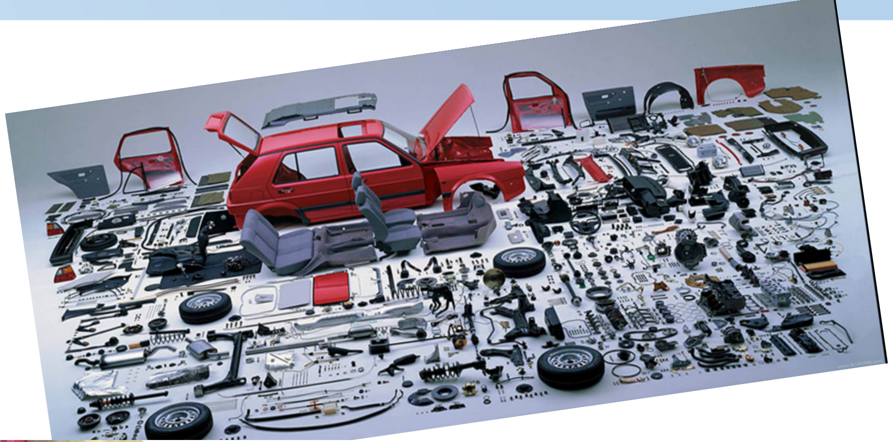
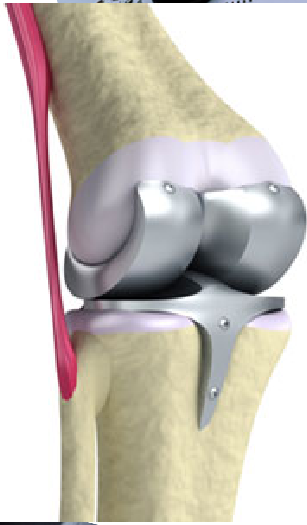
PHY109: ENGINEERING PHYSICS
Unit VI: Solid State Physics



Solid

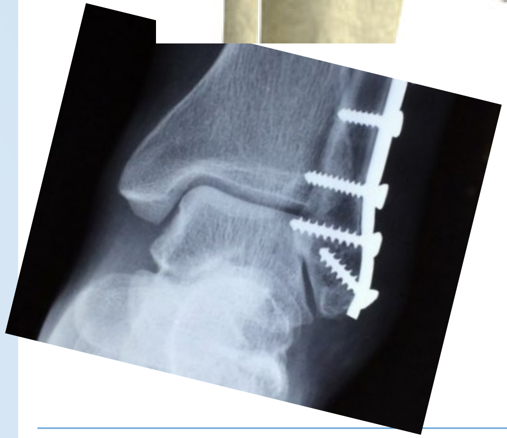


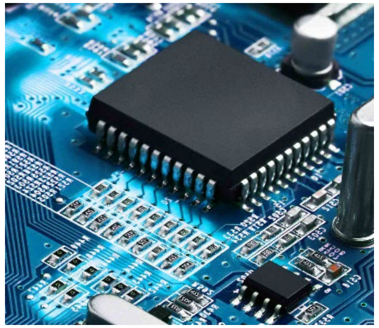
Metals:

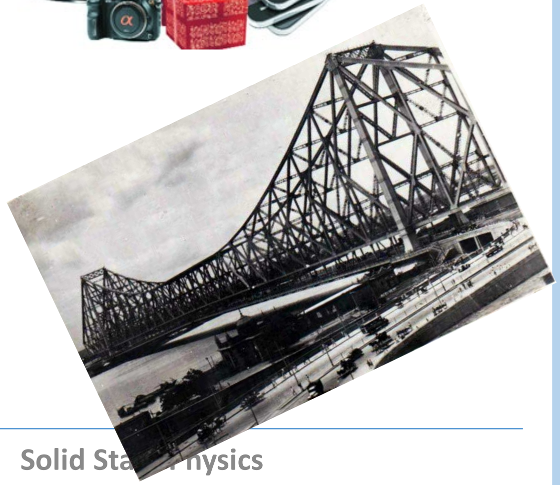
Na, Fe, Cu, Al, Au, Ag, Ti, Ni, Pt etc.

Semiconductor/Insulators:

Si, Ge, GaAs, BN, Al_2O_3, ZnO, TiO_2, SiO_2, CdTe, PbS, ZnS etc.







Classical Picture

- 1900, Drude explained electrical and thermal conductivity of metals using the concept of mobile free electrons.
- Later, Drude and Lorentz proposed the free electron theory (Lorentz-Drude theory).

