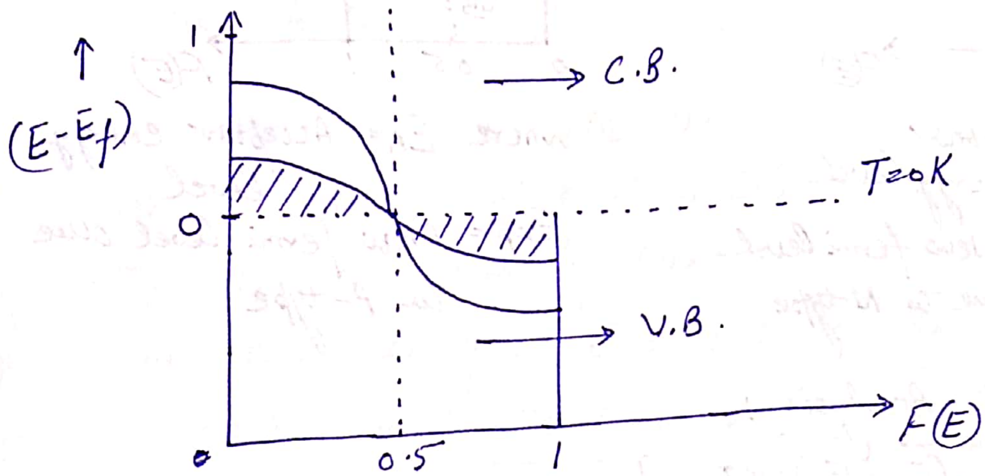
$= x$ (Indeterminate) for $E = E_f$

Empty states

E_f

Filled states.

Fermi Level: It is the reference level which seperates filled states with the empty states.



At $T \neq 0K$ & $E = E_f$.

$$F(E) = \frac{1}{1 + e^{(E-E_f)/KT}} = \frac{1}{1+e^0} = \frac{1}{2} = 0.5$$

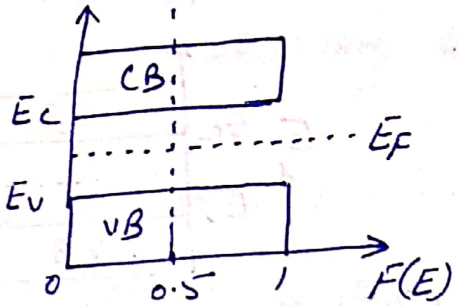
a) At $T = 0K$, the fermi level line will be a flat line.

b) At $T \neq 0K$, the fermi level will be a curvature in nature.

Ee. Note → Fermi level is not a constant level & depends on doping.

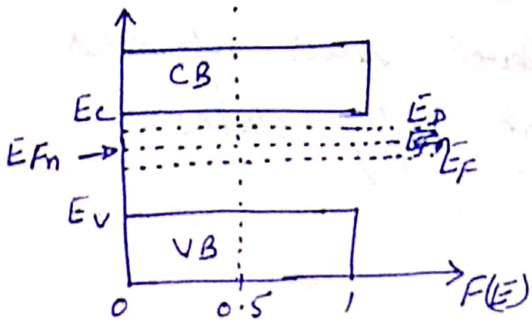
10. Energy band diagrams :

a) Intrinsic semiconductor →



b) Extrinsic semiconductor

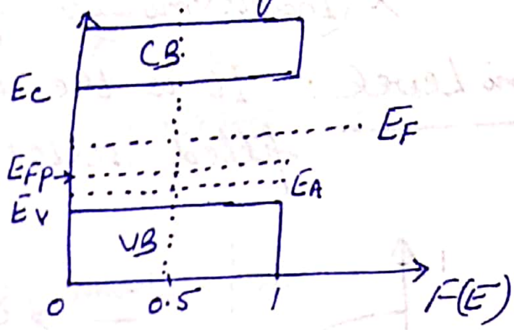
i) N-type



where E_D = Donor energy level

E_{Fn} = New fermi level due to N-type

P-type



where E_A = Acceptor energy level

E_{FP} = New fermi level due to P-type.

11. Mathematical Analysis :

$$\left.\begin{aligned} n &= N_c\, e^{-(E_c - E_F)/KT} \\ p &= N_v\, e^{-(E_F - E_v)/KT} \end{aligned}\right\}$$ Fermi dirac probability function.

where n = Concentration of $\bar{e}$

p = Concentration of holes

N_c = Effective density of states in C.B.

N_v = Effective density of states in V.B.

E_c = Lowest energy level in C.B.

