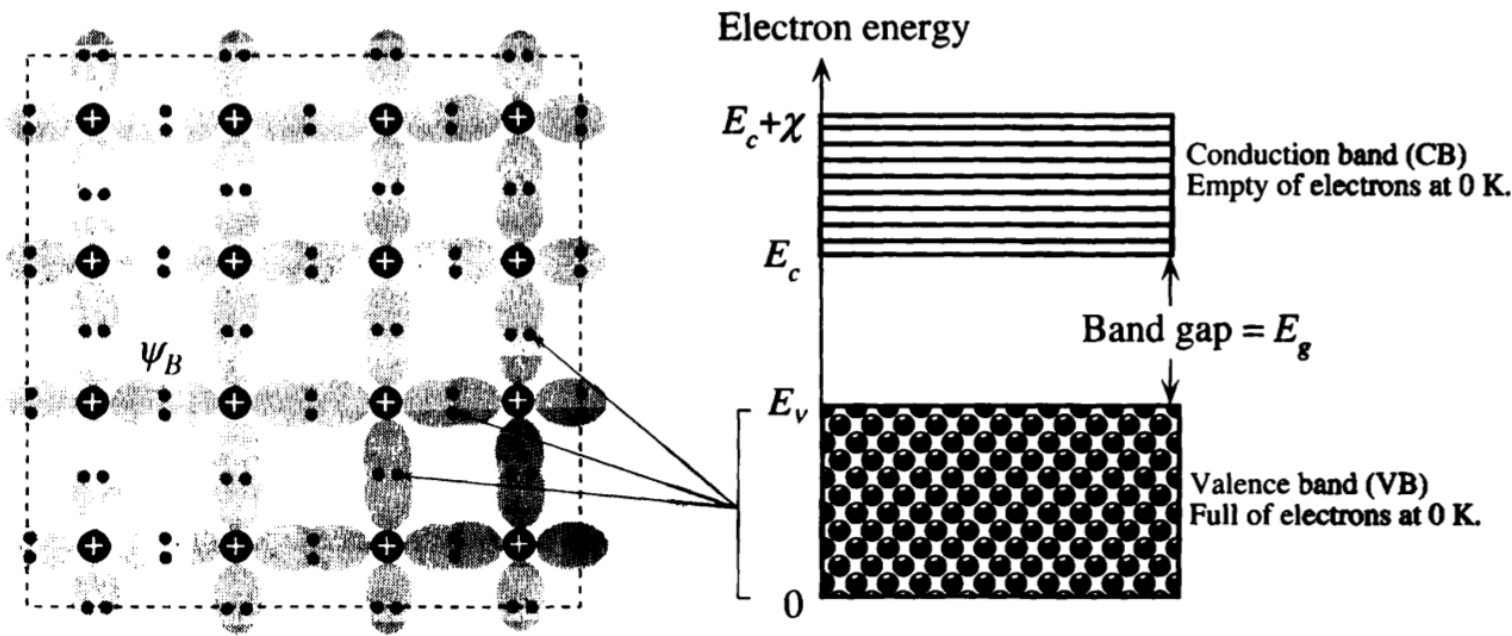


Semiconductors

Semiconductors

- In Si (Example)
- At 0K, the last band is completely filled!
- The last filled band is called as valence band
- The first empty band is called as conduction band!

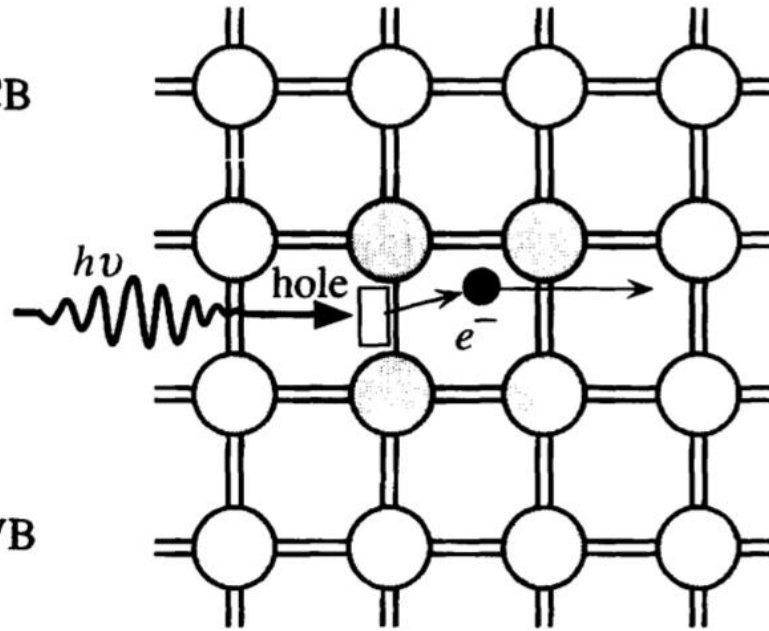
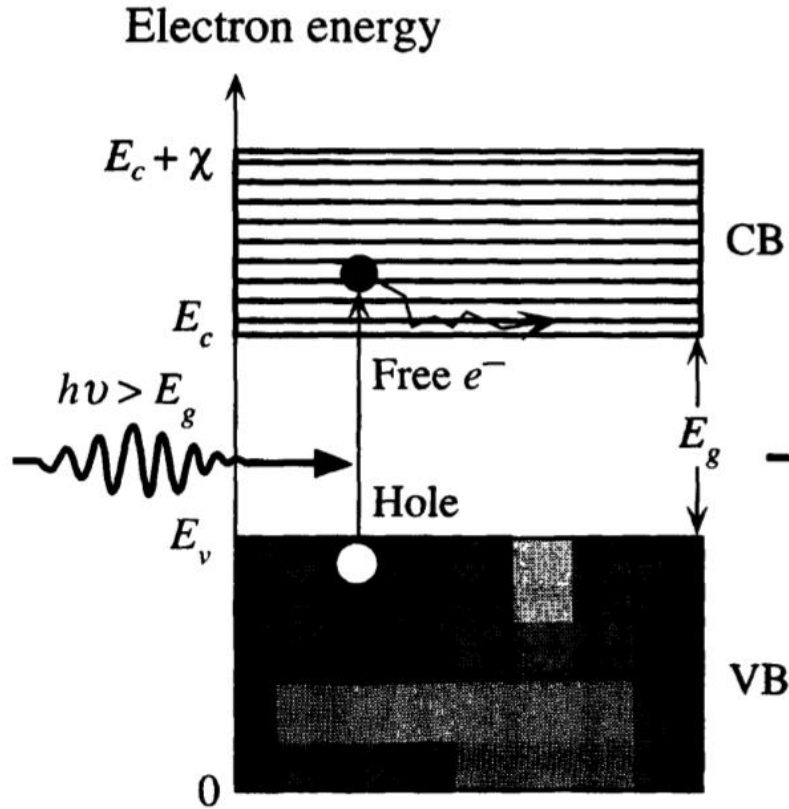


