Electrical and electronics materials:

- Response of the material to electric field
- Mainly the mobile electrons inside the materials decide the property
- The study is done with the help of different simplified models by the scientists
- Classical Free Electron Theory of Metals
  - Electrical Conductivity
  - Thermal Conductivity
- Quantum Theory of Free Electrons
- Band Theory of Solids
- classification into Conductors, Insulators and semiconductors

Free Electron Theory

Classical – Drude- Lorenz's Theory (1900) for metals

Assumptions:

- **In materials with metallic bond, the outer electrons are free, i.e., are not bound to any particular metal ion .**
- **These free electrons are non- localized , i.e., instead of confined to a particular atom, they belong to the entire material.**
- **These free electrons move freely and continuously but can not escape the boundary of the metal.**

- There is no interaction amongst the electrons or between the electrons and positive metal ions. The electrons move in a zero potential field. ($V=0$)

- These electrons behave like the particles of a gas and hence called electron gas following all gas laws.

  $PV = Nk_\beta T$

  Av. electron thermal energy= $3/2\ k_\beta T$

- The motion of these electrons give rise to conduction of current inside the material.

Electrical conductivity:

Electron gas:

- Av. Thermal energy of free electrons in the gas is

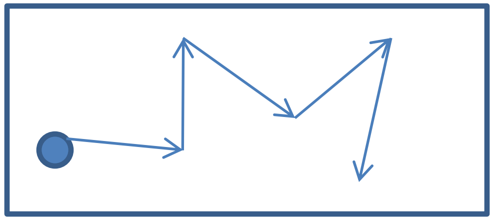
  $E_{av} = \frac{3}{2}k_\beta T = \frac{1}{2}mv^2$

with thermal velocity $v = \sqrt{\frac{3k_\beta T}{m_e}} \approx 10^5$ m/s

- These free electrons , however are in constant motion & hence collide with each other & with the ions in a solid
- τ is the average time between collision = $\frac{\lambda}{v}$

  where λ is the average distance covered between collision is the mean free path

- so, $\tau = \lambda\sqrt{\frac{m_e}{3k_\beta T}}$



- $\lambda = 10^{5} \times 10^{-14} = 10^{-9}$ m= 1 nm, if $\tau = 10^{-14}$ sec

When external electric field is applied

- When an ext. electric field is present, the free electrons experience a force and are accelerated with a velocity called "drift velocity"
- V_d = at or $v_d = \frac{F}{m_e} t$ = qEt/m
- If $< v_d >$ is the average drift velocity and τ is the average collision time , then

$$\frac{d < v >}{dt} + \frac{< v >}{\tau} = \frac{qE}{m}$$

Solution of the equation gives $< v > = \frac{qE\tau}{m}(1 - e^{-\frac{1}{\tau}})$

For small values of τ , the steady state value of drift velocity gives

$<v> = \frac{qE\tau}{m}$

The current density J = nq <v> = nq $\left(\frac{qE\tau}{m} \right)$ = $nq^2\tau E / m$

J α E in consistence with Ohm's law

- as according to Ohm’s law $\mathbf{J = \sigma E}$
- Hence electrical conductivity $\boxed{\sigma = nq^2\tau / m}$

Also, $\sigma = nq\,(q\tau / m)$

But , $q\tau / m = \langle v\rangle / E = \mu$, is the mobility of the electrons, which is drift velocity acquired per electric field.

$$\mu = \langle v\rangle / E = q\tau / m$$

In terms of mobility conductivity can be written as $\boxed{\sigma = nq\,\mu}$

Electrical resistivity

- Electrical resistivity is the reciprocal of electrical conductivity

  Hence, $\rho = 1/\sigma = 1 / nq\,\mu = m / nq^2\,\tau$
- Resistance is offered due to the collision between the electrons and ions or impurities and defects present inside the material
- $\rho = m / nq^2 (1/\tau_{ion} + 1/\tau_{imp} + 1/\tau_{def})$
- $\rho_{tot} = \rho_{ion} + \rho_{imp} + \rho_{def}$

