EC8252 **ELECTRON DEVICES** **L T P C**
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UNIT I SEMICONDUCTOR DIODE 9

PN junction diode, Current equations, Energy Band diagram, Diffusion and drift current densities, forward and reverse bias characteristics, Transition and Diffusion Capacitances, Switching Characteristics, Breakdown in PN Junction Diodes.

UNIT II BIPOLAR JUNCTION TRANSISTORS 9

NPN -PNP -Operations-Early effect - Current equations – Input and Output characteristics of CE, CB, CC - Hybrid -π model - h-parameter model, Ebers Moll Model- Gummel Poon-model, Multi Emitter Transistor.

UNIT III FIELD EFFECT TRANSISTORS 9

JFETs – Drain and Transfer characteristics, - Current equations - Pinch off voltage and its significance- MOSFET- Characteristics- Threshold voltage -Channel length modulation, D-MOSFET, E-MOSFET- Characteristics – Comparison of MOSFET with JFET.

UNIT IV SPECIAL SEMICONDUCTOR DEVICES 9

Metal-Semiconductor Junction- MESFET, FINFET, PINFET, CNTFET, DUAL GATE MOSFET, Schottky barrier diode-Zener diode-Varactor diode –Tunnel diode- Gallium Arsenide device, LASER diode, LDR.

UNIT V POWER DEVICES AND DISPLAY DEVICES 9

UJT, SCR, Diac, Triac, Power BJT- Power MOSFET- DMOS-VMOS. LED, LCD, Photo transistor, Opto Coupler, Solar cell, CCD.

TOTAL: 45 PERIODS

OUTCOMES:

At the end of the course the students will be able to:

- Explain the V-I characteristic of diode, UJT and SCR
- Describe the equivalence circuits of transistors
- Operate the basic electronic devices such as PN junction diode, Bipolar and Field effect Transistors, Power control devices, LED, LCD and other Opto-electronic devices

TEXT BOOKS:

1. Donald A Neaman, ―Semiconductor Physics and Devices‖, Fourth Edition, Tata Mc GrawHill Inc. 2012.

2. Salivahanan. S, Suresh Kumar. N, Vallavaraj.A, ―Electronic Devices and circuits‖, Third Edition, Tata McGraw- Hill, 2008.

REFERENCES:

1. Robert Boylestad and Louis Nashelsky, ―Electron Devices and Circuit Theory‖ Pearson Prentice Hall, 10th edition, July 2008.

2. R.S.Sedha, ― A Text Book of Applied Electronics‖ S.Chand Publications, 2006.

3. Yang, ―Fundamentals of Semiconductor devices‖, McGraw Hill International Edition, 1978.

THE ATOM

All matter is composed of atoms; all atoms consist of electrons, protons, and neutrons except normal hydrogen, which does not have a neutron. Each element in the periodic table has a unique atomic structure, and all atoms within a given element have the same number of protons. At first, the atom was thought to be a tiny indivisible sphere. Later it was shown that the atom was not a single particle but was made up of a small dense nucleus around which electrons orbit at great distances from the nucleus, similar to the way planets orbit the sun. Neil's Bohr proposed that the electrons in an atom circle the nucleus in different obits, similar to the way planets orbit the sun in our solar system. The Bohr model is often referred to as the planetary model. Another view of the atom called the *quantum model* is considered a more accurate representation, but it is difficult to visualize.

The Bohr Model

An **atom** is the smallest particle of an element that retains the characteristics of that element. According to the classical Bohr model, atoms have a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons, as illustrated. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons.** The basic particles of negative charge are called **electrons**.

Fig 1.1: The Bohr model of an atom showing electrons in orbits around the nucleus, which consists of protons and neutrons. The "tails" on the electrons indicate motion.

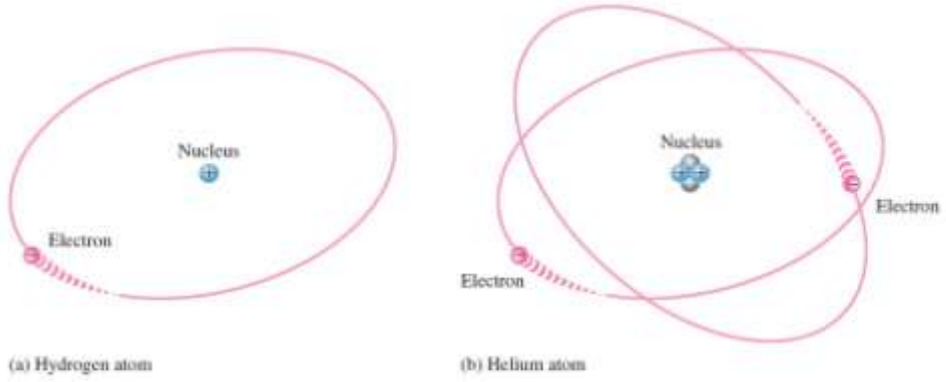


Fig 1.2: Two simple atoms, hydrogen and helium.

Atomic Number

The **atomic number** equals the number of protons in the nucleus, which is the same as the number of electrons in an electrically balanced (neutral) atom. For example, hydrogen has an atomic number of 1 and helium has an atomic number of 2.

Electrons and Shells

Energy Levels Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits. Only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Each discrete distance (**orbit**) from the nucleus corresponds to a certain energy level. In an atom, the orbits are grouped into energy levels known as **shells**. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons. The shells (energy levels) are designated 1, 2, 3, and so on, with 1 being closest to the nucleus.