For conduction, atleast an empty state is required!

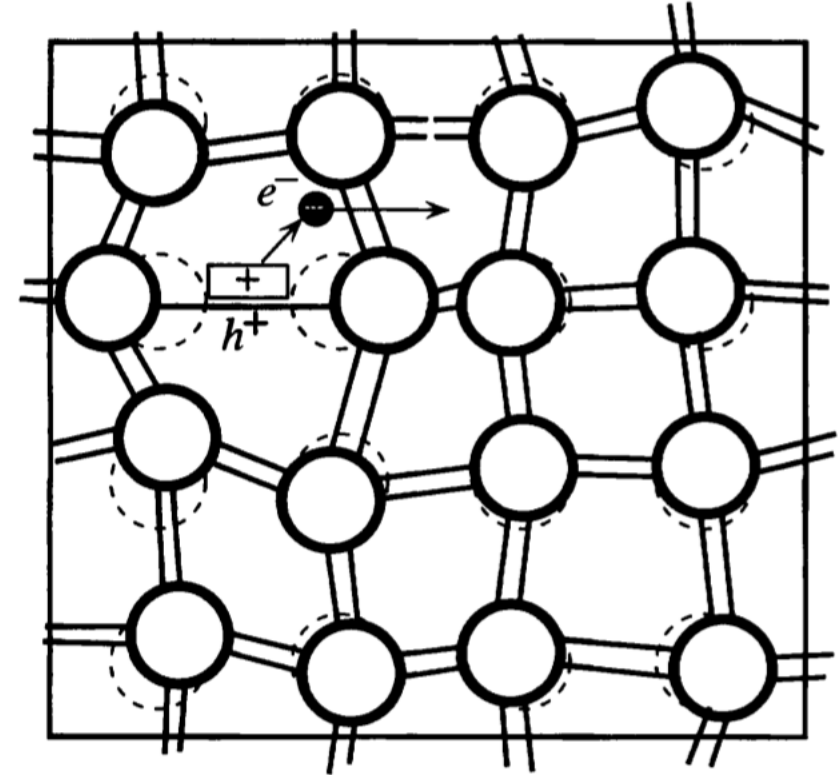
A completely filled band cannot conduct!