The assumptions of free electron theory are:

- Metal consists of ion cores (nucleus and core electrons).
- The free (valence) electrons in a metal are treated as an ideal gas of free particles.
- The valence electrons surround the ion core and are free to move within the metal and consequently responsible for the conductivity.

- The electrons obey Maxwell-Boltzmann statistics: the free electrons are in thermal equilibrium with a Maxwell-Boltzmann velocity distribution => $v_{rms} = \sqrt{\frac{3k_BT}{m}}$

Electrical properties

Mean free path (λ): The mean distance between two successive collision.

Mean collision time (τ): The mean time between two successive collision.

Drift velocity: motion of charge carriers (electron or hole) in electric field

$$v_d = \frac{\lambda}{\tau}$$

Mobility: $\mu = \frac{v_d}{E}$; unit: $cm^2 V^{-1} sec^{-1}$

Electrical conductivity: $\boldsymbol{\sigma} = \frac{J}{E}$; J and E are current density and electric field. Unit: $(ohm\ m)^{-1}$

The relation between $\boldsymbol{\sigma}$ and $\boldsymbol{\mu}$ is: $\boldsymbol{\sigma = ne\mu}$

Electrical properties

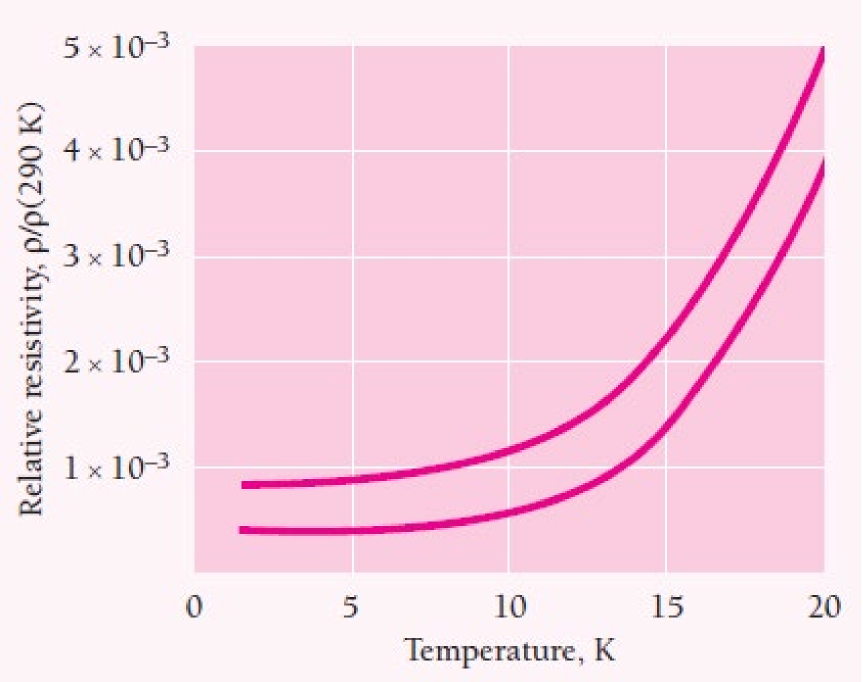
Variation of electrical resistivity of metals with temperature:

$$\rho = \rho_i + \rho_T$$

- ρ_i is the residual resistivity, due to the scattering by impurities.
- Independent of temperature.
- At zero temperature, the residual resistivity ρ_i dominates..

- ρ_T is the resistivity due to the scattering by phonons (lattice vibrations).
- Depends on temperature.

  As temperature increases, resistivity of metals increases due to the increase of lattice vibrations => the scattering of electron with phonons increases.