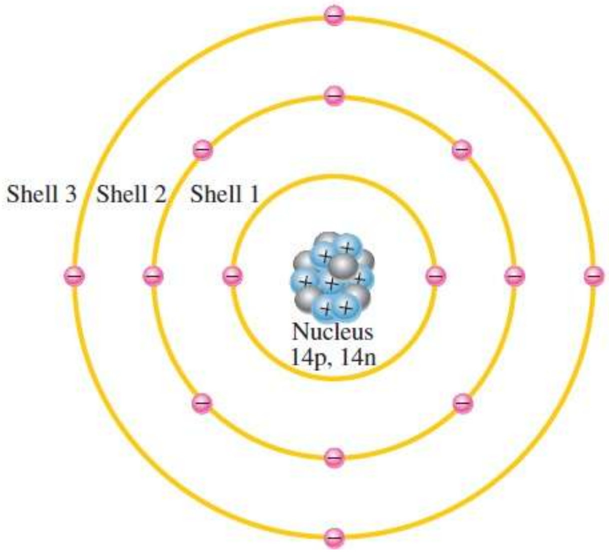


Fig: Illustration of the Bohr model of the silicon atom.

The Maximum Number of Electrons in Each Shell: The maximum number of electrons (*Ne*) that can exist in each shell of an atom is a fact of nature and can be calculated by the formula

$$\boldsymbol{N_e = 2n^2}$$

n - Number of the shell

The maximum number of electrons that can exist in

Innermost shell (Shell 1) –

Shell 2 –

Shell 3 –

Valence Electron

Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Electrons with the highest energy exist in the outermost shell of an atom and are relatively loosely bound to the atom. This outermost shell is known as the **valence** shell and electrons in this shell are called *valence electron.*

These valence electrons contribute to chemical reactions and bonding within the structure of a material and determine its electrical properties. When a valence electron gains sufficient energy from an external source, it can break free from its atom. This is the basis for conduction in materials

Ionization

When an atom absorbs energy from a heat source or from light, for example, the energies of the electrons are raised. The valence electrons possess more energy and are more loosely bound to the atom than inner electrons, so they can easily jump to higher energy shells when external energy is absorbed by the atom.

If a valence electron acquires a sufficient amount of energy, called *ionization energy,* it can actually escape from the outer shell and the atom's influence. The departure of a valence electron leaves a previously neutral atom with an excess of positive charge (more protons than electrons). The process of losing a valence electron is known as **ionization**, and the resulting positively charged atom is called a *positive ion.* For example, the chemical symbol for hydrogen is H. When a neutral hydrogen atom loses its valence electron and becomes a positive ion, it is designated H_. The escaped valence electron is called a **free electron**.

The reverse process can occur in certain atoms when a free electron collides with the atom and is captured, releasing energy. The atom that has acquired the extra electron is called a *negative ion*. The ionization process is not restricted to single atoms. In many chemical reactions, a group of atoms that are bonded together can lose or acquire one or more electrons.

Drawback of Bohr Model:

- It is not a complete model

The Quantum Model

- Considered to be more accurate.
- It is a statistical model and very difficult to understand or visualize.
- Like the Bohr model, the quantum model has a nucleus of protons and neutrons surrounded by electrons.

Two important theories under lie the quantum model: the wave-particle duality and the uncertainty principle.

1. ***Wave-particle duality***
2. ***Uncertainly principle***

Orbitals:

In the quantum model, each shell or energy level consists of up to four subshells which are designated *s*, *p*, *d*, and *f*.

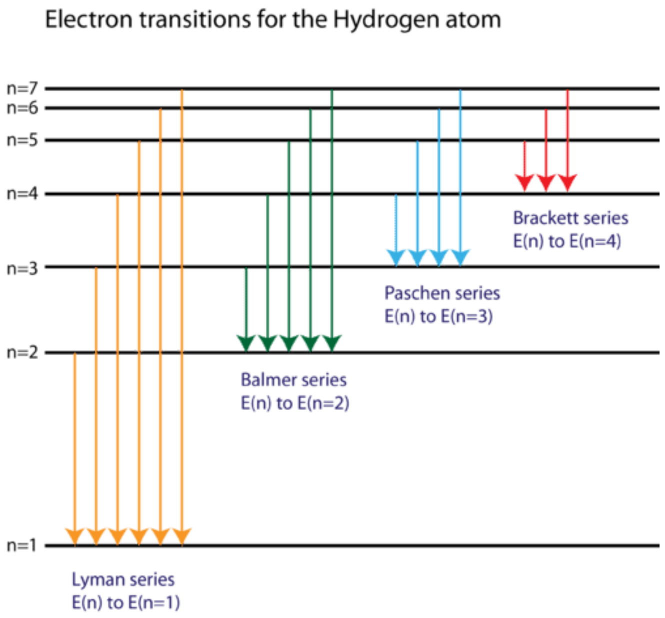
Orbital s - 2 electrons

Orbital p - 6 electrons

Orbital d - 10 electrons

Orbital f - 14 electrons

Atomic Energy Level Diagram



MATERIALS USED IN SEMICONDUCTOR

In terms of their electrical properties, materials can be classified into three groups: **Conductors, semiconductors, and insulators.** When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within the crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms. Silicon is a crystalline material.