Valence bands are bonding orbitals
Conduction bands have non-bonding orbitals

Excitations

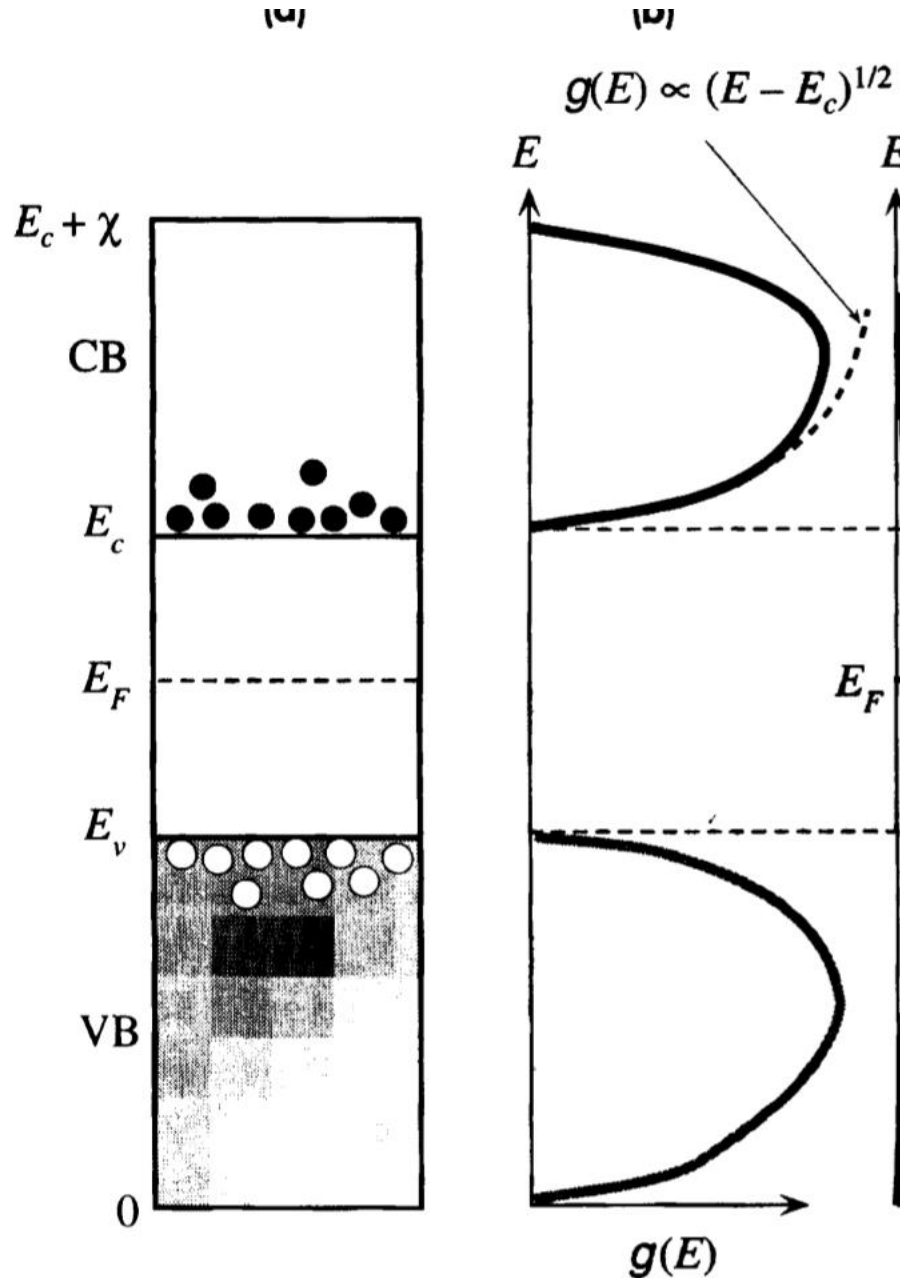


Thermal vibration of atoms break bonds.
Excite electrons to conduction band.



- Significant energy is required to excite an electron from valence to conduction.
- An energy almost equivalent to breaking of bonds!

Carrier statistics in Semiconductors



- The total number of electrons in a semiconductor is conserved!
- Either by photon or by thermal, if an electron is excited to conduction,
 - A corresponding hole is generated!
- Probability of an electron occupation at energy E $P(E) = \frac{1}{1 + e^{\beta(E - E_F)}}$
- In the same way, the probability of a hole at energy E $P(E) = 1 - \frac{1}{1 + e^{\beta(E - E_F)}}$
- $\beta = \frac{1}{kT}$

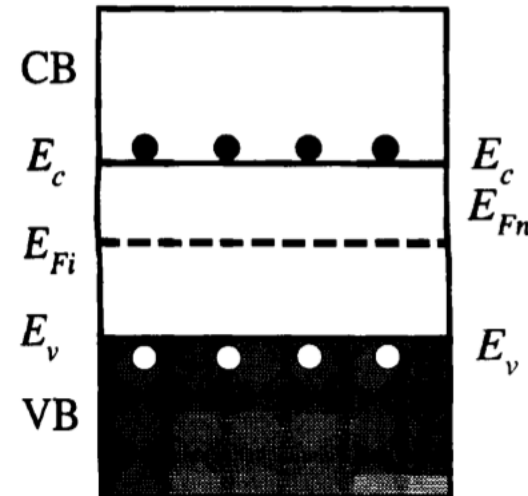
Intrinsic Semiconductor

- At any non-zero temperature, The conduction band always has non-zero probability of occupation.

