

PHY 102.2: GENERAL PHYSICS II (3 UNITS)

SEMICONDUCTORS

INTRODUCTION

In nature, there are some materials that are neither good conductor (class of materials that conduct heat every and have low resistivity) or insulators (materials are classified as semiconductors and have high resistivity). These materials are classified as semiconductors and are majorly applicable in the electronics industry. Silicon (Si) and germanium (Ge) are commonly used semiconductors in electronics.

WHAT ARE SEMICONDUCTORS

Semiconductors are not easily defined. In this lecture, we would define semiconductors in terms of electrical conductivity and temperature conductivity. Semiconductors are class of materials that has very high resistivity of 10^4 to $0.5 \Omega \text{ m}$ high range in between good conductors and insulators).

Semiconductors are substances with negative temperature coefficient of resistance. Thermal property plays high significance in describing them. Their temperature conductivity also lies in between good conductors and insulators.

EXAMPLES OF SEMICONDUCTORS, THEIR BAND GAP, AND USES

Germanium Ge, (band gap 0.67). Used in early radar detection diodes and first transistors; requires lower purity than silicon. A substrate for high efficiency multijunction photovoltaic cells. Very similar lattice constant to gallium arsenide. High-purity crystals used for gamma spectroscopy. May grow whiskers, which impair reliability of some devices.

Silicon Si, (band gap). Used in conventional crystalline silicon (c-Si) solar cells, and in its amorphous form as amorphous silicon (a-Si) in thin-film solar cells. Most common semiconductor material in photovoltaics; dominates worldwide PV market; easy to fabricate; good electrical and mechanical properties. Forms high quality thermal oxide for insulation purposes. Most common material used in the fabrication of Integrated Circuits.

Gallium arsenide, Indium phosphide, Indium arsenide, Cadmium selenide, Cadmium telluride, Lead (II) sulfide, Tin (II) sulfide, Tin (IV) sulfide, Cadmium arsenide, Copper (I) oxide etc.

PROPERTIES OF SEMICONDUCTORS

- The resistivity of a semiconductor is less than an insulator but more than a conductor.
- Semiconductors have negative temperature coefficient of resistance i.e., the resistance of a semiconductor **increases** with the increase in temperature.
- Doping: when a suitable metabolic impurity, (e.g., arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably.

BONDS AND STRUCTURE OF SEMICONDUCTORS

In semiconductors, bonds are formed by sharing of valence elections. Such bonds are called covalent bonds.

All Semiconductors have crystalline structure because their atoms or molecules are arranged in an orderly pattern such that each atom is surrounded by neighboring atoms in a tetrahedral or manner.

EFFECT OF TEMPERATURE ON SEMICONDUCTORS

At Absolute Zero: The electrical conductivity of semiconductor changes with temperature variations. At absolute zero temperature, all the electrons are tightly held by the semiconductor atoms. The inner orbit electrons are bound whereas the

valence electrons are engaged in a covalent bonding. At this absolute zero temperature, the covalent bonds are very strong and there are no free electrons. Therefore, the semiconductor crystal behaves as a perfect insulator.

In terms of energy band description, the valence band is filled and there is a large gap between the valence band and conduction band. Therefore, no valence electrons to reach conduction band to become free electrons which resulted in semiconductor behaves as an insulator.

Above Absolute Zero: When the temperature is raised, some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons free which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a tiny electric current if potential difference is applied across the semiconductor crystal. This shows that the resistance of a Semiconductor decreases with the Rise in temperature. It has a negative temperature coefficient of resistance. It may be added that at room temperature current through a semiconductor is too small to be of any practical value. As the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons will constitute electric current. It may be noted that each time a valence electron enters the conduction Band, a hole is created in the violence band.

INTRINSIC SEMICONDUCTOR

A semiconductor in an extremely pure form is known as an intrinsic semiconductor. In an intrinsic semiconductor, even at room temperature hole – electron pairs are created. When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes: by free electrons and holes. the free electrons produced due to the breaking up of some covalent bonds by thermal energy. At the same time, holes are created in the covalent bonds. Under the influence of electric field, conduction through this semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of current due to free electrons and holes.