INSULATOR	CONDUCTORS	SEMICONDUCTORS
A material that does not conduct electrical current under normal conditions.	A material that easily conducts electrical current. Most metals are good conductors.	A material that is between conductors and insulators in its ability to conduct electrical current
Most good insulators are compounds rather than single-element materials and have very high resistivities. Examples: rubber, plastics, glass, mica, and quartz.	The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminium (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom.	A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), Silicon (Si), and germanium (Ge).
Valence electrons are tightly bound to the atoms; therefore,	These loosely bound valence electrons become free electrons.	The single-element semi-conductors are characterized by

there are very few free electrons in an insulator	Therefore, in a conductive material the free electrons are valence electrons.	atoms with four valence electrons. Silicon is the most commonly used semiconductor.

Band Gap

When an electron acquires enough additional energy, it can leave the valence shell, become a *free electron*, and exist in what is known as the *conduction band.*

The difference in energy between the valence band and the conduction band is called an *energy gap* or **band gap**. This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band.

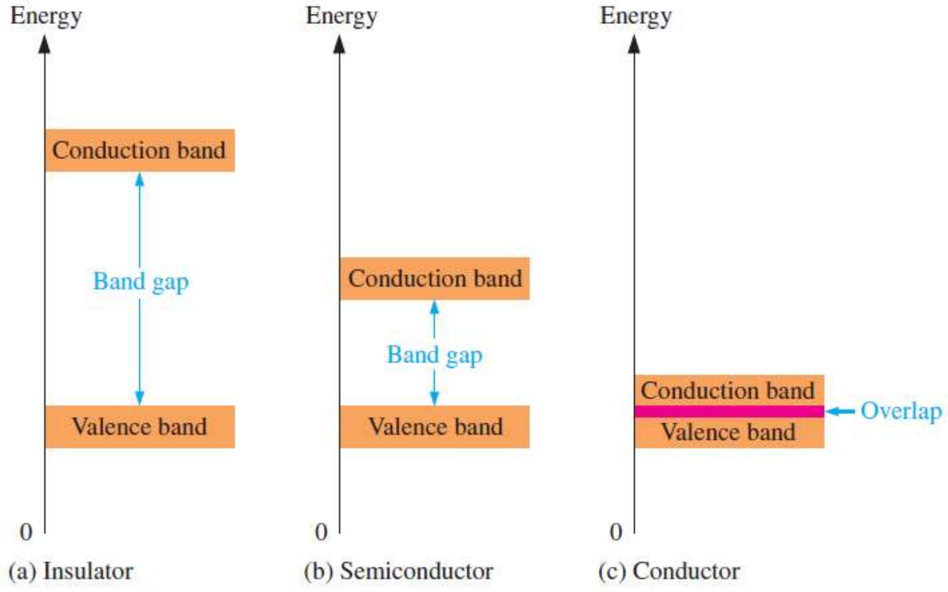


Fig 1. : Energy Band Gap in (a) Insulators (b) Semiconductors & (c) Conductors

Semiconductor

The current density due to motion of electrons

$$J_n = n\mu_n qE = \sigma_n E$$

μ_n – Electron Mobility

The current density due to motion of holes

$$J_p = p\mu_p qE = \sigma_p E$$

$$\mu_p - \text{Hole Mobility}$$

Total current density J in a Semiconductor

$$\mathrm{J} = (n\mu_n + p\mu_p)qE = \sigma E$$

Where,

$\sigma = (n\mu_n + p\mu_p)q - Total\ conductivity\ of\ a\ Semiconductor$

Pure Semiconductor (Intrinsic Semiconductor)

Number of free electrons = Number of Holes

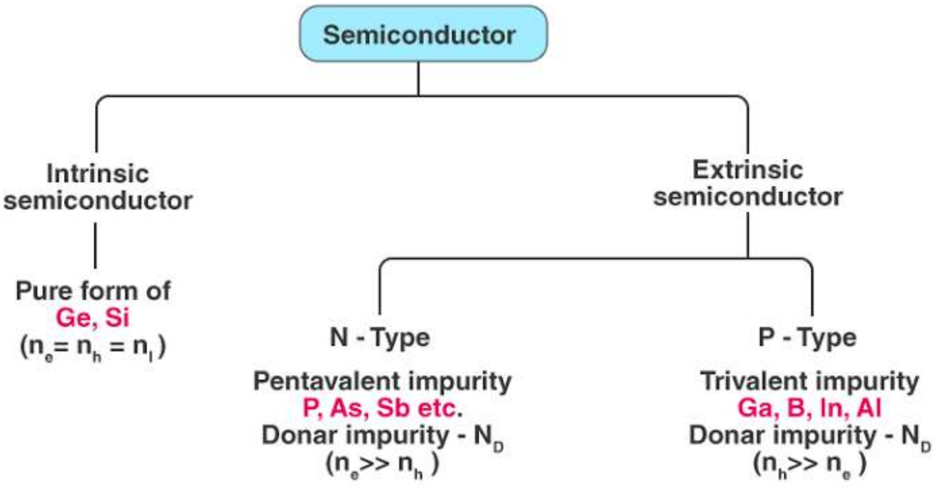
$$\mathbf{J = n_i(\mu_n + \mu_p)qE}$$

$$\mathbf{n_i = n = p}$$

Effective mass

$$\mathbf{qE = ma}$$

Classification of Semiconductor



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Intrinsic Semiconductor

A Semiconductor which is in extremely pure form

Extrinsic Semiconductor

N – type Semiconductor

To increase the number of conduction-band electrons in intrinsic silicon, **pentavalent** impurity atoms are added. These are atoms with five valence electrons such as arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb).