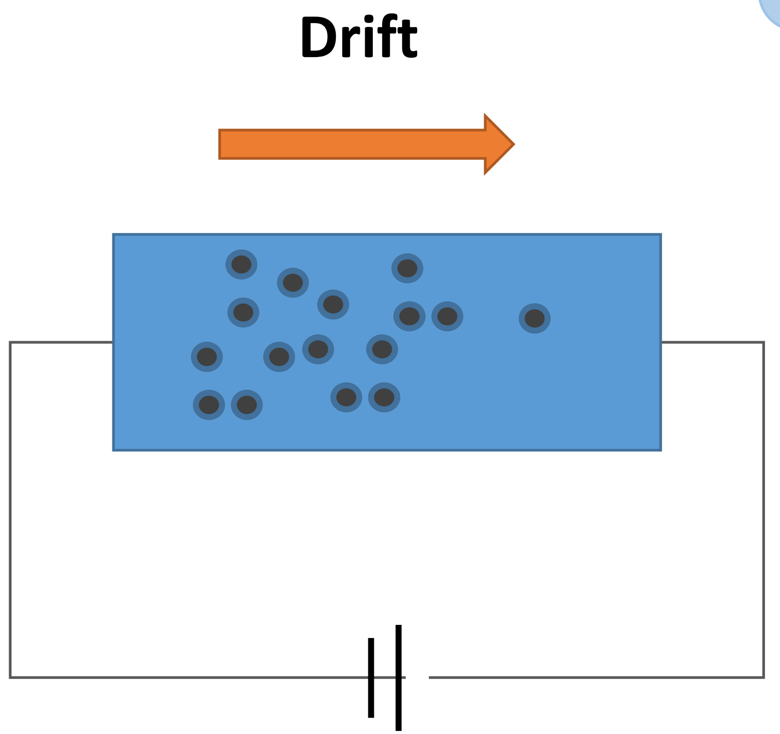
Drift current: Current due to drift of charge carriers in electric field.

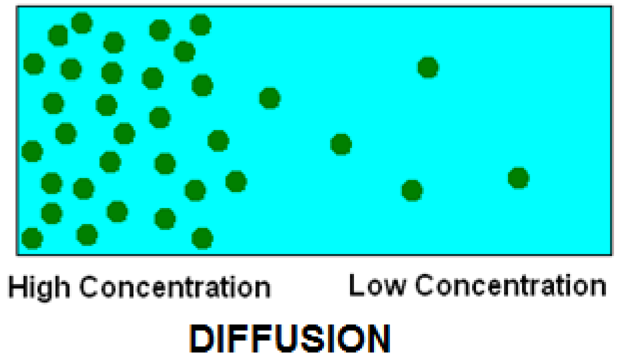
$$J = nev_d$$

Diffusion current: Current due to diffusion of charge carriers from heavily concentrated region to the low concentrated region.

$$J = eD_e \frac{dn}{dx}$$

D_e and $\frac{dn}{dx}$ are diffusion coefficient and concentration gradient.





Explanation of experimental phenomena

- Wiedemann-Franz law: ratio of thermal conductivity (k) to the electrical conductivity (σ) is proportional to the absolute temperature

$$\frac{k}{\sigma T} = L$$

The thermal conductivity (k) is defined as:

$$q = k\frac{dT}{dx}$$

q is heat flow per unit time per unit area (W/m^2),

k is thermal conductivity and unit is W/(K.m).

L is Lorentz number = 2.45×10^{-8} WΩ/K^2

Hall Effect

Hall Effect: Transport of charge carriers in electric and magnetic field.

- Generation of voltage (Hall voltage), when a current carrying semiconductor is placed in the perpendicular magnetic field.
- The direction of Hall voltage is perpendicular to the current and magnetic field.
- The Hall voltage (V_H) developed in the semiconductor of thickness (t) is related to the current (I) and magnetic field (B) as:

$$V_H = \frac{R_H I B}{t}$$

- Note: thickness (t) is the dimension of the semiconductor placed along the direction of magnetic field.
- The quantity R_H is known as Hall coefficient. R_H is related to the carrier density (n) as:

$$R_H = \frac{1}{ne}$$

- SI unit of R_H is cm^3/C.

- The sign of Hall coefficient (R_H) determines the type of majority carriers.

If R_H is negative, semiconductor is n-type (majority carriers are electrons).

If R_H is positive, semiconductor is p-type (majority carriers are holes).

- Relation between mobility (μ), electrical resistivity (ρ) and Hall coefficient:

$$\mu = \frac{R_H}{\rho}$$

- Thus, from Hall effect measurement, we can determine the type of semiconductor, carrier density and mobility.

Limitation of free electron theory

- Unable to explain, why only some crystal are metallic.
- Type of conductivity (n-type or p-type) was not explained in semiconductors/metals.
- Temperature dependent electrical conductivity was not explained.

