DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY
SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

18PY103J – Physics: Semiconductor Physics
Module-III, Lecture-15

The Drude Model of electrical conduction

The Drude Model of electrical conduction

Due to the quantum mechanical nature of electrons, a problem of electron movement in a solid (i.e. conduction) would require consideration of not only all the positive ion cores interacting with each electron, *but also each electron with every other electron*.

Even with advanced models, this rapidly becomes far too complicated to model adequately for a material of macroscopic scale.

The *Drude model simplifies* things considerably by using classical mechanics approach to *describe the conductivity in metals*. This model makes several key assumptions (some of which are better approximations than others)

The Drude Model of electrical conduction

Drude Theory

In Drude model, when atoms of a metallic element are brought together to form a metal, the valence electrons from each atom become detached and wander freely through the metal, while the metallic ions remain intact and play the role of the immobile positive particles.

Electrons in a metal behave much like particles in an ideal gas (no Coulombic interaction and no collisions between particles).

The Drude Model of electrical conduction

In a single isolated atom of the metallic element has a nucleus of charge e Za as shown in Fig. 1 below.

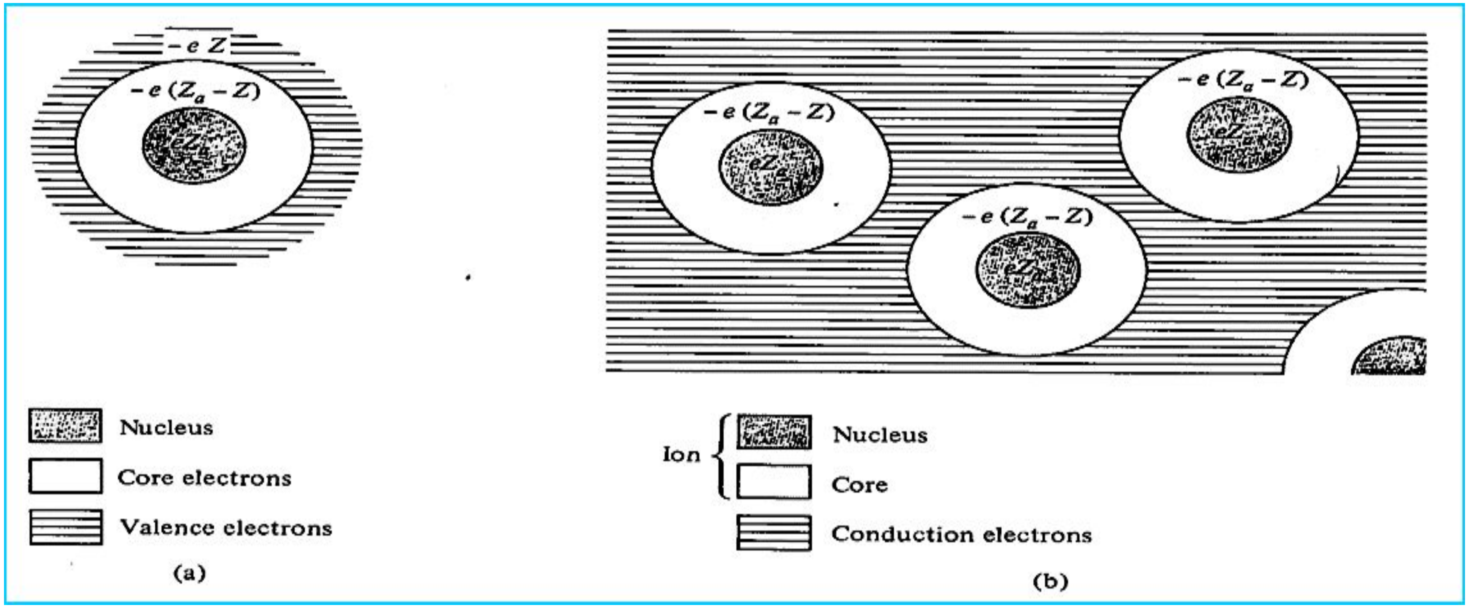

Figure 1 | Arrangement of atoms in a metal

where Z_a - is the atomic number and e - is the magnitude of the electronic charge $[e = 1.6 X 10^{-19}$ *coulomb]* surrounding the nucleus, there are Z_a electrons of the total charge $-eZ_a$.