Each pentavalent atom (antimony, in this case) forms covalent bonds with four adjacent silicon atoms. Four of the antimony atom’s valence electrons are used to form the covalent bonds with silicon atoms, leaving one extra electron. This extra electron becomes a conduction electron because it is not involved in bonding. Because the pentavalent atom gives up an electron, it is often called a *donor atom.* The number of conduction electrons can be carefully controlled by the number of impurity atoms added to the silicon. A conduction electron created by this doping process does not leave a hole in the valence band because it is in excess of the number required to fill the valence band.

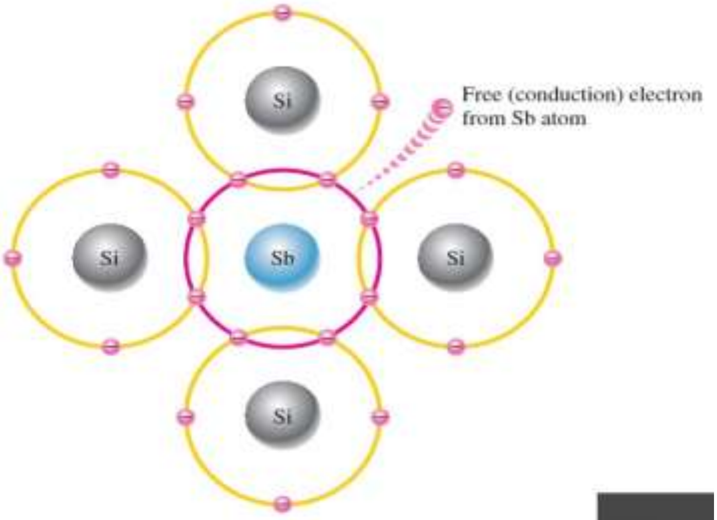

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Fig: Pentavalent impurity atom in a silicon crystal structure.

Majority and Minority Carriers Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron). The electrons are called the **majority carriers** in *n*-type material. Although the majority of current carriers in *n*-type material are electrons, there are also a few holes that are created when electron-hole pairs are thermally generated. These holes are *not* produced by the addition of the pentavalent impurity atoms. Holes in an *n*-type material are called **minority carriers.**

P – Type Semiconductor

To increase the number of holes in intrinsic silicon, **trivalent** impurity atoms are added. These are atoms with three valence electrons such as boron (B), indium (In), and gallium (Ga). As illustrated in Figure 1–18, each trivalent atom (boron, in this case) forms covalent bonds with four adjacent silicon atoms. All three of the boron atom’s valence electrons are used in the covalent bonds; and, since four electrons are required, a hole results when each trivalent atom is added. Because the trivalent atom can take an electron, it is often referred to as an *acceptor atom.* The number of holes can be carefully controlled by the number of trivalent impurity atoms added to the silicon. A hole created by this doping process is *not* accompanied by a conduction (free) electron.

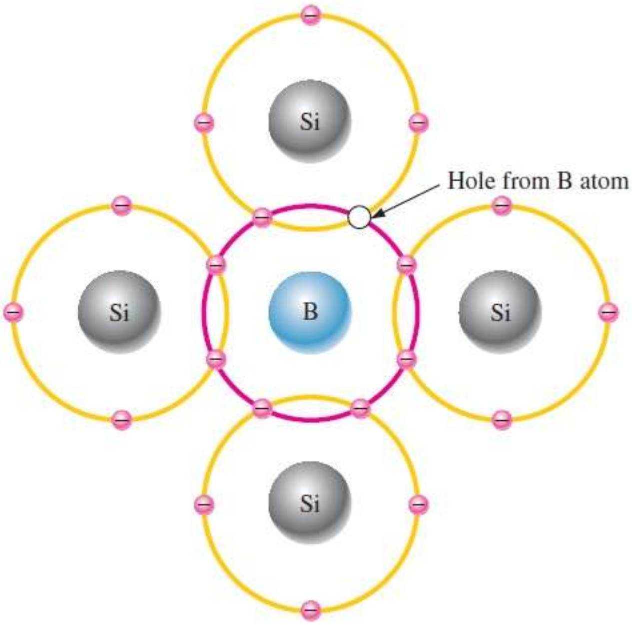


Fig: Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

Majority and Minority Carriers Since most of the current carriers are holes, silicon (or germanium) doped with trivalent atoms is called a *p*-type semiconductor. The holes are the majority carriers in *p*-type material. Although the majority of current carriers in *p*-type material are holes, there are also a few conduction-band electrons that are created when electron-hole pairs are thermally generated. These conduction-band electrons are *not* produced by the addition of the trivalent impurity atoms. Conduction-band electrons in *p*-type material are the minority carriers.

Conductivity of Semiconductor

$$\boldsymbol{J = J_n + J_p}$$

$$\boldsymbol{= n\mu_n qE + p\mu_p qE}$$

$$\boldsymbol{= (n\mu_n + p\mu_p)qE = \sigma E}$$

$$J_n - electron\ drift\ current\ density$$

$$J_p - hole\ drift\ current\ density$$

$$n - number\ of\ electrons\ per\ unit\ volume$$

$$p - number\ of\ holes\ per\ unit\ volume$$

$$E - applied\ electric\ field\ strength, V/m$$

$$q - charge\ of\ electron\ or\ hole, Coulomb$$

Resistivity (ρ) of a semiconductor is the reciprocal of conductivity, i.e.,

$$\boldsymbol{\rho = \frac{1}{\sigma}}$$

Energy Distribution of Electrons

Carrier Concentration In Intrinsic Semiconductor

To calculate the conductivity of a semiconductor, the concentration of free electrons and the concentration of free holes must be known

$$dn = N(E)f(E)dE$$

dn - Number of conduction electrons per unit cubic meter whose energies lie between E & E + dE.

