Module 5

Solid & Semiconductor

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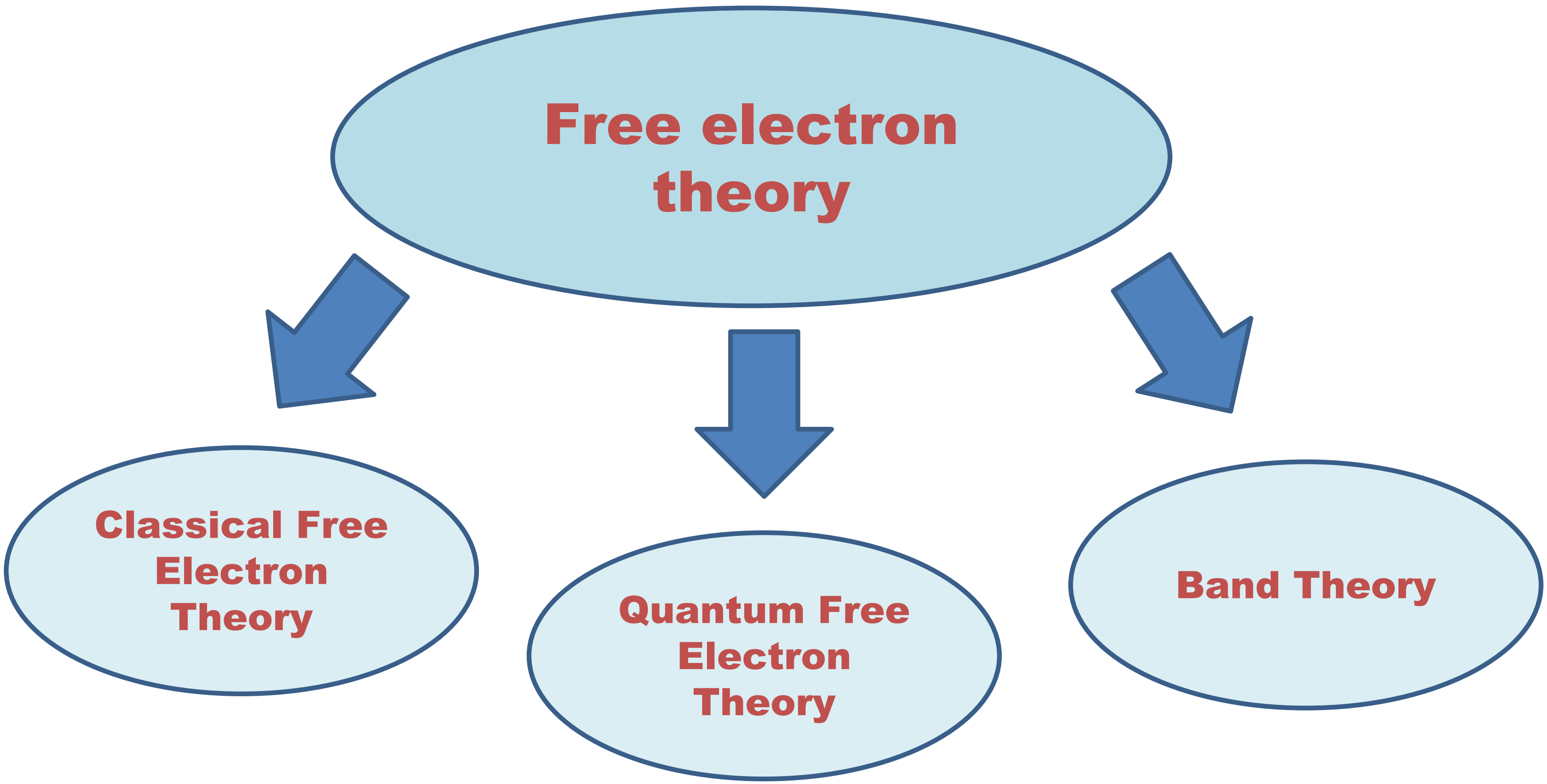
Contents