Fermi energy

Fermi distribution function: average number of particles in energy state (E):

$$f(E) = \frac{1}{e^{\frac{E-E_F}{k_B T}} + 1}$$

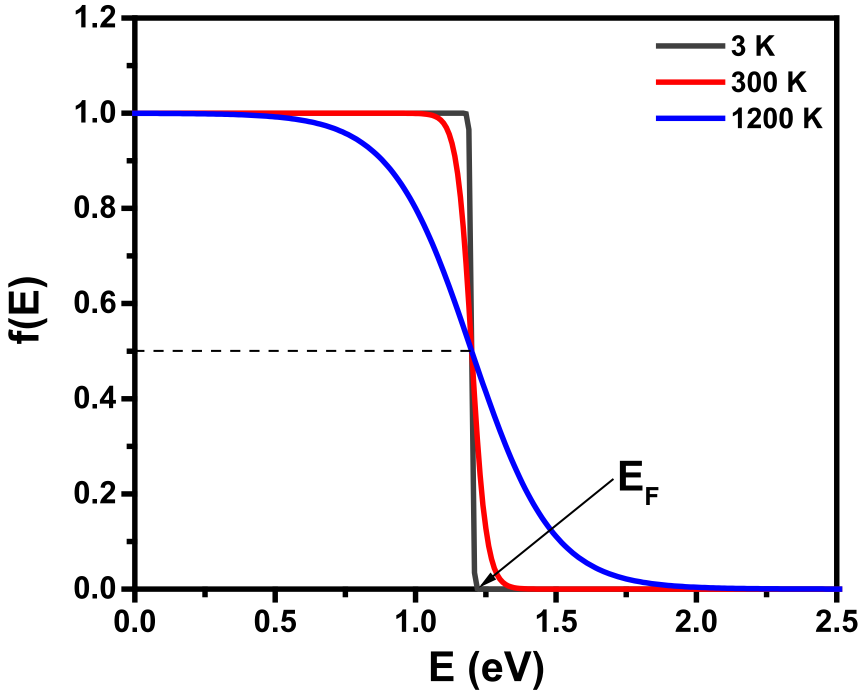
For T = 0 K,

if E < E_F => $f(E)$ = 1

if E > E_F => $f(E)$ = 0

For T ≠ 0 K,

if E = E_F => $f(E)$ = 0.5



Fermi energy (E_F): The energy level up to which all states are occupied at 0 K; whereas at non-zero temperature the occupancy is half.

Fermi energy

- Fermi energy (E_F) is related to the number of free electrons (N) as:

$$E_F = \frac{\hbar^2}{2m}\left(\frac{3\pi^2 N}{V}\right)^{2/3}$$

V is volume and m is mass of electron.

- Fermi velocity is obtained from the classis relation: $E_F = \frac{1}{2}mv^2$; substituting E_F we get

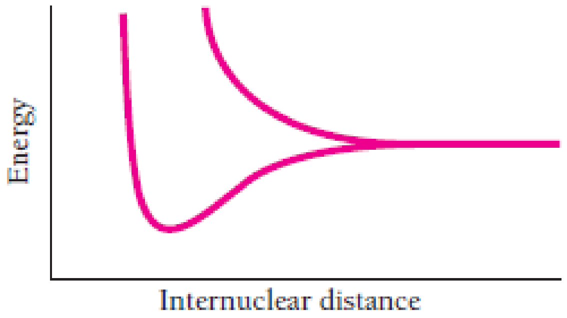
$$v_F = \frac{\hbar}{m}\left(\frac{3\pi^2 N}{V}\right)^{1/3}$$

- Relationship between Fermi energy (E_F) and average energy (E_{av}) of electron at 0K:

$$E_{av} = \frac{3}{5}E_F$$

BAND THEORY

Material	Resistivity	Material	Resistivity
Conductors:		*Semiconductors:*	
Silver	1.59×10^{-8}	Salt water (saturated)	4.4×10^{-2}
Copper	1.68×10^{-8}	Germanium	4.6×10^{-1}
Gold	2.21×10^{-8}	Diamond	2.7
Aluminum	2.65×10^{-8}	Silicon	2.5×10^{3}
Iron	9.61×10^{-8}	*Insulators:*	
Mercury	9.58×10^{-7}	Water (pure)	2.5×10^{5}
Nichrome	1.00×10^{-6}	Wood	$10^{8} - 10^{11}$
Manganese	1.44×10^{-6}	Glass	$10^{10} - 10^{14}$
Graphite	1.4×10^{-5}	Quartz (fused)	$\sim 10^{16}$



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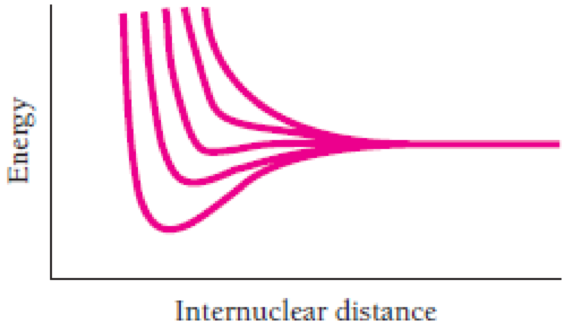