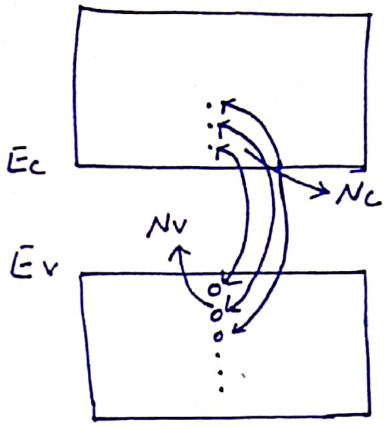
E_v = Highest energy level in V.B.

E_F = Fermi level

K = Boltzmann constant $= 1.38 \times 10^{-23}$ J/K

T = Temp. in K.

At $T \neq 0K$



N_c = The density of energy states where the $\bar{e}$ are filled.

N_v = Density of energy states where the $\bar{e}$ are missing.

$N_c \approx N_v \rightarrow$ Intrinsic s/c (Perfect material)

$N_c \neq N_v \rightarrow$ Extrinsic s/c (Imperfect material)

$N_c = N_v$ (Ideal Condition).

Also,

$$N_c = 4.82 \times 10^{15} \left(\frac{m_n}{m}\right)^{3/2} T^{3/2} \ /cm^3$$

$$N_v = 4.82 \times 10^{15} \left(\frac{m_p}{m}\right)^{3/2} T^{3/2} \ /cm^3$$

If $m_n = m_p \Rightarrow N_c = N_v$

m_n = Effective mass of $\bar{e}$ in C.B.

m_p = Effective mass of holes

m = Rest mass of an $\bar{e}$ = 9.18×10^{-31} Kg.

12. Expression for fermilevel in case of intrinsic semiconductor

$n = p$

$$N_c e^{-(E_c - E_F)/KT} = N_v e^{-(E_F - E_v)/KT}$$

$$KT \ln\left[\frac{N_c}{N_v}\right] = E_c + E_v - 2E_F$$

$$E_F = \frac{E_c + E_v}{2} - \frac{KT}{2} \ln\left[\frac{N_c}{N_v}\right] \rightarrow [\text{If } N_c \neq N_v]$$

& $$E_F = \frac{E_c + E_v}{2} \longrightarrow [\text{If } N_c \approx N_v]$$

Expression for fermilevel in case of extrinsic semiconductor

For N type

$n \approx N_D$ (Donor concentration)

For P type

$p \approx N_A$ (Acceptor concentration)

13. Law of mass action :-

For intrinsic s/c $\rightarrow$ $n \cdot p = n_i^2$

& $n = p$

For N type $\rightarrow$ $n \cdot p = n_i^2$

Majority Minority

For P type $\rightarrow$ $n \cdot p = n_i^2$

Minority Majority.

14. Charge neutrality equation :-

Any part of semiconductor bar is always electrically neutral.

i.e. Total +ve charge densities = Total −ve charge densities

$$p + N_D = n + N_A$$

In case of N-type :- $p + N_D = n + N_A$

Here $n >> p$ & $N_A \approx 0$

$$\therefore \frac{n_i^2}{n} + N_D = n + 0$$

$$\Rightarrow \cancel{n^2 = N_D}$$

$$\Rightarrow n^2 - N_D \cdot n - n_i^2 = 0$$

$$\Rightarrow n = \frac{N_D}{2} \pm \sqrt{\left[\frac{N_D}{2}\right]^2 + n_i^2} = \frac{N_D}{2} + \sqrt{\left[\frac{N_D}{2}\right]^2 + n_i^2}$$

Since $N_D >> n_i$

$$\cancel{n =} \boxed{n \approx N_D}$$

Similarly for P-type :- $p = \frac{N_A}{2} + \sqrt{\left[\frac{N_A}{2}\right]^2 + n_i^2}$

$$\boxed{p \approx N_A}$$

N-type

$$n = N_c \, e^{-(E_c - E_f)/KT}$$

$$KT \ln\left[\frac{N_c}{N_D}\right] = E_c - E_{fn}$$

$$\boxed{E_{fn} = E_c - KT \ln\left[\frac{N_c}{N_D}\right]}$$

P-type

$$p = N_v \, e^{-(E_f - E_v)/KT}$$

$$N_A = N_v \, e^{-(E_{fp} - E_v)/KT}$$

$$KT \ln\left[\frac{N_v}{N_A}\right] = E_{fp} - E_v$$

$$\boxed{E_{fp} = E_v + KT \ln\left[\frac{N_v}{N_A}\right]}$$

→ The fermi level moves toward the intrinsic fermi level in case of n & p-type.

→ At very high temp., extrinsic semiconductor will behave like intrinsic semiconductor.