The Drude Model of electrical conduction

Some of these electrons 'Z', are the relatively weakly bound valence electrons. The remaining $(Z_a\text{-}Z)$ electrons are relatively tightly bound to the nucleus and are known as the *core electrons*.

These isolated atoms condense to form the metallic ion, and the valence electrons are allowed to wander far away from their parent atoms. They are called `*conduction electron gas*' or `*conduction electron cloud*'.

Due to kinetic theory of gas Drude assumed, conduction electrons of mass 'm' move against a background of heavy immobile ions.

The Drude Model of electrical conduction

The density of the electron gas is calculated as follows. A metallic element contains 6.023×10^{23} atoms per mole (Avogadro's number) and ρ_m/A moles per m^3

Here ρ_m is the mass density (in kg per cubic metre) and 'A' is the atomic mass of the element.

Each atom contributes 'Z' electrons, the number of electrons per cubic meter.

The conduction electron densities are of the order of 10^{28} conduction electrons for cubic meter, varying from 0.91×10^{28} for cesium upto 24.7×10^{28} for beryllium.

The Drude Model of electrical conduction

These densities are typically a thousand times greater than those of a classical gas at normal temperature and pressures.

Due to strong electron-electron and electron-ion electromagnetic interactions, the Drude model boldly treats the dense metallic electron gas by the methods of the kinetic theory of a neutral dilute gas.

In the absence of an externally applied electromagnetic fields, each electron is taken to move freely here and there and it collides with other free electrons or positive ion cores. This collision is known as elastic collision.

The neglect of electron–electron interaction between collisions is known as the "*independent electron approximation*".

The Drude Model of electrical conduction

In the presence of externally applied electromagnetic fields, the electrons acquire some amount of energy from the field and are directed to move towards higher potential. As a result, the electrons acquire a constant velocity known as *Drift velocity* V_d.

In Drude model, due to kinetic theory of collision, that abruptly alter the velocity of an electron. Drude attributed the electrons bouncing off the impenetrable ion cores.

Let us assume an electron experiences a collision with a probability per unit time $1/\tau$. That means the probability of an electron undergoing collision in any infinitesimal time interval of length ds is just ds/τ.

The Drude Model of electrical conduction

The time ‘τ’ is known as the relaxation time and it is defined as the time taken by an electron between two successive collisions. That relaxation time is also called *mean free time* [or] *collision time.*

Electrons are assumed to achieve thermal equilibrium with their surroundings only through collision. These collisions are assumed to maintain local thermodynamic equilibrium in a particularly simple way.

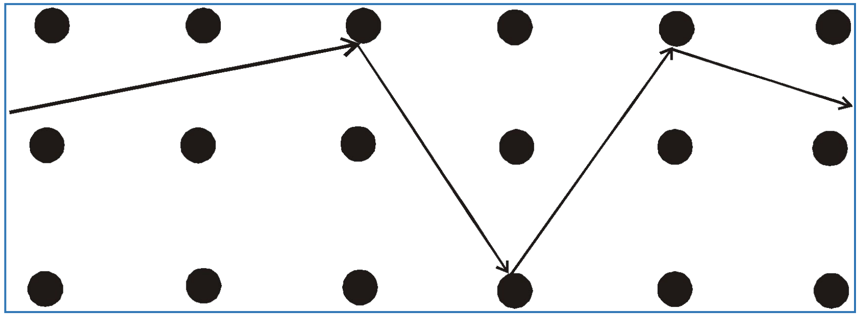

Figure 2 | Trajectory of a conduction electron

Determination of Electrical Conductivity

Determination of Electrical Conductivity of Semiconductor

To determine electrical conductivity by applying Drude theory, we consider a rectangular bar of intrinsic semiconductor connected to a battery as shown in Fig. 1.

If the direction of electric field is along *x*-direction then the free electrons will accelerate along negative *x*-axis and holes along *x*-direction.

So, the velocity of electrons along negative *x*-direction increases and attains some constant resultant velocity. This constant velocity is called drift velocity, represented as V_d.

