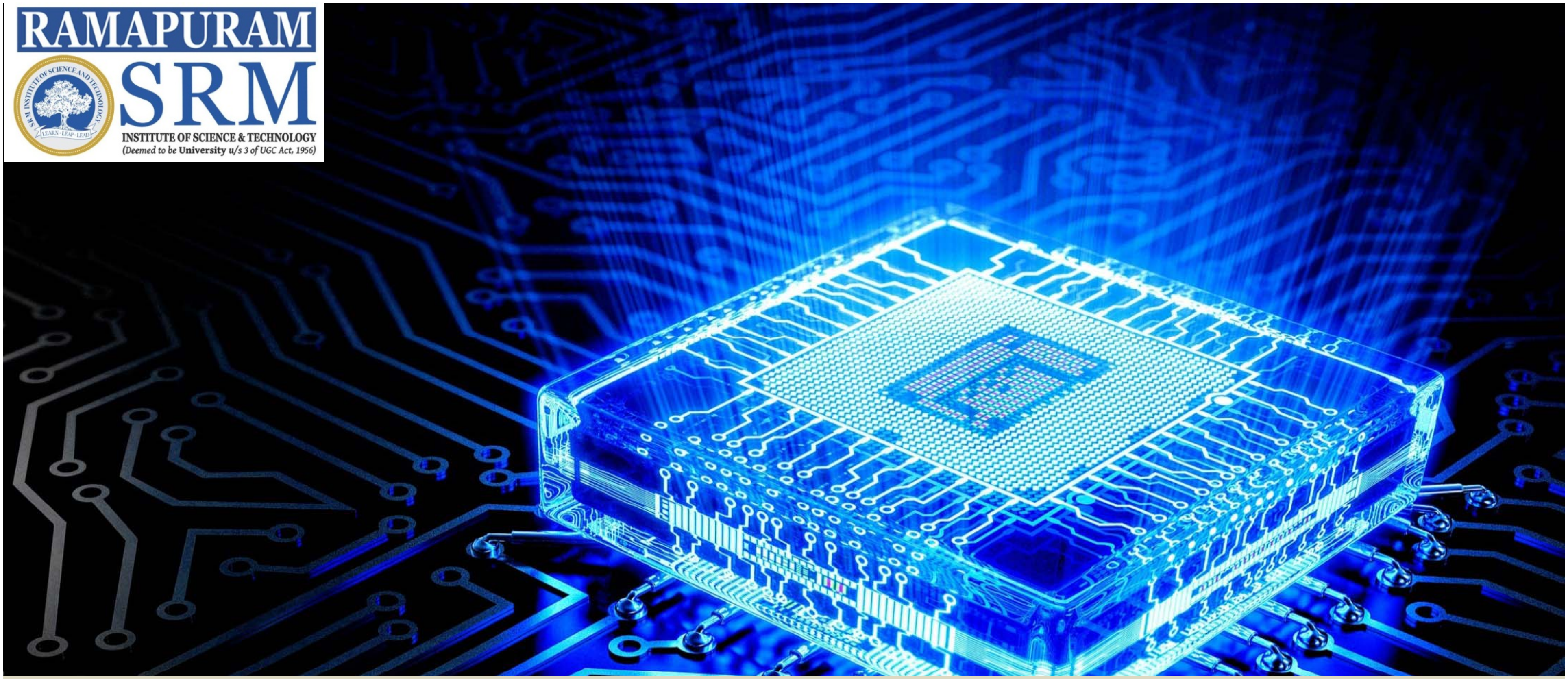

Semiconductor Physics(18PYB103J)

Module I

Lecture 1, 13 (SLO-2) & 14 (SLO-1)

Lecture 1, 13 (SLO-2) & 14 (SLO-1) Topics

- Classical Free electron theory
- Quantum Free electron theory
- Fermi level
- Probability of occupation