N(E) - Density of states

In a semiconductor the lowest energy in the conduction band is E_c and hence

$$N(E) = \Upsilon(E - E_c)^{1/2}$$

The Fermi Dirac probability function f(E) is given by

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

$$E_F - Fermi\ level\ or\ charcateristic\ energy\ for\ th\ crystal\ in\ eV.$$

The concentration of electrons in the conduction band is,

$$n = \int_{E_c}^{\infty} N(E)f(E)dE$$

For E >= E_c, E - E_F >> kT

$$f(E) = e^{-(E - E_F)/kT}$$

$$n = \int_{E_c}^{\infty} \Upsilon(E - E_c)^{1/2}\ e^{-(E - E_F/kT)}dE$$

Mass – Action Law:

Under thermal equilibrium for any semiconductor, the product of number of holes and the number of electrons is constant and is independent of the amount of donor and acceptor impurity doping.

$$\mathbf{n.p = n_i^2}$$

$$\mathrm{n - Number\ of\ free\ electrons\ per\ unit\ volume}$$

$$\mathrm{p - Number\ of\ holes\ per\ unit\ volume}$$

$$\mathrm{n_i - Intrinsic\ Concentration}$$

Drift Current

When an electric field is applied across the semiconductor material, the charge carriers attain a certain drift velocity

$$v_d = mobility\ of\ charge\ carriers * applied\ electric\ field\ intensity\ E$$

The holes move towards the negative terminal and electrons move towards the positive terminal. This combined effect of movement of charge carriers constitutes a current known as the drift current.

"Drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field"

Drift Current Density

A conducting wire of length *l cm* contains N electrons. If an electron travels a distance of *l cm* in the conductor in time T sec, the total number of electrons passing through any cross section of wire per second is $\frac{N}{T}$.

The total current flowing through the wire with area of cross – section A is given by

$$I = \frac{Nq}{T} = \frac{Nqv_d}{l}$$

$$v_d - drift\ velocity\ \&\ time\ T = \frac{1}{v_d}$$

The drift current density J is defined as the current per unit area of the conducting medium.

$$J = \frac{I}{A} = \frac{Nqv_d}{lA}\ A/cm^2$$

$$lA\ is\ the\ volume\ containing\ N\ electrons\ and\ the\ electron\ concentration, n = \frac{N}{lA}$$

$$J = nqv_d = \rho v_d$$

$$\rho = nq, charge\ density\ in\ coloumbs\ per\ cubic\ centimeter$$

$$J = nqv_d = nq\mu E = \sigma E$$

$$E - Applied\ Electric\ field\ intensity\ in \frac{V}{cm}$$

$$\mu - mobility\ of\ electrons\ in\ cm^2/V - s$$

$$v_d - drift\ velocity\ in\ cm/s$$

$$Conductivity, \sigma = nq\mu\ in\ S.m^{-1}$$

The drift current density due to the charge carriers such as free electrons and holes are the current passing through a square centimetre perpendicular to the direction of flow. The equation for the drift current density, J_n due to free electrons is given by

$$J_n = qn\mu_n E\ \ A/cm^2$$

drift current density, J_p due to holes is given by

$$J_p = qp\mu_p E\ \ A/cm^2$$

$$n = number\ of\ free\ electrons\ per\ cubic\ centimetre$$

$$p = number\ of\ holes\ per\ cubic\ centimetre$$

$$\mu_n = mobility\ of\ electrons\ in\ cm^2/V - s$$

$$\mu_p = mobility\ of\ holes\ in\ cm^2/V - s$$

$$E - Applied\ Electric\ field\ intensity\ in \frac{V}{cm}$$

$$q = charge\ of\ an\ electron = 1.602 * 10^{-19}\ Coloumb$$

Diffusion Current

It is possible for an electric current to flow in a semiconductor even in the absence of the applied voltage provided a concentration gradient exists in the material. A concentration gradient exists if the number of either electrons or holes is greater in one region of a semiconductor as compared to the rest of the region. In a semiconductor material, the charge carriers have the tendency to move from the region of higher concentration to that of lower concentration of the same type of charge carriers. Thus, the movement of charge carriers takes place resulting in a current called diffusion current.

Diffusion Current depends on

- Material of the Semiconductor
- Type of Charge Carriers
- Concentration Gradient

Diffusion current density due to holes, J_p is given by,

$$J_p = -qD_p \frac{dp}{dx}\ A/cm^2$$

Hole density p(x) decreases with increasing x.

Diffusion current density due to free electrons, J_n is given by,

$$J_n = qD_n \frac{dn}{dx}\ A/cm^2$$

$$dn/dx\ \&\ dp/dx - concentration\ gradients\ for\ electrons\ and\ holes.$$

$$\boldsymbol{Total\ Current = Drift\ Current + Diffusion\ Current}$$

Total current density for an P – type Semiconductor

$$J_p = qp\mu_p E - qD_p \frac{dp}{dx}$$

Total current density for an N – type Semiconductor

$$J_n = qn\mu_n E + qD_n \frac{dn}{dx}$$

Continuity Equation

Theory of PN Junction Diode

PN junction Diode in Equilibrium with no Applied Voltage

In a piece of semiconductor material, one half is doped by P – type impurity and the other half is doped by N – type impurity, a PN junction is formed. The plane dividing the two halves or zones is called **PN junction**.