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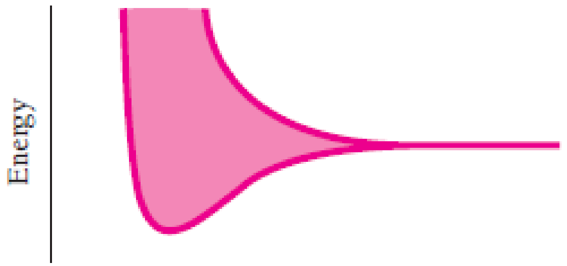


Semiconductor materials

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Type of semiconductors

Intrinsic semiconductor:

Number of electron and hole are equal.

- Fermi level lies in the mid of conduction band and valence band.

Charge carriers are generated due to thermal excitation.

Extrinsic semiconductor:

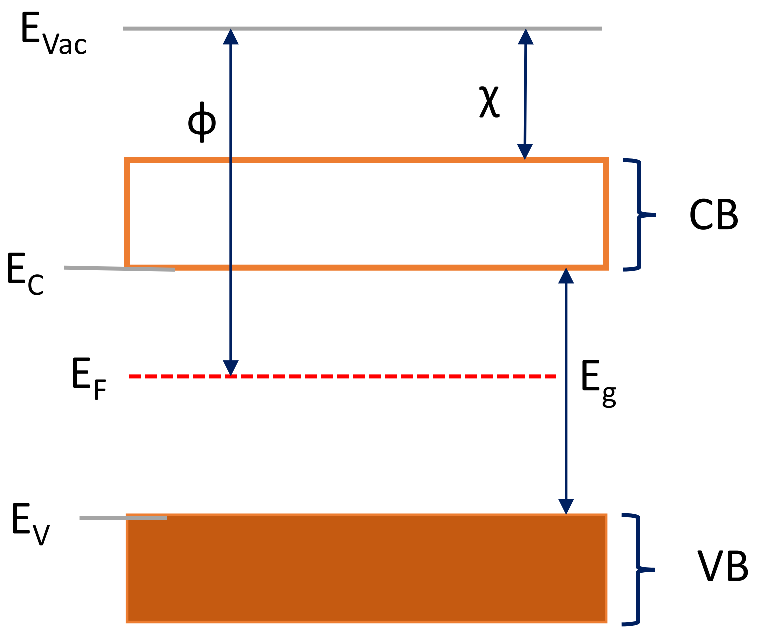
Number of electron (n) >> number of hole (p) => n-type semiconductor

- Fermi level (Donor level) is close to the conduction band

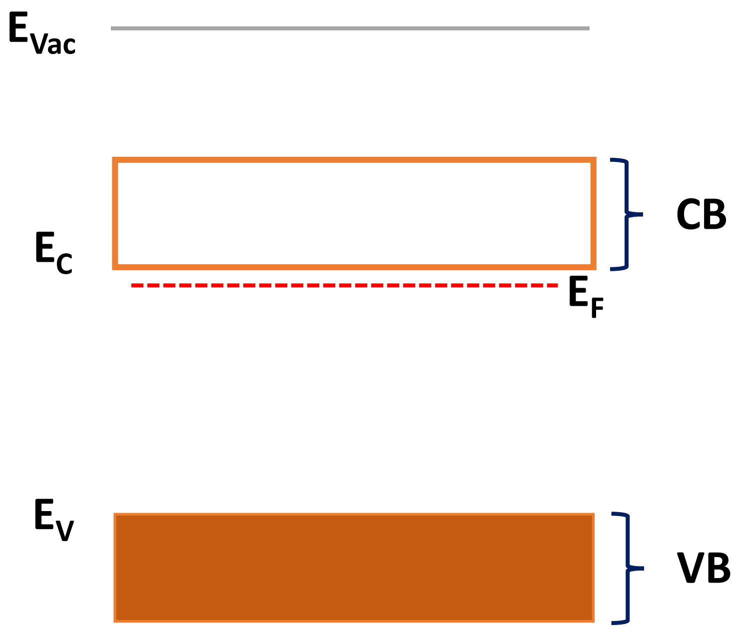
Number of hole (p) >> number of electron (n) => p-type semiconductor