EXTRINSIC SEMICONDUCTOR

The intrinsic semiconductor had little current conduction capability at room temperature. To be useful in electronic devices, the pure semiconductor must be altered to significantly increase its conducting properties. This is achieved by adding a small amount of suitable impurity to a semiconductor. It is then called impurity or extrinsic semiconductor. The process of adding impurities to a semiconductor is known as doping. The amount and type of such impurities must be closely controlled during the preparation of extrinsic semiconductor. Generally, for 10^8 atoms of semiconductor, one impurity atom is added.

Semiconductors are categorized into two classifications namely: n – type semiconductor and p – type semiconductor.

n – type semiconductor

When a small amount of pentavalent impurity (e.g., arsenic, atomic no. 33) is suitably duped with an intrinsic semiconductor (pure semiconductor) like Germanium is kwon as n – type semiconductor. Current conduction in this semiconductor is majorly by free electrons.

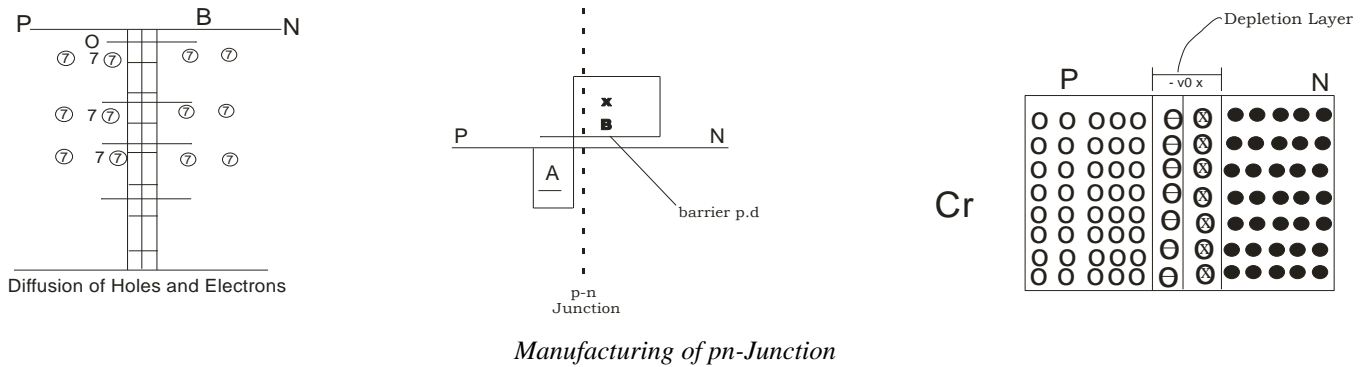
p – type semiconductor

When a small amount of trivalent impurity (e.g., gallium, atomic no. 31) is suitably duped with an intrinsic semiconductor (pure semiconductor) like Silicon is kwon as n – type semiconductor. Current conduction in this semiconductor is majorly by holes.

PN –JUNCTION

INTRODUCTION

When a p-type s/c is suitably joined to n-type s/c, the contact surface is called pn-junction. By special manufacturing process, p- and n-s/c can be melted so that a boundary or junction is formed between them. This junction is extremely thin and of the order 10^{-3} mm see the figure below



PROPERTIES OF PN-JUNCTION

At the instant of formation, the pn-junction exhibit the following properties:

- There are two layers of positive and negative charges that is formed. The two layers the depletion region (depletion layer).
- The depletion is depleted (emptied) of charges (free electrons and holes) due to diffusion across the junction. Once pn-junction is formed, and depletion region is created, the diffusion of free electrons stops.
- The depletion region has positive and negative charges that set up an electric field. The electric field is a barrier to the free electrons in the n-region. The electric field across the depletion layer create p.d across depletion layer and is called barrier potential (V_0) V_0 of a pn-Junction depends upon several factors: s/c material, the amount of doping and temperature.

BIASING A PN-JUNCTION

In electronics, the term bias refers to the use of dc voltage to establish certain operating conditions. There are two biasing in relation to pn-Junction in electronics:

- Forward Biasing and
- Reverse Biasing

FORWARD BIASING

When external D.C. voltage applied to the junction is in such a direction that it cancels the potential barrier, this permitting current flows, it is called forward biasing.

To apply forward bias, connect terminal of the battery to p-type and negative terminal to n-type as shown below. The applied forward potential establishes an electric field which acts against the field due to barrier P.D. Therefore, the resultant field is weakened, and the barrier height is reduced at the junction.