- The total number of electrons in the conduction band

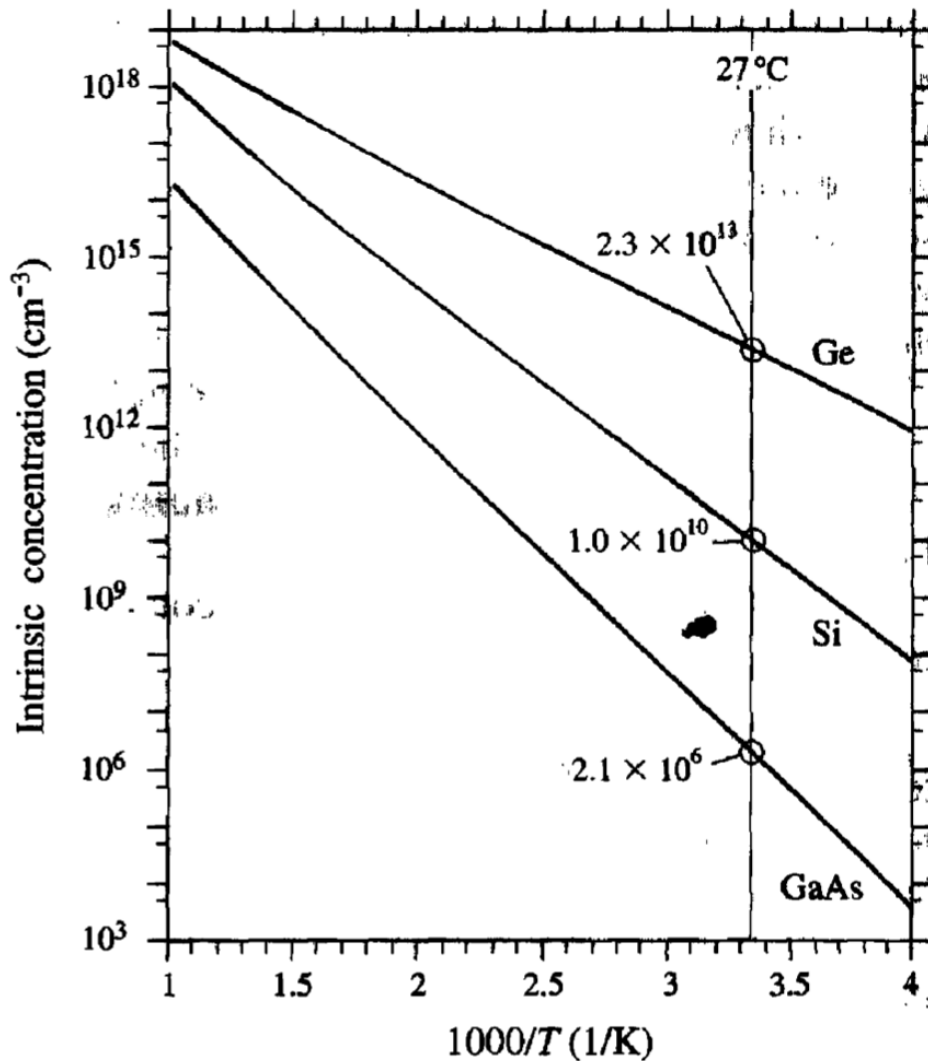
$$n_i = \int_{E_C}^{\infty} F(E)D(E)dE$$

- The Fermi level is in the middle of the bandgap
- The total number of electrons = total number of holes
- $n = p = n_i$ Other wise called as intrinsic carrier density
- Typical semiconductors (Si,Ge,GaAs...) have very small intrinsic carrier density $\sim 10^6 - 10^{13} \text{ cm}^{-3}$



Temperature dependence of carrier density

Intrinsic carrier density



$$n_i^2 = C e^{-\frac{E_G}{kT}}$$

- Larger bandgap leads to smaller n_i
- Higher temperature leads to exponential increase in n_i

$$C = N_C N_V$$

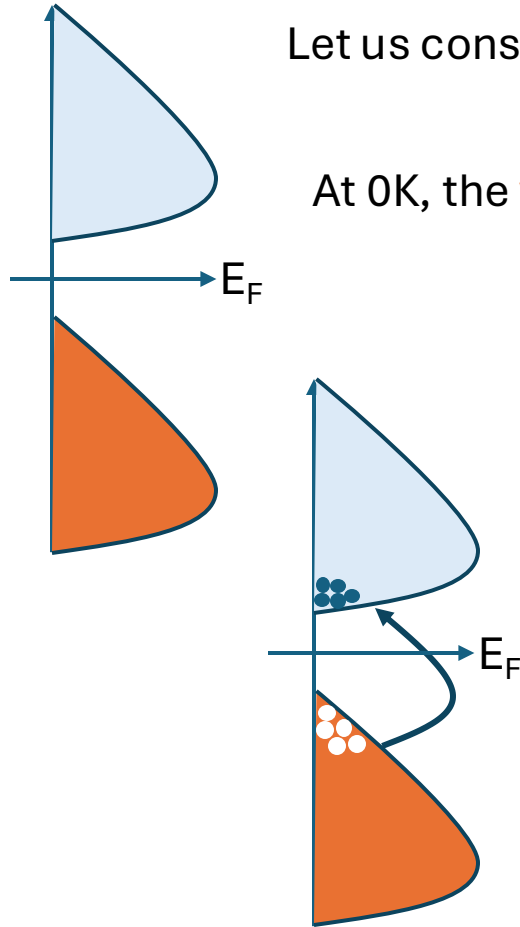
Effective density of states at band Edge

$$n = N_C e^{-\beta(E_C - E_F)}$$

$$p = N_V e^{\beta(E_V - E_F)}$$

Let us consider a semiconductor

At 0K, the **valence band** is completely filled and **conduction band** is empty. No current is possible.