- N – type material – high concentration of free electrons
- P – type material – high concentration of holes

At the junction, there is a tendency for the free electrons to diffuse over to the P – side and holes to the N – side. This process is called **Diffusion.** As the free electrons move across the junction from N – type to P – type, the donor ions become positively charged. Hence positive charge is built on the N – side of the junction. Therefore, a net negative charge is established on the P – side of the junction. This net negative charge on the P – side prevents further diffusion of electrons into the P – side. Similarly, the net positive charge on the N – side repels the hole crossing from P – side to N – side. Thus, a barrier is set – up near the junction which prevents further movement of charge carriers, i.e., electrons and holes. As a consequence a induced electric field across the depletion layer, an electrostatic potential difference is established between P – and N – regions, which is called the potential barrier, diffusion potential or contact potential, V_o. The magnitude of contact potential V_o varies with doping levels and temperature.

The electrostatic field across the junction caused by the positively charged N – type region tends to drive the holes away from the junction and negatively charged P – region tends to drive the electrons away from the junction. The majority holes diffusing out of the P – region leave behind negatively charged acceptor atoms bound to the lattice, thus exposing negative space charge in a previously neutral region. Similarly, electrons diffusing from the N – region expose positively ionised donor atoms, and a double space charge layer builds up at the junction. It is noticed that the space – charge layers are of opposite sign to the majority carriers diffusing into them, which tends to reduce the diffusion rate.

Calculation of Depletion Width

Consider the width of the Depletion region contains space charge since, donors on the N – side and acceptors on the P – side have lost their accompanying electrons and holes. Hence, an electric filed is established which, in turn, causes a difference in potential energy, qV_o.

$$\boldsymbol{\rho} = \begin{cases} -\boldsymbol{qN_A}, & \mathbf{0} > x > \boldsymbol{X_1} \\ -\boldsymbol{qN_D} & \boldsymbol{X_2} > x > 0 \\ \mathbf{0}, & \boldsymbol{elesewhere} \end{cases}$$

The potential variation in the space charge region can be calculated by using poisson's equation, which is given by

$$\nabla^2 V = -\frac{\rho(x,y,z)}{\varepsilon_o \varepsilon_r}$$

$$\varepsilon_r - relative\ permittivity$$

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon_o \varepsilon_r}$$

Applying the above equation to the P – side of the junction, we get

$$\frac{d^2V}{dx^2} = \frac{qN_A}{\varepsilon_o \varepsilon_r}$$

Integrating twice we get,

$$V = \frac{qN_A x^2}{2\varepsilon_o \varepsilon_r} + Cx + D$$

Where C and D are the constants of integration.

V = 0 at x = 0 and hence D = 0. When $x<X_1$ on the P – side, the potential is constant, so that $\frac{dV}{dx} = 0\ at\ x = X_1$. Hence

$$C = -\frac{qN_A}{\varepsilon_o \varepsilon_r} \,.X_1$$

$$V = \frac{qN_A x^2}{2\varepsilon_o \varepsilon_r} - \frac{qN_A}{\varepsilon_o \varepsilon_r} \,.X_1 \,.x$$

$$V = \frac{qN_A}{2\varepsilon_o \varepsilon_r}\left(\frac{x^2}{2} - X_1 \,.\; x\right)$$

As V = V_1 at x = X_1, we have

$$V_1 = -\frac{qN_A}{2\varepsilon_o \varepsilon_r} \,.X_1^2$$

If we apply the same procedure to the N – side, we get

$$V_2 = \frac{qN_D}{2\varepsilon_o \varepsilon_r} \,.X_2^2$$

Therefore, the total built – in potential or the contact potential is V_o, where

$$V_o = V_1 - V_2 = \frac{q}{2\varepsilon_o \varepsilon_r}(N_A X_1^2 + N_D X_2^2)$$

We know that the positive charge on the N – side must be equal in magnitude to the negative charge on the P – side for the neutral specimen.

$$N_A X_1 = -N_D X_2$$

Substituting this relationship in the above equation

$$X_1 = -\left[\frac{2\varepsilon_o \varepsilon_r V_o}{qN_A\left(1 + \frac{N_A}{N_D}\right)}\right]^{1/2}$$

$$X_2 = -\left[\frac{2\varepsilon_o \varepsilon_r V_o}{qN_D\left(1 + \frac{N_D}{N_A}\right)}\right]^{1/2}$$

The total depletion width, $W = X_2 - X_1$ and hence, $W^2 = X_1^2 + X_2^2 - 2X_1X_2$, and then substituting for $X_1 \; and \; X_2$ from the above equations, we find

$$W = \left[\frac{2\varepsilon_o \varepsilon_r V_o}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)\right]^{1/2}$$

Here, in an alloy junction,

The depletion region width W is proportional to $(V_o)^{1/2}$

Under Forward Bias Condition

Under Forward Bias Condition

When positive terminal of the battery is connected to the P – type and the negative terminal to the N – type of the PN junction diode, the bias applied is known as forward bias.

Operation

The applied potential with external battery acts in opposition to the internal potential barrier and disturbs the equilibrium. As soon as the equilibrium is disturbed by the application of an external voltage, the fermi level is no longer continuous across the junction. The applied positive potentials repel the holes in the P – type region so that the holes moves towards the junction and the applied negative potentials repels the electrons in the N – type region and the electrons move towards the junction. Eventually, when the applied potential is more than the internal barrier potential, the depletion region and internal potential barrier disappears.