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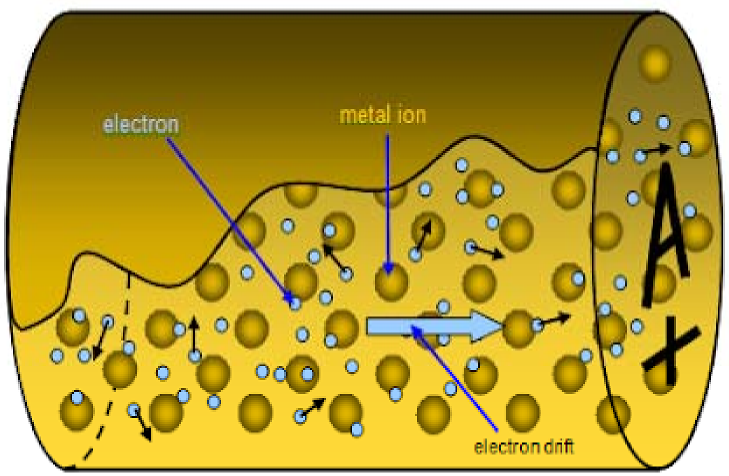
INTRODUCTION

- Conducting materials are low resistivity materials.
- They conduct heat and electricity effectively.
- A conductor (metal) is a collection of positive ions fixed at their position and a large number of free electrons moving freely anywhere in the conductor.
- Therefore the electrical conductivity depends on the number of free electrons available.
- The thermal conductivity depends on the availability of phonons also.

BASICS TERMINOLOGIES

- *Bounded Electrons*: Valence electrons in isolated atoms bound to their parent nuclei are bounded electrons.
- *Free electrons*: In a solid many atoms are present whose boundaries overlap. Hence the valence electrons find continuity to move and are termed free electrons.
- *Free electron gas*: Collection of free electrons is termed as free electron gas. It is charged.

Figure 1



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BASICS TERMINOLOGIES

- *Electric Field (*E*)*: It is defined as potential drop (V) per unit length (l).
- *Current density (*J*):* Current flowing through a solid per unit area is current density.
- *Drift Velocity (*v_d*):* The average velocity acquired by the free electron in a particular direction, due to the application of electric field.
- *Mobility (μ):* Drift velocity acquired by the free electron per unit electric field applied to it is mobility.

BASICS TERMINOLOGIES

- *Relaxation Time* (τ): Relaxation time can be defined as the time taken for the drift velocity of the electron to decay to 1/e of its initial value.
- *Collision Time* (τ_c): The average time taken by the free electron between two successive collisions is known as collision time.
- *Mean Free Path* (λ) : The average distance travelled by an electron between two successive collisions in the presence of an applied field is known as mean free path.

ELECTRON THEORY OF SOLIDS

- Classical Free electron theory:
  Year: 1900 | Developers: Drude and Lorentz
  Metals contain free electrons
  They obey laws of classical mechanics.
- Quantum Free electron theory:
  Year: 1920 | Developer: Sommerfield
  Free electrons obey quantum laws and move in a constant potential.
- Zone theory (Brillouin/ Band theory)
  Year: 1928 | Developer: Bloch
  Free electrons move in a periodic potential provided by the lattice. Explains semiconductivity based on bands

CLASSICAL FREE ELECTRON THEORY OF METALS

Postulates

- The metal consists of positive ion core with valence electron moving randomly with constant potential in all directions.
- The force between the valence electrons and the positive Ion core negligible. The valence electrons are freely moving about the whole volume of the metals
- The movements of free electrons is similar like the molecules of perfect gas in a container and obey the laws of classical kinetic theory of gases
- The free electrons collide with each other positive ions are the other free electrons the valence electrons in a metal.
- When the electric field is applied all the valence electrons a drifted in the direction opposite to that of the electric field.

Failures of Classical Free Electron Theory:

- It fails to explain the electric specific heat and the specific heat capacity of metals.
- It fails to explain ferromagnetism, superconducting properties of metals etc.
- It fails to explain new phenomena like photoelectric effect, Compton effect, black
- body radiation, etc.
- It fails to explain electrical conductivity of semiconductors or insulators.

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QUANTUM FREE ELECTRON THEORY OF METALS

Postulates

- The energy levels of the electrons moving inside the metal are discrete.
- The allowed energy levels of the electrons are quantized.
- The electrons are free to move inside the metal with uniform potential and obey Pauli's exclusion principle.
- The wave nature of the electron is described by Schrödinger’s wave equation.
- Electrons are free to move within the crystal and cannot escape from the crystal
- due to potential barrier at the surface.
- The number of free electrons in various states is obtained by Fermi – Dirac distribution formula.