At any temperature $T \neq 0$, some of the electrons from valence band can occupy states in the higher lying conduction band

The number of electrons that can occupy the conduction at temperature T is determined by the Fermi-Dirac function

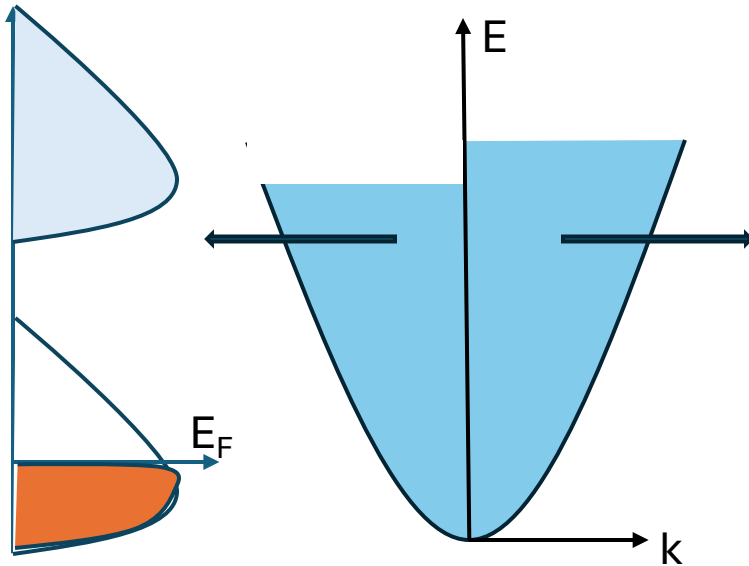
$$P(E) = \frac{1}{1 + e^{\beta(E - E_F)}}$$

Total number of electrons in the conduction band $n = \int_0^\infty P(E) D_C(E) dE$

Total number of holes in the valence band $p = \int_0^\infty [1 - P(E)] D_V(E) dE$

Conduction in Semiconductors

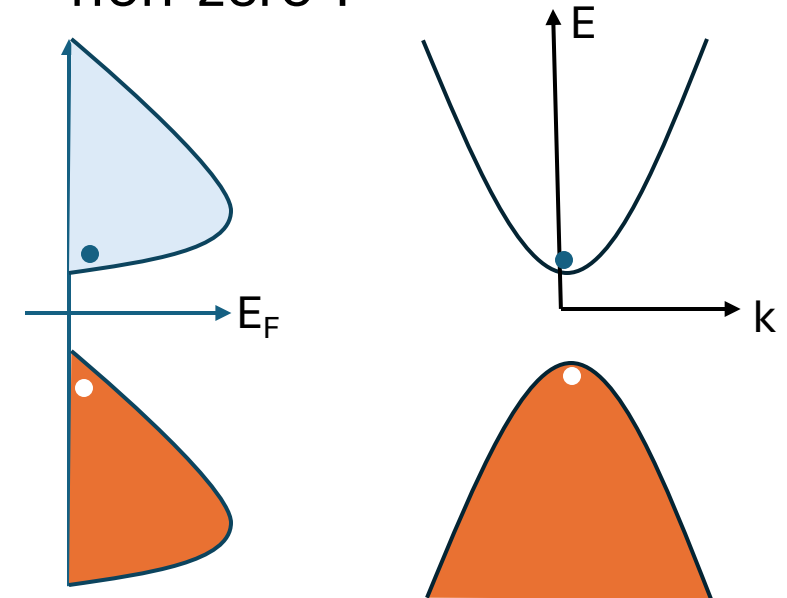
Case of metal



Existence of states immediately above E_F allows for immediate and high conductivity.

A large density of electrons are available for conduction!

Case of Semiconductor at non-zero T



The electron in the conduction band
And the hole in the valence band are free to move!
Any small electrical field will cause conduction.

However, the total number of carrier density is very low

Expression for conductivity

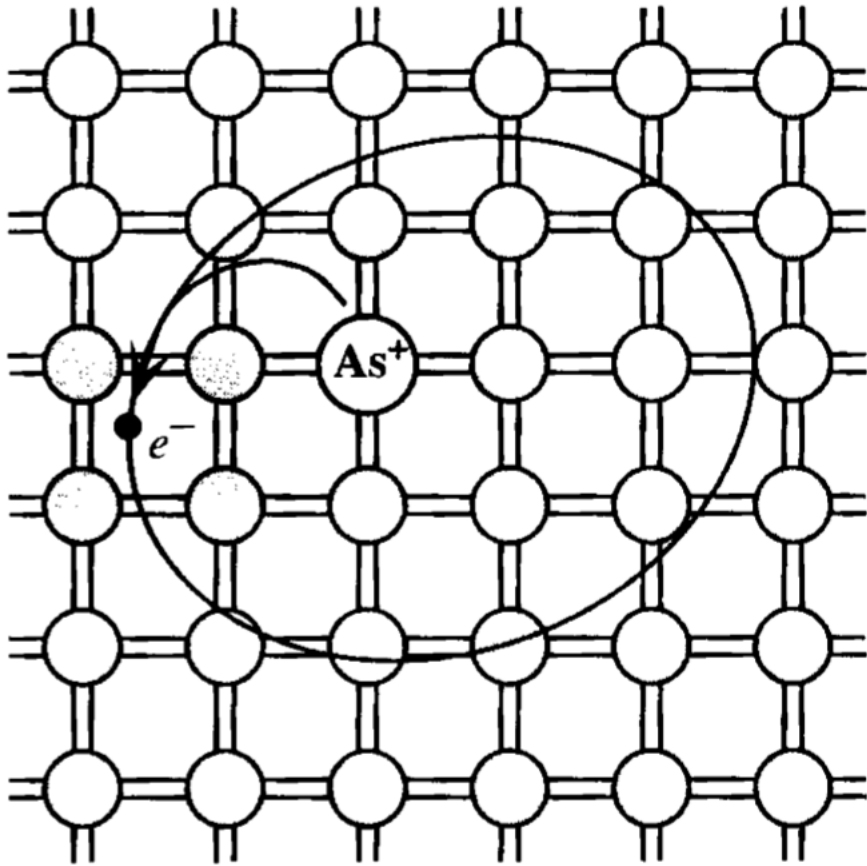
- For a metal, the conductivity:

- $\sigma = \frac{ne^2\tau}{m} = ne\mu$
- n – number of electrons in the proximity to E_F
- $\mu = \frac{e\tau}{m}$ mobility of electrons
- Mobility is a very small value due to larger scattering.
- Conductivity dominated by carrier density (n)

- For semiconductor, the conductivity:

- $\sigma = \frac{ne^2\tau}{m} = ne\mu_n + pe\mu_p$
- Mobility of electron $\mu_n = \frac{e\tau_n}{m_e}$
- Typically, a much higher value.
- Mass of electron and hole are different!
- Mean free path of electron and hole are different!
- Lower n, p makes conductivity lower!

Extrinsic Semiconductors



Si – $1S^2 2S^2 2P^6 3S^2 3P^2$ Quad-valent

As – $[Ar] 3d^{10} 4S^2 4P^3$ Penta-valent

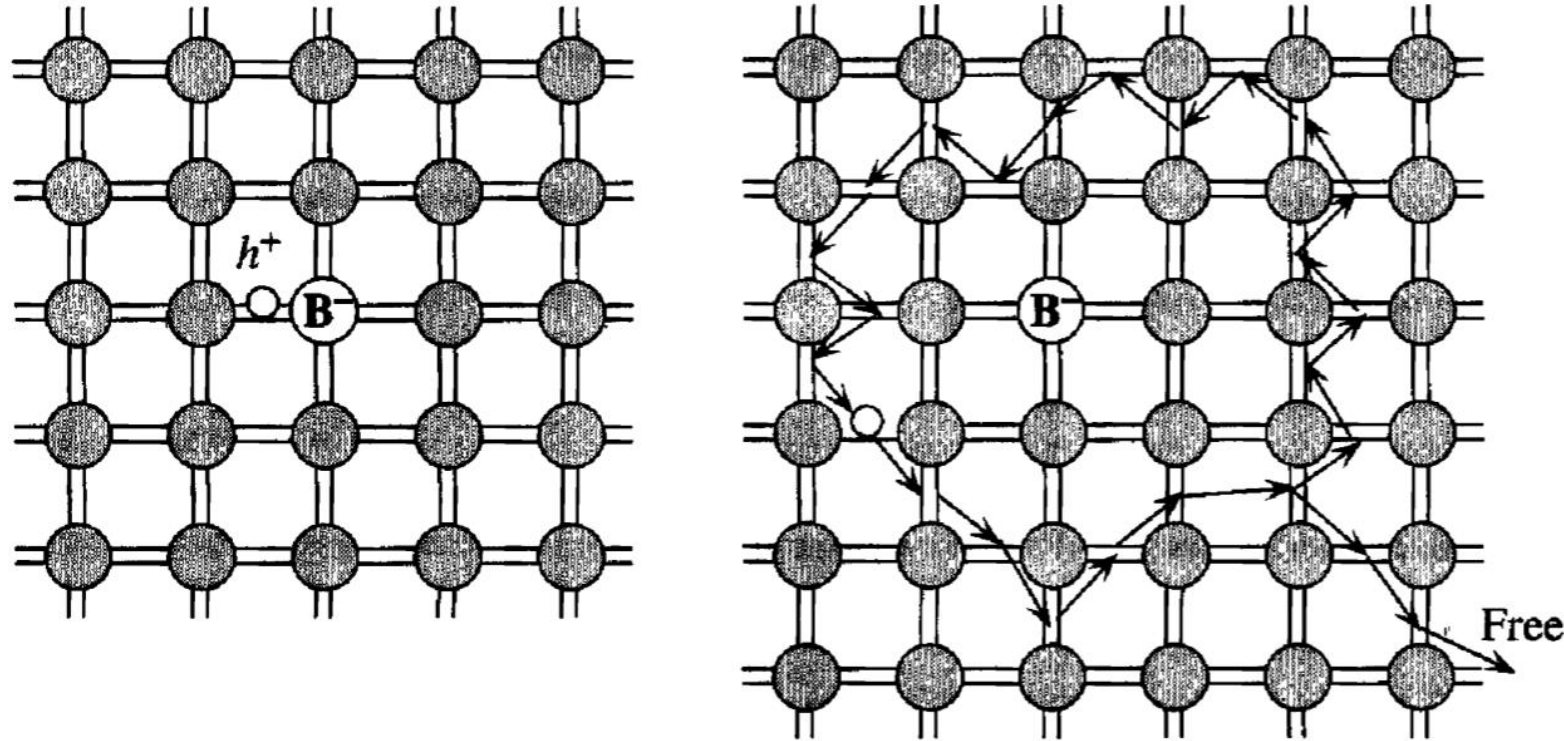
Additional electron of As is un-bonded!