V – I characteristics of a diode under Forward Bias

Forward Voltage (V_F) is increased

$V_F < V_o$, Forward current (I_F) is almost zero (region OA)

The potential barrier prevents the holes from P – region and electrons from N – region to flow across the depletion region in the opposite direction.

$V_F > V_o$ - The potential barrier at the junction completely disappears and hence, the holes cross the junction from P – type to N – type and the electrons cross the junction in the opposite direction, resulting in relatively large current flow in external circuit.

For Germanium (Ge) – 0.3 V, Silicon – 0.7 V.

Under Reverse Bias Condition

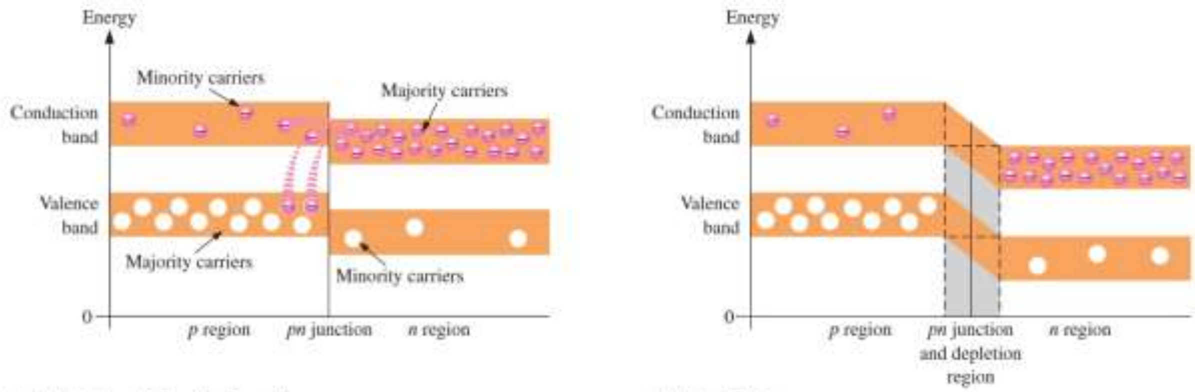
When negative terminal of the battery is connected to the P – type and the positive terminal to the N – type of the PN junction diode, the bias applied is known as reverse bias.

Operation

Under applied reverse bias holes which form the majority carriers of the P – side move towards the negative terminal of the battery and electrons which form the majority carrier of the N – side are attracted towards the positive terminal of the battery. Hence, the width of the depletion region which is depleted of mobile charge carriers increases.

V – I characteristics of a diode under Reverse Bias

Energy Band Structure of Open – Circuited PN junction



(a) At the instant of junction formation

(b) At equilibrium

Fig: Energy – band Structure

Contact difference of Potential

A contact difference of potential exists across an open circuited PN junction.

$$E_F - E_{vp} = \frac{1}{2}E_G - E_1$$

$$E_{cn} - E_F = \frac{1}{2}E_G - E_2$$

$$E_o = E_1 + E_2 = E_G - (E_{cn} - E_F) - (E_F - E_{vp})$$

W.K.T $np = N_C N_V e^{-E_G/kT}$

$$np = n_i^2 \ (Mass - action\ law)$$

From the above equation, we get

$$E_G = kTln\frac{N_C N_V}{n_i^2}$$

We know that for N – type material $E_F = E_C - kTln\frac{N_C}{N_D}$

$$E_{cn} - E_F = \ kTln\frac{N_C}{n_n} = kTln\frac{N_C}{N_D}$$

We know that for P – type material $E_F = E_V - kTln\frac{N_V}{N_A}$

$$E_F - E_{vp} = \ kTln\frac{N_V}{p_p} = kTln\frac{N_V}{N_A}$$

$$E_o = kT\left[ln\frac{N_C N_V}{n_i^2} - ln\frac{N_C}{N_D} - ln\frac{N_V}{N_A}\right]$$

$$E_o = kT\left[\frac{N_C N_V}{n_i^2} * \frac{N_D}{N_C} * \frac{N_A}{N_V}\right]$$

$$E_o = kTln\frac{N_D N_A}{n_i^2}$$

As $E_o = qV_o$, then the contact difference of potential or barrier voltage is given by

$$\boldsymbol{V_o = \frac{kT}{q} ln\frac{N_D N_A}{n_i^2}}$$

Quantitative theory of PN Diode Currents

Let us now drive the expression for the total current as a function of applied voltage assuming that the width of the depletion region is zero. When a forward bias is applied to a diode, holes are injected from the P – side into the N – side. Due to this, the concentration of holes in the N – side (p_n) is increased from its thermal equilibrium value (p_{no}) and injected hole concentration [$P_n(x)$] decreases exponentially with respect to distance (x).

$$P_n(x) = p_n - p_{no} = P_n(0)e^{-x/L_P} \dots\dots\dots (1)$$

$$L_P - Diffusion\ Length\ for\ holes\ in\ the\ N - material$$

$$p_n(x) = p_{no} + P_n(0)e^{-x/L_P} \dots\dots\dots (2)$$

Injected hole concentration at x=0 is

$$P_n(0) = p_n(0) - p_{no} \dots\dots\dots (3)$$

These several components of hole concentration in the N – side of a forward biased diode, in which the density $p_n(x)$ decreases exponentially with distance (x).

$$p_p\ \&\ p_n - hole\ concentration\ at\ the\ edges\ of\ the\ space\ charge\ in\ the\ P - and\ N - sides\ respectively.$$

$$V_B = V_o - V\ be\ the\ effective\ barrier\ potential\ across\ the\ depletion\ layer.$$

$$p_p = P_n e^{V_B/V_T} \dots\dots\dots (4)$$

$$V_T - Volt - Equivalent\ Temperature$$

This is the Boltzmann's relation of kinetic gas theory. This equation is valid as long as the hole current is small compared with diffusion or drift current. This condition is called low level injection.