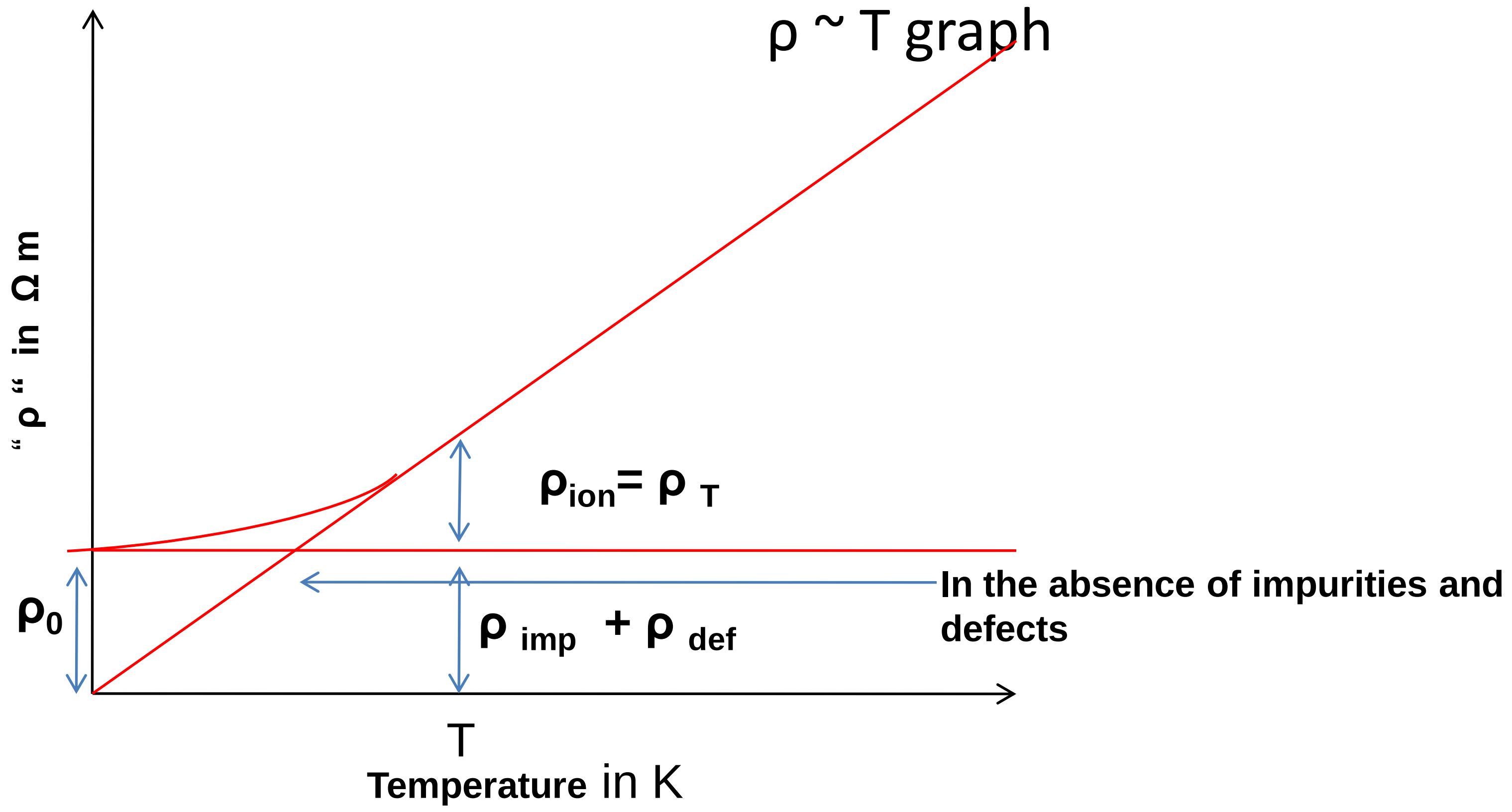
- Out of the three terms in ρ , the first term depends on the temperature, but 2nd and 3rd term do not depend on the temperature. Hence we can write

$$\boxed{\boldsymbol{\rho_{tot} = \rho_{o} + \rho\,(T)}}$$

This is called Matthiessen's rule

- ➢ Mobility depends on the scattering of electrons
- ➢ Scattering is caused by phonons(ions) and the impurities and defects
- ➢ Scattering by phonons increases with temperature, so resistivity also increases
- ➢ Scattering by impurities and defects is independent of temp., but increases with their concentration, hence resistivity also increases $(\rho = m / ne^2\tau = m\,v / ne^2 \lambda)$
- ➢ Resistivity also depends on the magnetic field if present
- ➢ Resistivity depend on strain produced as it creates defects

Electrical conductivity and resistivity are the parameters to determine the electrical property



- ρ_0 is called the residual resistivity, which is due to impurities and defects

- **Electrical conductivity and resistivity are the important parameters to determine the electrical properties of any material**

  i) high conductivity(low resistivity)------metals

  ii) low conductivity (even at room temp.)—ceramics

  iii) poor conductivity ------ polymers

- **Applications:**

  i) Zero resistivity materials: Superconductors (Nb,Sn…)

  SC magnets, storage devices, energy saving devices for power system

  ii) Low resistivity materials: metals and alloys (Ag,Al…)

  Conductors, electrical contacts, power transmission, wires of motors and transformers

  iii) High resistivity: Insulators (W,Pt,Ni….)