- Fermi level (Acceptor level) is close to the valence band

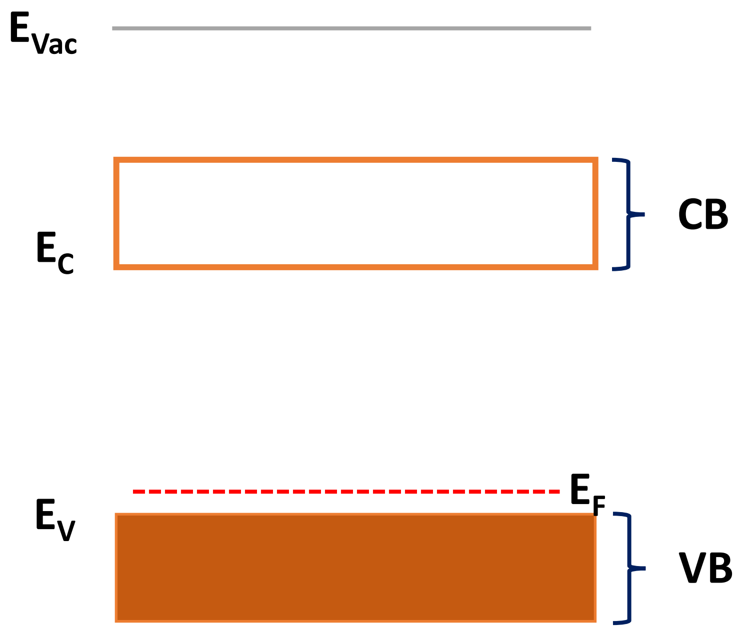
Energy band representation



Intrinsic semiconductor



Extrinsic semiconductor (n-type)



Extrinsic semiconductor (p-type)

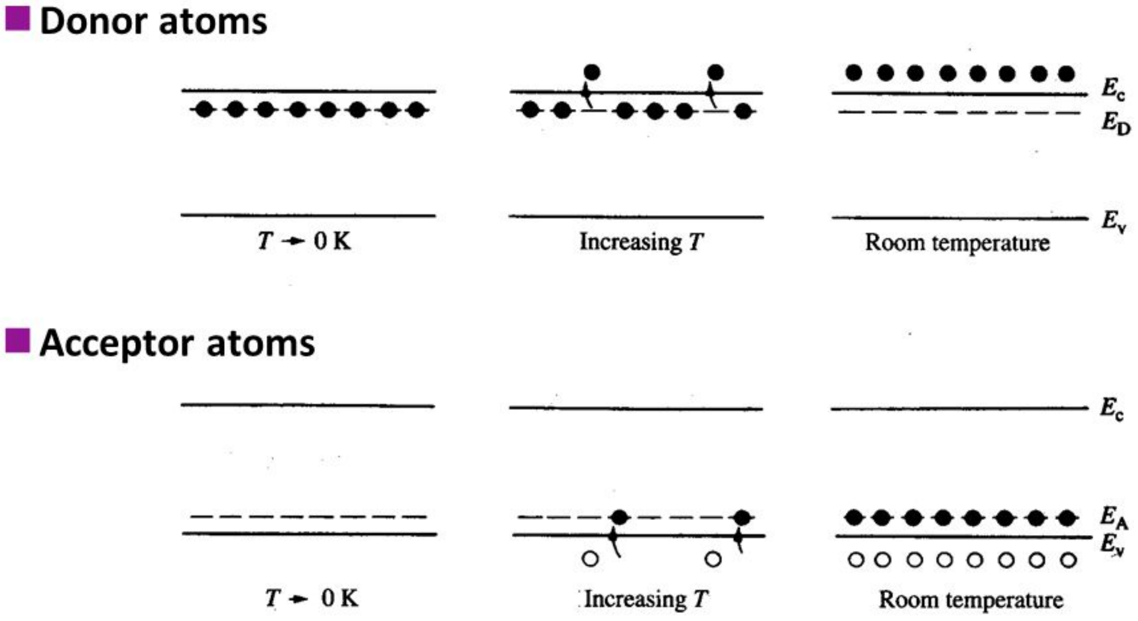
Band gap (E_g) = $E_C - E_V$
Work function (ϕ) = $E_{Vac} - E_F$
Electron affinity (χ) = $E_{Vac} - E_C$

Fermi level is close to the conduction band.

Fermi level is close to the valence band.