→ As doping concentration increases, the fermilevel moves towards the conduction band in case of n-type & moves towards the valence band in case of p-type.

15. Drift Current :- It occurs in metals & semiconductors.

The current produced due to drifting of free $\bar{e}$ is called drift current.

Mobility :— Defined as the ratio of drift velocity to the electric field.

i.e. $\text{Mobility}(\mu) = \dfrac{\text{Drift velocity}}{\text{Electric field}}$

→ Effect of electric field on mobility :-

$\mu = \text{constant}$ if $E < 10^3$ V/cm.

$\mu \propto \dfrac{1}{\sqrt{E}}$ if $10^3 < E < 10^4$ V/cm.

$\mu \propto \dfrac{1}{E}$ if $E > 10^4$ V/cm.

→ Effect of temperature & impurity on mobility :—

The $\bar{e}$ & hole mobility are influenced by two scattering phenomenon.

a) Lattice scattering ⇒ As the temp. increases, there will be vibration in crystal lattice which reduces the mobility. i.e. $\boxed{\mu \propto T^{-m}}$

b) Impurity scattering ⇒ As temp. decreases, impurity scattering will become more dominant.

$\boxed{\mu \propto T^{m}}$

16. **Diffusion Current** :→ It occurs in non uniformly doped Semiconductor.

The best eg example of non uniformly doped semiconductor is pn junction.

→ The rate ~~at which~~ of change of concentration w.r.t. distance x is called diffusion current.

→ Diffusion current mechanism can also be called as concentration gradient $\left[\frac{dn}{dx}\right]$.

→ Drift current mechanism can also be called as potential gradient $\left[\frac{dV}{dx}\right]$.

→ Current density in n-type, $J_n \propto q \frac{dn}{dx}$

$$\Rightarrow J_n = q D_n \frac{dn}{dx}$$

where D_n = Diffusion constant of $\bar{e}$.

$$\therefore \text{Current}, \; I_n = A q D_n \frac{dn}{dx}$$

→ Current density in p-type, $J_p \propto -q \frac{dp}{dx}$

$$\Rightarrow J_p = -q D_p \frac{dp}{dx}$$

where D_p : Diffusion Constant of holes.

$$\therefore \text{Current}, \; I_p = -A q D_p \frac{dp}{dx}$$

→ Total current in a semiconductor :-

$$I = I_{drift} + I_{diffusion}$$

$$= nq\mu_n EA + pq\mu_p EA + Aq D_n \frac{dn}{dx} - Aq D_p \frac{dp}{dx}$$

→ There is an important relation b/w diffusion constant & mobility. i.e. $D \propto \mu$

$$D = V_T \cdot \mu$$

where V_T = Thermal voltage.

$$V_T = \frac{K \cdot T}{q} = \frac{T}{11600}.$$

where K = Boltzmann constant
T = Temperature.

$V_T = 26\,mV$ at $T = 300K$

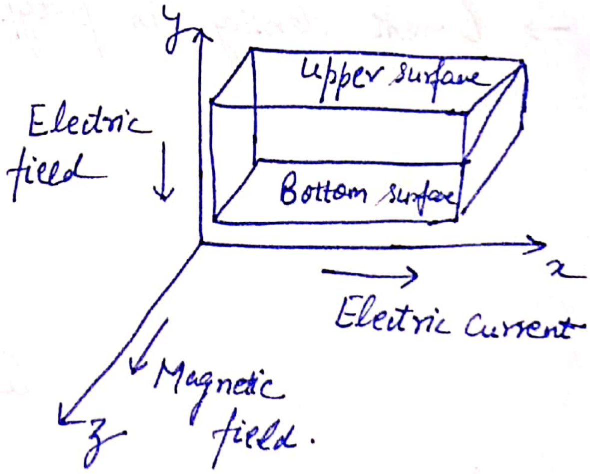
17. Einstein's Relation:

$$\boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T}$$

18. Hall Effect: When a magnetic field is applied to a current carrying conductor in a direction perpendicular to that of flow of current, a potential difference or transverse electric field is created across a conductor. This phenomenon is called Hall effect.

Hall voltage

$$V_H = \frac{I\,B}{q\,n\,d}$$



V_H = Hall voltage
I = Current flowing through the material
B = Magnetic field strength
q = charge
n = number of mobile charge carriers / unit volume
d = thickness of material.

Applications of Hall effect:

1) Used to find whether a semiconductor is N-type or P-type.
2) Used to find carrier concentration.
3) Used to calculate mobility of charge carriers.
4) Used to measure conductivity.
5) Used to measure a.c. power & strength of magnetic field.
6) Used in an instrument called Hall effect multiplier which gives output proportional to product of two input signals.