An energy E_b is required to remove the electron from the Ar atom

Adds a single electron to the conduction band!

An atom adding an electron is called as N-type dopant

P-type dopant (Tri-valent atoms)



The un-bonded electron keeps hopping between atoms.

The hopping looks as if the hole is moving around in the crystal.

A tri-valent atom leaves an unbonded Si atom.

This leaves an electron – less in the bonding orbital! A vacant state in the valence band

Carrier densities in Extrinsic semiconductors



Intrinsic

1. Equal number of electron and holes
2. Fermi level at middle of bandgap

1. We get a N-type semiconductor when some of the Si atoms are replaced by penta-valent atoms
2. A donor energy level with filled electron is found near conduction band
3. Given enough thermal energy, the donor is ionized and the electron enters the conduction band and can increase conductivity!
4. If all the Donor atoms are ionized, then $n \cong N_D$

Law of Mass Action

- If N_D is the density of As added into Si (N-type dopant)
- $n \cong N_D$ at high enough temperature.
- Similarly, if N_A is the density of B added into Si
- $p \cong N_A$ at high enough temperature.

Law of mass action states that at any given temperature T:

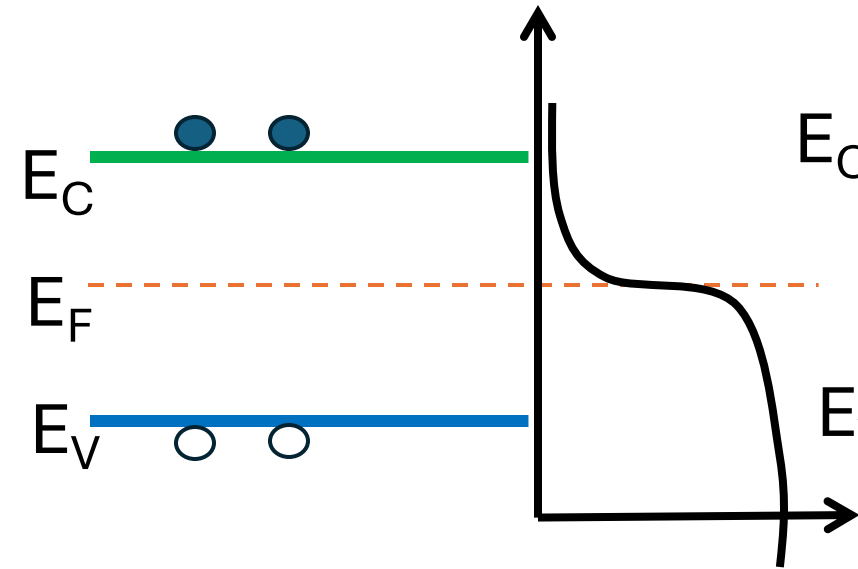
$$n * p = n_i^2(T)$$

Where n_i is the thermally generated electron-hole pairs in an intrinsic semiconductor at the same temperature!

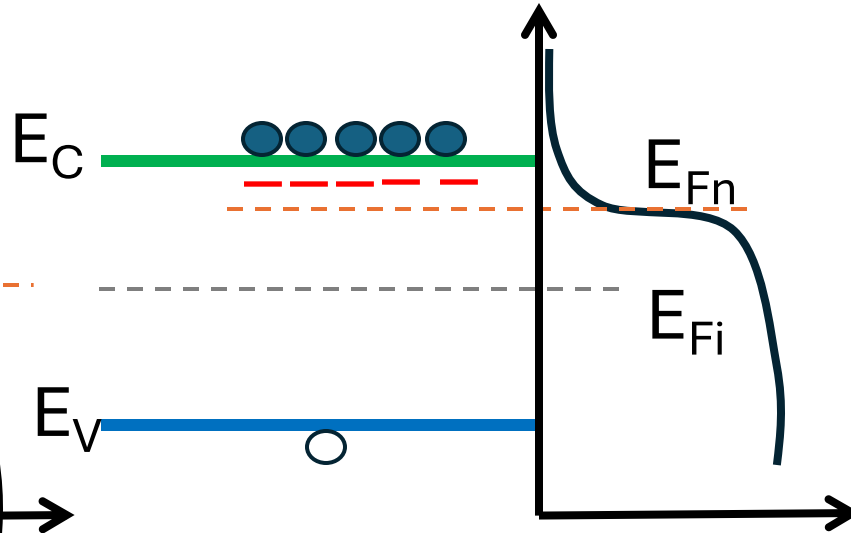
What happens to Fermi Level ?

- Say for example at room temperature, I add $N_D \gg n_i$
- All the donors are ionized ! $n \cong N_D$
- By law of mass action $n * p = n_i^2$. Therefore $p = \frac{n_i^2}{N_D} \ll n_i$
- In an electron doped semiconductor, the hole density is very low!
- Alternatively in a hole doped semiconductor, electron density is low!