Failures of Quantum Free electron theory

- Fails to explain “why some crystals have metallic properties and other do not”.
- Fails to differentiate metals, semiconductors and insulators.
- Fails to explain the positive value of Hall coefficient.

Fermi Energy and Fermi level

- "Fermi level" is the term used to describe the top of the collection of electron energy levels at absolute zero temperature.
- This concept comes from Fermi-Dirac statistics.
- Electrons are fermions and by the Pauli exclusion principle cannot exist in identical energy states.
- So at absolute zero they pack into the lowest available energy states and build up a "Fermi sea" of electron energy states.
- The Fermi level is the surface of that sea at absolute zero where no electrons will have enough energy to rise above the surface.
- The concept of the Fermi energy is a crucially important concept for the understanding of the electrical and thermal properties of solids.

- Both ordinary electrical and thermal processes involve energies of a small fraction of an electron volt.
- But the Fermi energies of metals are on the order of electron volts. This implies that the vast majority of the electrons cannot receive energy from those processes because there are no available energy states for them to go to within a fraction of an electron volt of their present energy.
- Limited to a tiny depth of energy, these interactions are limited to "ripples on the Fermi sea".
- At higher temperatures a certain fraction, characterized by the Fermi function, will exist above the Fermi level.
- The Fermi level plays an important role in the band theory of solids. In doped semiconductors, p-type and n-type, the Fermi level is shifted by the impurities, illustrated by their band gaps.

Fermi level and Fermi energy:

The distribution of energy states in a metal is explained by Fermi –Dirac statistics since it deals with the particles having half integral spin like electrons. Consider that the assembly of electrons as electron gas which behaves like a system of Fermi particles or fermions. The Fermions obeying Fermi –Dirac statistics and Pauli’s exclusion principle.

Fermi energy:

It is the energy of state at which the probability of electron occupation is ½ at any temperature above 0K. It separates filled energy states and unfilled energy states.

Fermi level:

The highest energy level that can be occupied by an electron at 0 K is called Fermi energy level It is a level at which the electron probability is ½ at any temperature above 0K.

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FERMI-DIRAC DISTRIBUTION FUNCTION

Fermi distribution function F(E) represents the probability of an electron occupying a given energy state. It is given by,

$$F(E) = \frac{1}{1 + e^{\frac{E-E_F}{kT}}} \quad \dots\dots\dots..(1)$$

where, F(E) – Fermi function

E_F – energy of the Fermi level

K_B – Boltzmann's constant

T – absolute temperature

Probability of occupation of electron

(i) At temperature T= 0K and $E < E_F$,

the equation (1) becomes,

$$F(E) = \frac{1}{1 + e^{-\infty}}$$

$$= \frac{1}{1+0} = \frac{1}{1}$$

$$F(E) = 1$$

F(E) = 1, for T = 0K, the energy level below the Fermi energy level E_F is fully occupied by electrons leaving the upper levels vacant.

Therefore, there is 100% probability that the electrons to occupy energy level below Fermi level.

Probability of occupation of electron

(ii) At temperature T= 0K and $E > E_F$, the equation (1) becomes,

$$F(E) = \frac{1}{1 + e^{\infty}}$$

$$= \frac{1}{\infty}$$

$$F(E) = 0$$

F(E) = 0, for T = 0K,

the energy levels above the Fermi energy level E_F are completely empty.

Probability of occupation of electron

(iii) At temperature T = 0K and $E = E_F$,
the equation (1) becomes,

$$F(E) = \frac{1}{1 + e^{\frac{E_F - E_F}{kT}}}$$

$$= \frac{1}{1+e^0}$$

$$= \frac{1}{1 + 1}$$

$$F(E) = \frac{1}{2} = 0.5$$

F(E) = 0.5, for T = 0K, The above condition states that there is a 50% probability for the electrons to occupy Fermi energy.

Fermi Energy Level Diagram

At T > 0 K, some levels above Fermi level are partially filled and some levels below Fermi level are partially empty.