Ionization of the donor and acceptor impurities: Extrinsic Carriers

Dopant Ionization (Band Model)



$$E_I = 13.6\left(\frac{m_e^*}{m_0}\right)\left(\frac{\varepsilon_0}{\varepsilon_s}\right)^2 eV$$

$$r_0 = 0.53\left(\frac{m_0}{m_e^*}\right)\left(\frac{\varepsilon_s}{\varepsilon_0}\right)\text{Å}$$

For Germanium:

$\boldsymbol{\varepsilon_s = 16\varepsilon_0}$

$\boldsymbol{m_e^* = 0.5m_0}$

$\boldsymbol{E_I = 0.026\, eV}$

$\boldsymbol{r_0 = 16\text{Å}}$

$\boldsymbol{m_e^*}$ **is effective mass of electron**

Effective mass

- Mass associated with electron/hole moving in crystal potential.

- Effective mass, $m_e^* = \frac{\hbar^2}{\left(\frac{\partial^2 E}{\partial k^2}\right)}$

denominator is double derivative of energy (E) with wave vector (k).

- The denominator $\left(\frac{\partial^2 E}{\partial k^2}\right)$ is the curvature of the energy band. More curvature of the energy band represents light effective mass, similarly less curvature means heavy effective mass of electron or hole.

Semiconductors based on doping

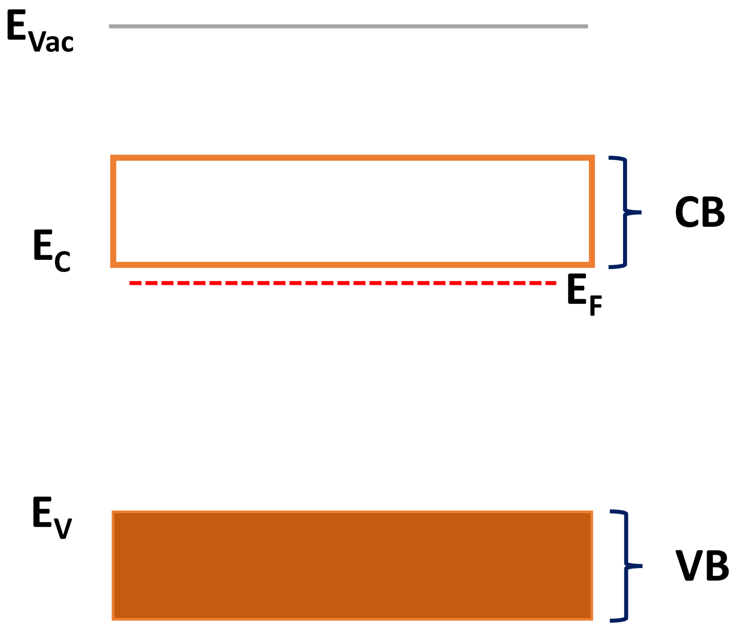
➢ Non degenerate semiconductors:

- Low doping; $n < N_C$ (for n-type semiconductor) or $p < N_V$ (for p-type semiconductor)
- Fermi level (donor level) lies below conduction band minima (for n-type semiconductor)
- Fermi level (acceptor level) lies above the valence band maxima (for p-type semiconductor)

➢ Degenerate semiconductors:

- Heavily doping; $n > N_C$ (for n-type semiconductor) or $p > N_V$ (for p-type semiconductor)
- Fermi level (donor level) lies in the conduction band (for n-type semiconductor)
- Fermi level (acceptor level) lies in the valence band (for p-type semiconductor)

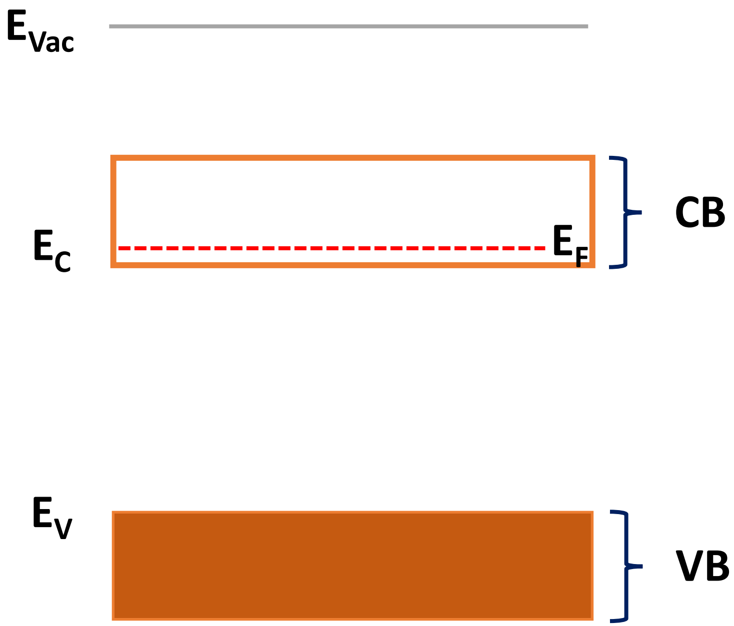
Energy band representation



Non-degenerate semiconductor
(n-type)

$n < N_C$

Fermi level (E_F) is below the conduction band minima.