Free Electron Theory

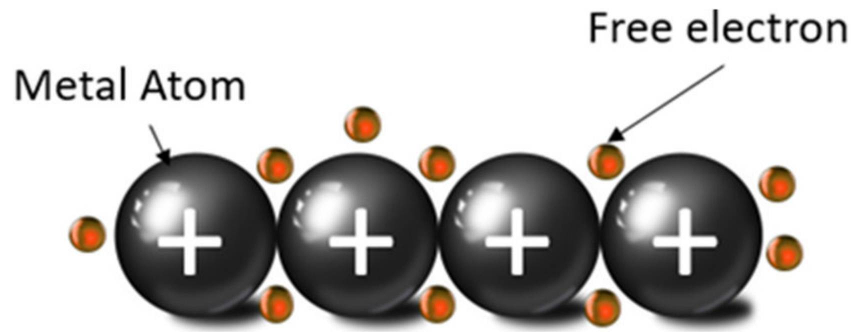
- **The electron theory aims to describe the structure and properties of material through their electronic structure.**
- **The electron theory has been developed in three stages**



Classical Free Electron Theory of Metals

- **Drude, in 1900 assumed that metals consist of positive ion cores with the valance electrons moving freely among these cores.**

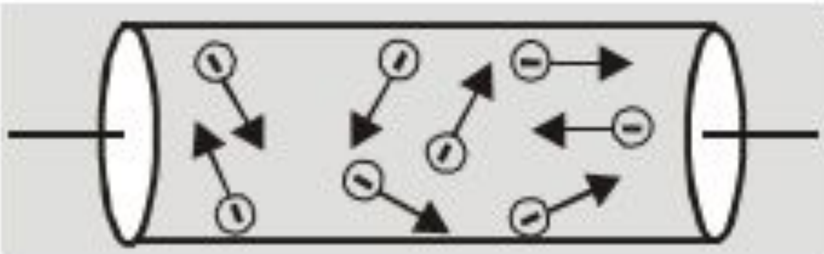
Element	Symbol	Electronic configuration
Lithium	Li	$1s^2 2s^1$
Sodium	Na	$1s^2 2s^2 2p^6 3s^1$
Potassium	K	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$
Rubidium	Rb	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s^1$
Caesium	Cs	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2$ $4p^6 4d^{10} 5s^2 5p^6 6s^1$ or $[Xe]\ 6s^1$
Francium	Fr	$[Rn] 7s^1$

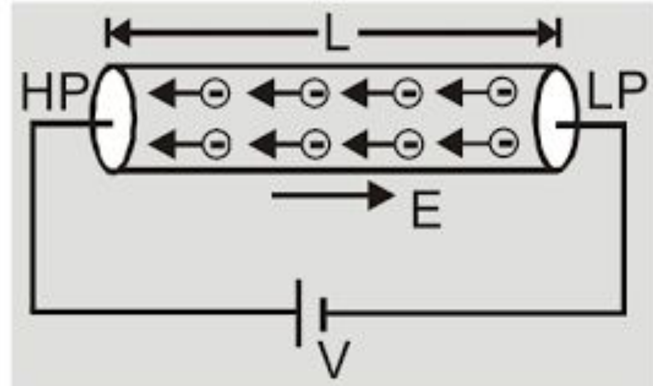


- **The potential of the ion cores is assumed to be constant through out the volume and mutual interaction among electrons is neglected.**

- **The motion of the electron is quite random.**

Contd.





- When an electric field is applied to the metal, free electrons are accelerated in the direction opposite to the applied field.

- The behavior of electrons moving inside the metals is considered to be similar to that of atoms or molecules in perfect gas, therefore referred to as the free electron gas.

- The movement of free electron follows the classical kinetic theory of gases

- It obeys the Classical Maxwell Boltzmann Distribution.