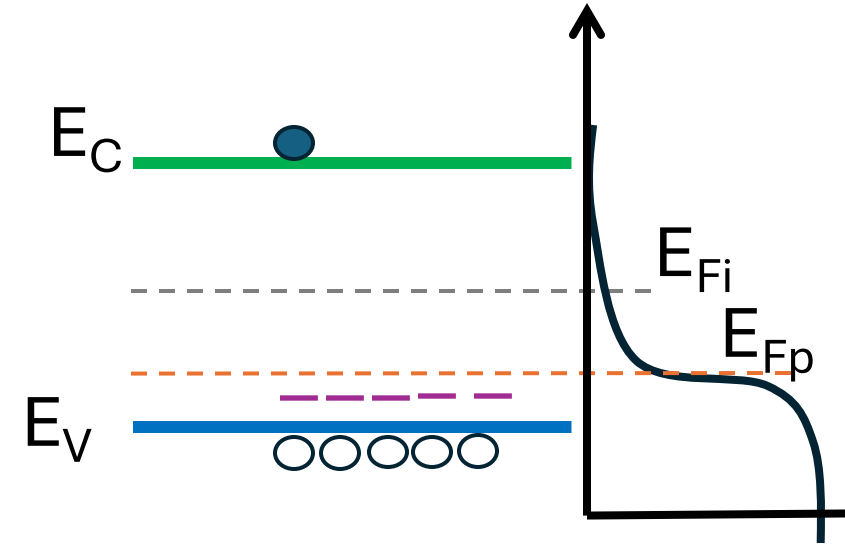
Intrinsic



N-Type



P-Type



Intrinsic - $n = p = n_i(T)$ and $E_F = E_{Fi}$

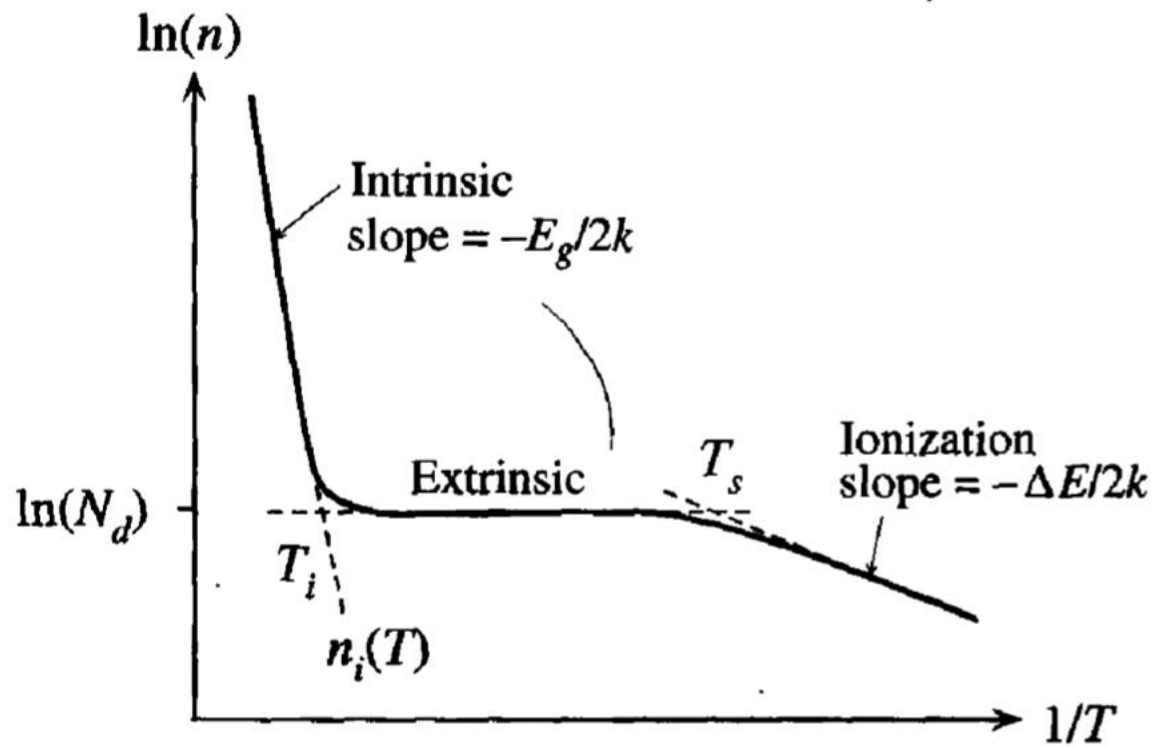
N-Type $n = N_D = \frac{n_i^2}{p}$ and $E_F > E_{Fi}$

Always

$$n + N_A^- = p + N_D^+$$

Electrical neutrality

Extrinsic Semiconductor



- Three temperature ranges

1. Ionization range $T < T_s$

Temperature lower than 'all-dopant ionization' Point

2. Extrinsic range $T_s < T < T_i$

All dopants ionized. $n \gg n_i$

3. Intrinsic Range

$n_i \gg N_A/N_D$

Mobility in Doped Semiconductors

- Mobility $\mu = \frac{e\tau}{m_e}$

- In semiconductors, there are two mobilities

$$\mu_{n/p} = \frac{e\tau_n}{m_{e/h}}$$

- τ mean scattering time depends on the scatterers. If there are 'n' scatters;

$$\frac{1}{\tau_{eff}} = \sum_i \frac{1}{\tau_i}$$

Different kinds of scatters:

1. Lattice vibration
2. Charged impurity
3. Surface/interface charge density