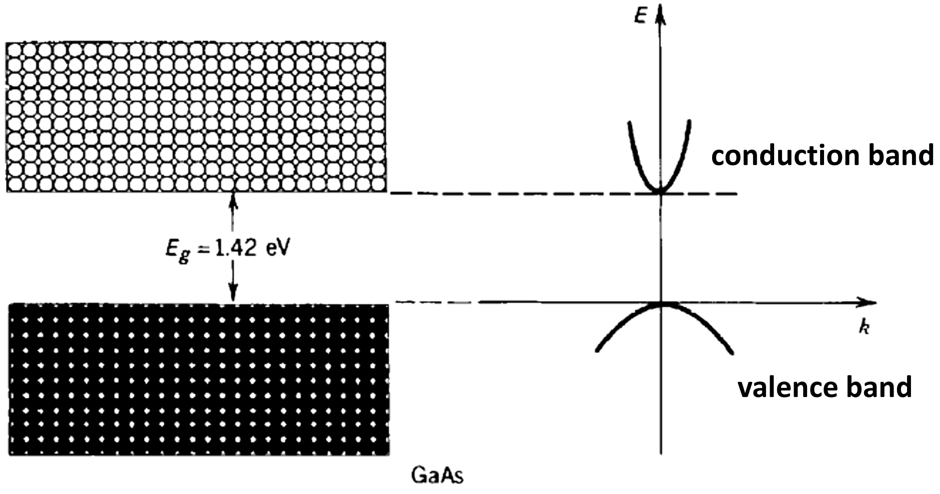
Degenerate semiconductor
(n-type)

$n > N_C$

Fermi level (E_F) is inside the conduction band.

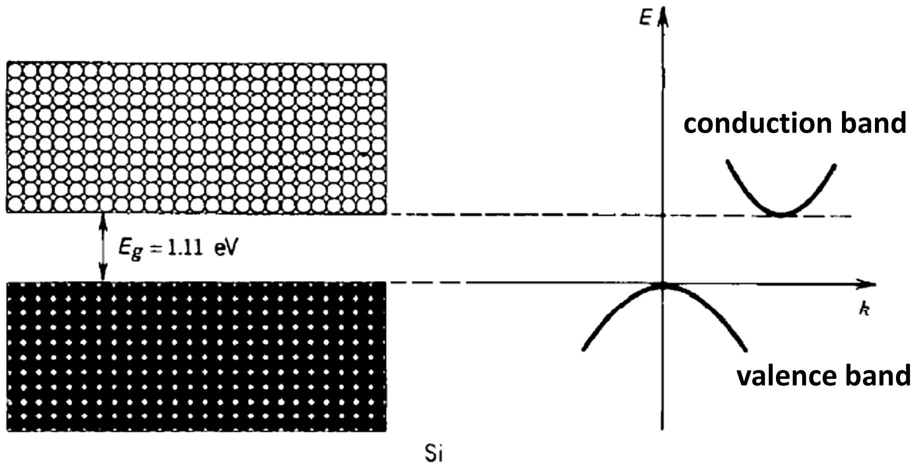
Semiconductors based on band gap

- **Direct bandgap semiconductors:**
  - The conduction band minima and valence band maxima lie at same k-point in the E-k diagram. (k = $2\pi/a$ is wavevector or electron momentum; a is lattice constant)
  - These semiconductors are efficient photon emitters.
  - Example: GaAs



Direct bandgap semiconductor

- **Indirect bandgap semiconductors:**
  - The conduction band minima and valence band maxima do not lie at same k-point in the E-k diagram.
  - The transition between the top of the valence band and the bottom of the conduction band includes change in the electron's momentum.
  - These semiconductors are not efficient photon emitters.
  - Example: Si, Ge



Indirect bandgap semiconductor

References

Text Books:

- **ENGINEERING PHYSICS**, Hitendra K Malik and A K Singh, *Mcgraw Hill Education*, 1st Edition, (2009).
- **ENGINEERING PHYSICS,** D K Bhattacharya and Poonam Tondon, *Oxford University Press*.

Further Readings:

- **CONCEPTS OF MODERN PHYSICS,** Arthur Beiser, *McGraw-Hill Higher Education, Sixth Edition*, (2003).