REVERSE BIASING

ATOMIC STRUCTURE

Thompson's model of the Atom

J.J. Thompson postulated an atomic model where he pictured the atom as a sphere of size $10^{-10} m$ and of positively charged matter in which electrons are embedded in it. This model of the atom could not explain all features of optical spectra of hydrogen and other elements.

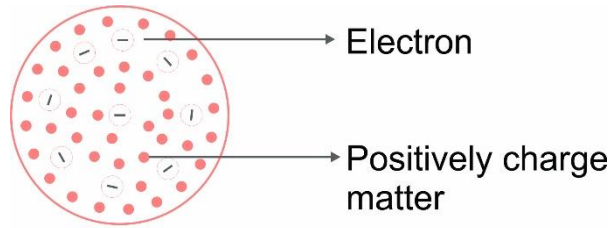


Fig. 1: Thompson model of the atom.

Rutherford Nuclear model of the Atom

In 1911 Ernest Rutherford gave a planetary nuclear model of the atom through his thin gold foil experiment of scattering of α – particles, he postulated that.

1. An Atom consisted of central massive nucleus of size of order $10^{-14} m$ and is positively charge and most of the mass are concentrated in it. Thus, this postulate makes the discovery of the nucleus of the atom due to Rutherford.
2. A cloud of negativity charged electrons revolving round the nucleus in a close orbit. The rotation of electrons is due to the centrifugal force which is balanced by the force of electrons. Rutherford models enable us to account for very large deviations.

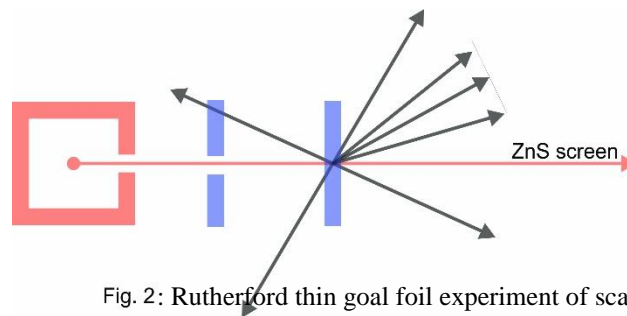


Fig. 2: Rutherford thin gold foil experiment of scattering of α – particles

Bohr Atomic Model

Neil Bohr picked all of Rutherford nuclear model postulate and refined them. He summarized his model in the following two postulates.

1. The electron can revolve round the nucleus only in those allowed or permissible orbits for which the angular momentum of the electron is an integral multiple of $\frac{h}{2\pi}$. This means that an electron cannot revolve round the nucleus in all possible orbits as suggested by classical theory. Where h is the plank constant $=6.64 \times 10^{-34} Js$. For an electron of mass m , revolving the nucleus with speed v in an orbit of radius r , the angular momentum l is given as

$$L = mVr = mV^2\omega = \frac{nh}{2\pi} \quad (1)$$

Where n is the principal quantum number and takes values from $n = 1, 2, 3, 4 \dots$

2. An electron radiates energy only when an electron jumps from stationary orbits of higher energy to orbits of lower energy level. If electrons jump from initial orbits of energy E_i to the final orbits of energy E_f (i.e., $E_i > E_f$), a photon of frequency f , is given as $f = \frac{E_i - E_f}{h}$ is emitted

The Bohr Formulae

From Bohr postulates above, Bohr derived the radius of stationary orbits and the total energy of the electron in the orbit.

Let's consider an atom whose nucleus has a positive charge Ze and mass M . Let an electron of charge $(-e)$ and mass m move round the nucleus in an orbit of radius r . since $M \gg m$, it means the nucleus is stationary.