Open Circuit Condition (i.e., V=0)

$$p_p = p_{po}, p_n = p_{no} \; and \; V_B = V_o$$

$$p_{po} = p_{no}e^{V_o/V_T} \ldots\ldots\ldots(5)$$

Under forward bias condition let V be the applied voltage, then the effective barrier voltage

$$V_B = V_o - V$$

The hole concentration throughout the P – side is constant and equal to the thermal equilibrium value $(p_p = p_{po})$. The hole concentration varies exponentially with distance into the N – side.

At x=0, $p_n = p_n(0)$

Equation (4) can be changed into

$$p_{po} = p_n(0)e^{(V_o - V)/V_T} \ldots\ldots\ldots(6)$$

Comparing Eqn (5) & (6)

$$p_n(0) = p_{no}e^{V/V_T}$$

This boundary condition is called the law of the junction. Substituting this into eqn (3), we get

$$P_n(0) = p_{no}e^{(e^{V/V_T} - 1)} \ldots\ldots\ldots(7)$$

The diffusion hole current in the N – side is

$$I_{pn}(x) = -AqD_p\frac{dp_n(x)}{dx}$$

$$= -AqD_p\frac{d}{dx}\left[p_{no} + P_n(0)e^{-x/L_p}\right]$$

$$= \frac{AqD_pP_n(0)}{L_P}e^{-x/L_P}$$

Forward Currents

The hole current crossing the junction into the N – side with x = 0 is

$$I_{pn}(0) = \frac{AqD_pP_n(0)}{L_p} = \frac{AqD_pp_{no}}{L_p}\left(e^{V/V_T} - 1\right)$$

The electron current crossing the junction into the P – side with x = 0 is

$$I_{np}(0) = \frac{AqD_nN_p(0)}{L_n} = \frac{AqD_nn_{po}}{L_n}\left(e^{V/V_T} - 1\right)$$

The total Diode Current

$$I = I_{pn}(0) + I_{np}(0) = I_o\left(e^{V/V_T} - 1\right)$$

Where $I_o = \frac{AqD_pp_{no}}{L_p} + \frac{AqD_nn_{po}}{L_n} = reverse\ saturation\ current$

Reverse Saturation Currents

We know that $p_n = \frac{n_i^2}{N_D}\ and\ n_p = \frac{n_i^2}{N_A}$. Applying these relationships in the above equation of reverse saturation current, I_o we get

$$I_o = Aq\left[\frac{D_P}{L_PN_D} + \frac{D_n}{L_nN_A}\right]n_i^2$$

Diode Current Equation

$$\boldsymbol{I = I_O\left[e^{(V/\eta V_T)} - 1\right]}$$

$$\mathrm{I = Diode\ Current}$$

$$\mathrm{I_o - Diode\ reverse\ saturation\ current\ at\ room\ temperature}$$

$$\mathrm{V - External\ voltage\ applied\ to\ the\ diode}$$

$$\eta - constant, 1\ for\ Germanium\ \&\ 2\ for\ Silicon$$

$$V_T = kT/q = T/11600\,, volt - equivalent\ of\ temperature$$

$$k = Boltzmann'sconstant\ \left(1.38 * 10^{-3}\frac{J}{K}\right)$$

$$q - Charge\ of\ the\ electron\ (1.602 * 10^{-19}\ C)$$

$$T - Temperature\ of\ the\ diode\ junction\ (K)$$

Transition or Space Charge (Depletion Region) Capacitance (C_T)

Under reverse bias condition, the majority carriers move away from the junction, thereby uncovering more immobile charges. Hence, the width of the space – charge layer at the junction increases with reverse voltage. This increase in uncovered charge with applied voltage may be considered a capacitive effect. The parallel layers of oppositely charged immobile ions on the two sides of the junction form the capacitance, C_T which is expressed as

$$\boldsymbol{C_T = \left|\frac{dQ}{dV}\right|}$$

dQ is the increase in charge caused by a change in voltage dV.

A change in voltage dV in a time dt will result in a current $I = dQ/dt$ given by

$$\boldsymbol{I = C_T\frac{dV}{dt}}$$

Step – graded function

The total charge density of a P – type material with area of the junction A is given by

$$Q = qN_AWA$$

Differentiating the above equation w.r.t. V, we get

$C_T = \left|\boldsymbol{\frac{dQ}{dV}}\right| = \boldsymbol{Aq}N_A\left|\boldsymbol{\frac{dW}{dV}}\right|$

$$C_T = \frac{\varepsilon A}{W}$$

$$\varepsilon - permittivity\ of\ the\ material$$

$$A - Cross - sectional\ area\ of\ the\ junction$$

$$W - Width\ of\ the\ depletion\ layer\ over\ which\ the\ ions\ are\ uncovered$$

$$\boldsymbol{W = \left[\frac{2\varepsilon_o\varepsilon_r(V_o - V)}{q}\left(\frac{N_A + N_D}{N_AN_D}\right)\right]^{1/2}}$$

<u>Types of Configuration</u>

- **a) CB Configuration**
- **b) CE Configuration**
- **c) CC Configuration**