  resistors, heating elements, resistance thermometers

THERMAL CONDUCTIVITY

- Heat energy transfer in a material occurs by the vibrating ions (phonons) as well as by the free electron in motion. In a metal the later is dominating. As per Fourier formula for conduction of heat in a solid material is given as

$$Q = KA\left(-\frac{d\theta}{dx}\right)t$$

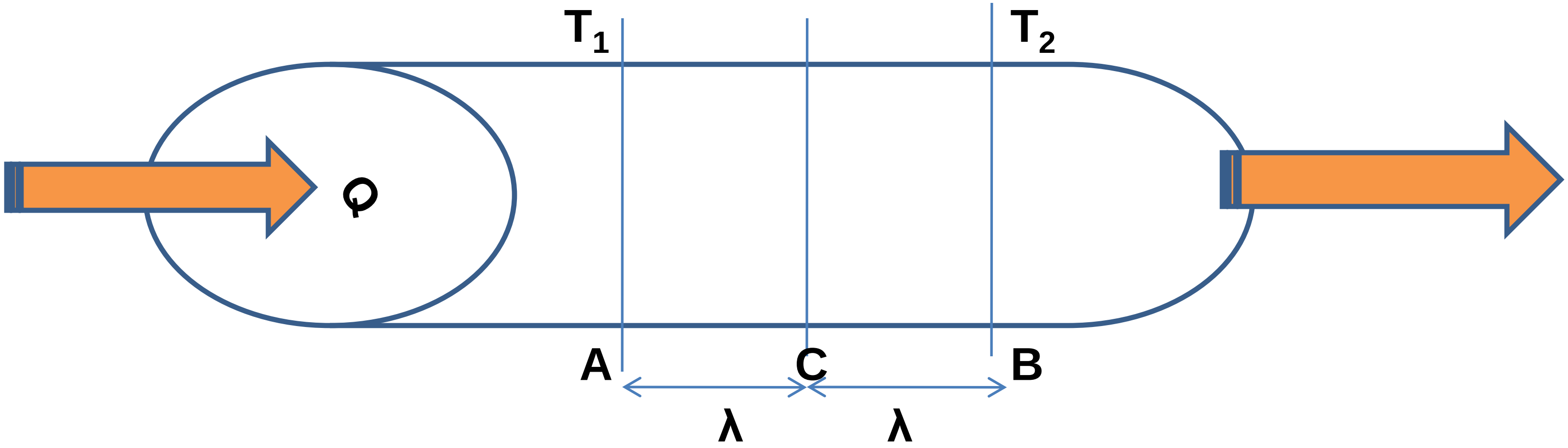
Or, **$K = J / (- d\theta / dx)$**

Where, $J = Q/At$ = heat flux fiowing per area per second

$d\theta / dx$ = temperature gradient

& K = Thermal conductivity of the material i.e., ability to allow heat to pass

- K = K phonon
- In metals K total = K phonon + K electron
- Where K electron » K phonon



- Av. Kinetic energy of the electrons at ‘A’ = **$3/2\ k_\beta\ T_1$**
- Av. Kinetic energy of the electrons at ‘B’ = **$3/2\ k_\beta\ T_2$**
- No of electrons crossing ‘C’ one way per area per second

  = **nv_{th} / 6**, n being the electron density

- Net heat energy transferred per second

J = $$\left(\frac{nv_{th}}{6}\right)\frac{3}{2}k_{\beta}T_1 - \left(\frac{nv_{th}}{6}\right)\frac{3}{2}k_{\beta}T_2$$

= $$\frac{nv_{th}}{4}k_{\beta}(T_1 - T_2)$$

Thermal conductivity , K = J / (- dθ/ dx)

= $$\frac{nv_{th}}{4}k_{\beta}(T_1 - T_2) \Big/ \frac{(T_1 - T_2)}{2\lambda}$$

or, K= ½ n v_{th} k_{β} λ

Weideman- Franz law

- In a metal the ratio of thermal conductivity to electrical conductivity is

$$K / \sigma = \frac{1}{2} n v_{th} k_\beta \lambda \Bigg/ \frac{nq^2\tau}{m_e}$$

$$= \frac{1 v_{th} k_\beta m_e \lambda}{2q^2\tau}$$

$$= m_e v^2 k_\beta / 2q^2$$

$$= 3 k_\beta^2 T / 2q^2 \quad (\text{as } 3/2\, k_\beta T = ½\, mv^2)$$

$$K / \sigma = (3k_\beta^2 / 2q^2)\, T \qquad \text{or, } \quad K / \sigma = L\, T$$

or, $\mathbf{K / \sigma} \quad \alpha \quad \mathbf{T}$

- This is known   Weideman- Franz law

L = **($3k_{\beta}^{2} / 2q^{2}$) is called the Lorenz No. & is same for all metals = 1.11×10^{-8} WΩ / K^{2}**

<u>Merits and demerits of classical free electro theory</u>

Merits: 1. Explains electrical and thermal conductivity

2. Consistence with Ohm's law

3. Explains Weideman- Franz law

4. Explains optical properties

Demerits: 1. Could not explain electronic sp. Heat

2. Could not explain superconducting phenomena

3. L = constant was not true for all temp. & did not agree with exptl. result

4. Could not explain PE effect, Compton Effect, blackbody radiation & 5. classify materials into semiconductor & insulators