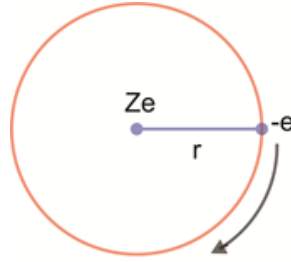


Fig. 3: Bohr's Atom

$$F = \frac{1}{4\pi\epsilon_0} \frac{(Ze)(-e)}{r^2} \text{ (2) (Electrostatic force between nucleus and electron)}$$

$$F = \frac{mv^2}{r} \text{ (3) (The centrifugal force on the electron)}$$

$$F = \frac{mv^2}{r} = \frac{1}{4\pi\epsilon_0} \frac{(Ze)(-e)}{r^2} \text{ (4) (For a stable system)}$$

From Bohr's first postulate,

$$mVr = \frac{nh}{2\pi} \text{ or } V = \frac{nh}{2\pi rm}.$$

$$\therefore V^2 = \frac{n^2 h^2}{4\pi^2 r^2 m^2} \text{ (5)}$$

Substituting this value of V^2 in (3)

$$\begin{aligned} \frac{m}{r} \left(\frac{n^2 h^2}{4\pi^2 r^2 m^2} \right) &= \frac{1}{4\pi\epsilon_0} \frac{Ze^2}{r^2} \\ r &= \frac{n^2 h^2 \epsilon_0}{\pi Ze^2 m} \text{ (6)} \\ r_n &= \frac{n^2 h^2 \epsilon_0}{\pi e^2 m} \quad (Z = 1 \text{ for hydrogen}) \end{aligned}$$

The radius of the first orbit for hydrogen atom is given as

$$r_1 = \frac{1^2 (6.625 \times 10^{-34})^2 (8.854 \times 10^{-12})}{\pi (1.6 \times 10^{-19})^2 (9.11 \times 10^{-31})} m = 0.053 nm.$$

This is called the Bohr radius. If $r_1 = 0.053 nm$, $r_2 = 2^2 r_1 \dots r_n = 2^n r_1$.

Bohr's Energy

The total energy of an electron in any orbit is the sum of its kinetic and potential energies. The potential energy of the electron is zero when it is at an infinite distance from the nucleus. Potential energy of an electron in an orbit is given by the work done in bringing the electron from infinity to that orbit. This amount of work done is gotten by integrating the electrostatic force of attraction between the nucleus and the electron from the limits ∞ to r .

$$P.E = \int_{\infty}^r \frac{Ze^2}{4\pi\epsilon_0 r^2} dr = -\frac{Ze^2}{4\pi\epsilon_0 r} \text{ (7)}$$

$$K.E = \frac{1}{2} mV^2 = \frac{Ze^2}{8\pi\epsilon_0 r} \text{ (8)}$$

From (4) for a stable system

$$\begin{aligned} mV^2 &= \frac{Ze^2}{4\pi\epsilon_0 r} & \text{Total Energy } E_n &= P.E + K.E \\ E_n &= -\frac{Ze^2}{4\pi\epsilon_0 r} + \frac{Ze^2}{8\pi\epsilon_0 r} = -\frac{Ze^2}{8\pi\epsilon_0 r} \end{aligned}$$

Substituting the value of r from (5)

$$E_n = -\frac{me^4 Z^2}{8\epsilon_0^2 n^2 h^2} \text{ (9)}$$

As the value of n increases, E_n increases. Hence, the outer orbits have greater energies than the inner orbits.

Bohr's Hydrogen Spectrum

From Bohr's second postulate, $f = \frac{E_i - E_f}{h}$, it means that if an electron jumps from an outer energy level to an inner energy level, and in the case of hydrogen where atom (i.e., $Z=1$)

$$\text{From (9) } E_{n_2} = -\frac{me^4}{8\epsilon_0^2 h^2} \frac{1}{n_2^2} \quad \text{and } E_{n_1} = -\frac{me^4}{8\epsilon_0^2 h^2} \frac{1}{n_1^2}$$

From frequency of emitted photon

$$\therefore f = \frac{E_i - E_f}{h} = \frac{E_{n_2} - E_{n_1}}{h} = \frac{me^4}{8\epsilon_0^2 h^2} \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \quad (10)$$

We can now define the wavenumber \bar{f} of a radiation as the reciprocal of its wavelength λ , in vacuum. $\bar{f} = \frac{1}{\lambda} = \frac{f}{c}$

$$\bar{f} = \frac{me^4}{8\epsilon_0^2 ch^2} \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \quad (11)$$

Where the Rydberg constant $R = \frac{me^4}{8\epsilon_0^2 ch^2}$ and

$$R = \frac{(9.11 \times 10^{-31})(1.6 \times 10^{-19})^4}{(8.854 \times 10^{-12})^2 (3 \times 10^8)(6.625 \times 10^{-34})^3} m = 1.091 \times 10^7 m^{-1}.$$