Determination of Electrical Conductivity

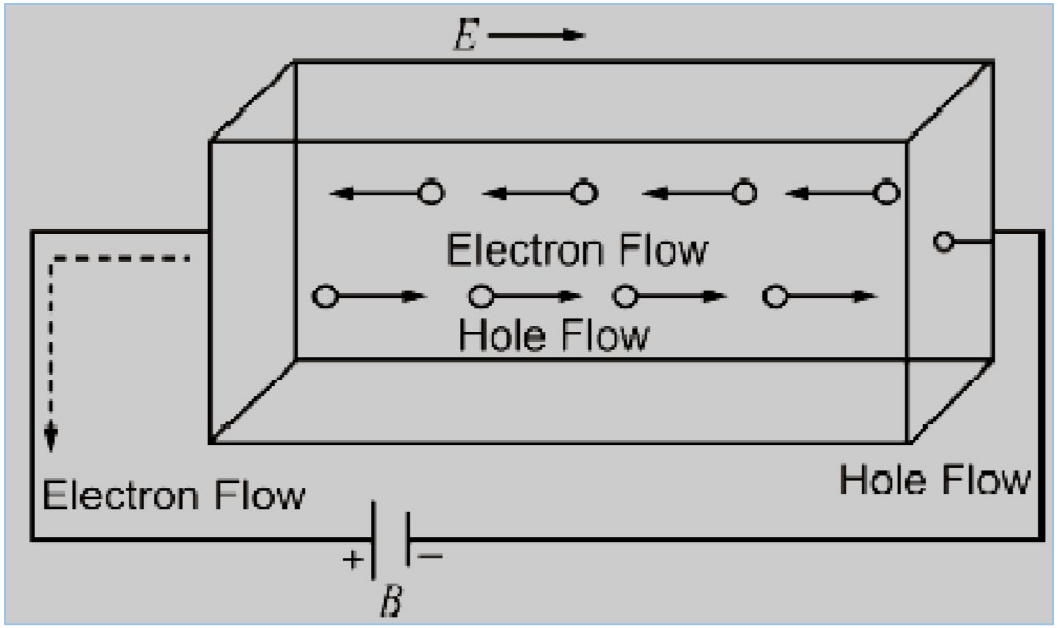

Figure 3 | A rectangular bar of semiconductor under the influence of Electric field E .

The total electrical current through the semiconductor is the sum of electron current I_e and hole current I_h.

Determination of Electrical Conductivity

To find the expression for electrical conductivity, consider a rectangular bar of length L and cross-section area A.

Let 'n' be the number of electrons per unit volume of the semiconductor *i.e.* its electron density, and E be the applied electric field.

Due to this applied electric field, let V_d be the average or drift velocity of the electrons. Assume a plane perpendicular to cross sectional area A.

Then the number of electrons crossing the imaginary plane in 1sec is

$$= nAV_d \qquad (1)$$

Determination of Electrical Conductivity

Then the current flowing across the plane is

$$I_e = neAV_d \qquad (2)$$

Then the electron current density is,

$$J_e = \frac{\mathrm{I_e}}{\mathrm{A}} = neV_d \qquad (3)$$

From Ohm's law, the current density J_e due to electrons is given as

$$\mathrm{V} = IR = \frac{IL\rho}{A}$$

$$\frac{I}{A} = J_e = \frac{\mathrm{V}}{\mathrm{L\rho}} = E\sigma_n \qquad (4)$$

Determination of Electrical Conductivity

Here electrical conductivity of electrons.

From eqn. 3 and eqn. 4, we have

$$J_e = neV_d = E\sigma_n \qquad (5)$$

The drift velocity produced per unit applied electric field is called the mobility of electrons represented as

$$\mu_e = \frac{V_d}{E}$$

Or

$$V_d = \mu_e E \qquad (6)$$

Substituting eqn. 6 in eqn. 5 gives

$$\sigma_n = ne\mu_e \qquad (7)$$

Determination of Electrical Conductivity

Eqn. 7 represents electrical conductivity due to electrons.

Similarly, the electrical conductivity of holes can be obtained.

Let p be the number of holes per unit volume of the material, μ_h is the mobility of holes and the charge of a hole is 'e', then

$$\sigma_p = pe\mu_h \qquad (8)$$

The total conductivity of a intrinsic semiconductor is given by the sum of eqn. 7 and eqn. 8.

$$\sigma = \sigma_n + \sigma_p = ne\mu_e + pe\mu_h$$

$$\sigma = ne[\mu_e + \mu_h] \qquad (9)$$