Some definitions and relations in metals

- **Drift Velocity (v_d) :** It is defined as **the average velocity acquired by the free electrons of a metal in a particular direction by the application of electric field.**

- **Relaxation time (t_r):** It is defined as the **time taken by the free electrons to reach its equilibrium position from the disturbed position in the presence of an electric field.**

- **Expression of relaxation time:**

When an external electric field is applied to a metal the electrons move opposite to the applied field. After removal

of electric field the drift velocity decays exponentially as

$$v_d = v_o e^{-t/\tau_r}$$

Where V_0 is the initial velocity of electron and

If $t = \tau_r$ then $v_d = v_o e^{-1}$ or $v_d = \frac{v_o}{e}$

Thus the relaxation time may be stated as **the time taken for the drift velocity to decay to 1/e of its original initial value.**

Contd.

- **Mean free path (λ): The average distance traveled by the electron between two successive collisions is called mean free path.**
- **Mobility of electrons (μ): The mobility of electrons is defined as the magnitude of drift velocity acquired by the electron in a unit field.**

$$\mu = \frac{v_d}{E}$$

$$\text{We know } \sigma = \frac{J}{E} = \frac{I}{AE} = \frac{neAv_d}{AE} = \frac{nev_d}{E} = ne\mu \qquad \because I = neAv_d$$

$$\therefore \mu = \frac{\sigma}{ne} = \frac{ne^2\tau}{mne} = \frac{e\tau}{m} \qquad \because \sigma = \frac{ne^2\tau}{m}$$

Classical free electron theory: Electrical conductivity

When an electric field E is applied between the two ends of a metal of area of cross section A

Force due to electric field, F = eE
According to Newton's Law, F = ma
Accelertaion, a= F/m=Ee/m

The average velocity acquired by the electron

$$v_d = a\tau = \frac{e\,E\,\tau}{m} \qquad (1)$$

$$v_d = a\tau = \frac{e\,E}{m} \cdot \frac{\lambda}{\bar{c}} \qquad (2)$$

$$since\ \tau = \frac{\lambda}{\bar{c}}$$

Contd.

The relation between current and drift velocity

$$i = neAv_d$$

$$j = nev_d \qquad (3)$$

Substituting the value of v_d in equation (3)

$$j = \frac{ne^2 E\,\tau}{m}$$

Conductivity

$$\sigma = \frac{j}{E} = \frac{ne^2\,\tau}{m} = \frac{ne^2\,\lambda}{m\,\bar{c}}$$

Resistivity

$$\rho = \frac{m}{ne^2\,\tau} = \frac{m\,\bar{c}}{ne^2\,\lambda}$$

According to kinetic theory of gases,

$$\bar{C} = \sqrt{\frac{3KT}{m}}$$

$$\sigma = \frac{ne^2 \lambda}{\sqrt{3m\,KT}}$$

$$\rho = \frac{\sqrt{3m\,KT}}{ne^2\ \lambda}$$

Mobility,

$$\mu = \frac{v_d}{E} = \frac{e\,\tau}{m}$$

$$\sigma = \frac{ne^2\,\tau}{m} = ne\mu$$

Interpretation of metallic properties on the basis of classical free electron model:

Success:

- It verifies Ohm's Law, i.e $V=IR$
- It explain electrical conductivity of metals.
- It explain thermal conductivity of metal.
- It derives Widemann-Franz Law, i.e., the ratio between thermal conductivity (K) to electrical conductivity (σ) is proportional to absolute temperature

Failures:

- It could not explain the photoelectric effect, Compton scattering and black body radiation.
- Ferromagnetism could not be explained by this theory. The theoretical value of paramagnetic susceptibility is greater than the experimental value.
- According to classical free electron theory the specific heat of metals is given by $4.5R$ where as the experimental value is given by $3R$.
- According to classical free electron the electronic specific heat is equal to R while the actual value is $0.01R$.