Spectral of H atom

There are five special series of hydrogen atom, and these are:

1. Lyman Series

When electron transitions (jumps) from higher orbits (second, third ... etc.) to the first orbit, energies are emitted that lies within the ultraviolet region.

$$\bar{f} = R \left(\frac{1}{1^2} - \frac{1}{n_2^2} \right), \text{ Where } n_1 = 1 \text{ and } n_2 = 2, 3, 4 \dots$$

2. Balmer Series

This is due to the transitions of electron from the outer orbits to the second orbit where $n_1 = 2$ and $n_2 = 3, 4, 5 \dots$ etc.

$$\bar{f} = R \left(\frac{1}{2^2} - \frac{1}{n_2^2} \right)$$

The Balmer Series lies within visible region of the spectrum. Where the first line ($n = 3$) is called H_α , the second line in the series ($n = 4$) is called H_β , etc.

3. Paschen Series

This lies within the infrared region and $n_1 = 3$ and $n_2 = 4, 5, 6 \dots$ etc

$$\bar{f} = R \left(\frac{1}{3^2} - \frac{1}{n_2^2} \right)$$

4. Bracket Series

If $n_1 = 4$ and $n_2 = 5, 6, 7 \dots$ etc; we would get the Bracket series.

$$\bar{f} = R \left(\frac{1}{4^2} - \frac{1}{n_2^2} \right)$$

5. Pfund Series

If $n_1 = 5$ and $n_2 = 6, 7, 8 \dots$ etc; we would get the Bracket series.

$$\bar{f} = R \left(\frac{1}{5^2} - \frac{1}{n_2^2} \right)$$

Bracket and Pfund series lie in the far infrared region of the hydrogen spectrum. If we put $n = \infty$ in each of the series, we would get the last line.

Energy Level Diagram

From (8)
$$E_n = -\frac{me^4 Z^2}{8\epsilon_0^2 n^2 h^2}$$

The above equation can be diagrammatically represented to estimate the energy level for hydrogen in the above equation by substituting the constant values, ω get.

$$\begin{aligned} R &= \frac{(9.11 \times 10^{-31})(1.6 \times 10^{-19})^4}{8(8.854 \times 10^{-12})^2 (6.625 \times 10^{-34})^3} = 21.76 \times 10^{-19} J \\ &= \frac{21.76 \times 10^{-19}}{1.6 \times 10^{-19}} eV = 13.6 eV \end{aligned}$$

The lowest energy E_1 , is called the ground state of the atom and the higher ones ($E_2, E_3, E_4 \dots$) are called the excited state.

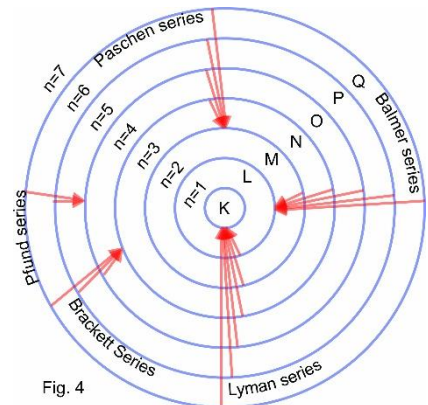


Fig. 4

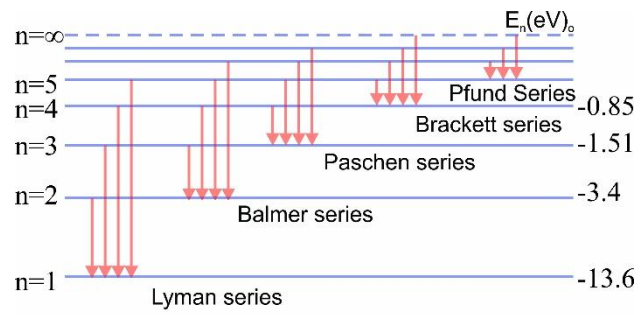


Fig. 5

Evidence in favor of Bohr's postulate:

1. The ratio of mass of electron to the mass of proton $m/MH = \frac{1}{1837}$
2. Spectrum of simply ionized helium
3. The discovery of deuterium