UNIT I

SEMICONDUCTOR DIODE

SEMICONDUCTOR

A **semiconductor** is a material which has electrical conductivity to a degree between that of a metal (such as copper) and that of an insulator (such as glass). Semiconductors are the foundation of modern electronics, including transistors, solar cells, light-emitting diodes (LEDs), quantum dots and digital and analog integrated circuits.

DIODE

Diode – Di + ode

Di means two and ode means electrode. So physical contact of two electrodes is known as diode and its important function is alternative current to direct current.

INTRINSIC SEMICONDUCTOR

An intrinsic semiconductor is one, which is pure enough that impurities do not appreciably affect its electrical behavior. In this case, all carriers are created due to thermally or optically excited electrons from the full valence band into the empty conduction band.

Thus equal numbers of electrons and holes are present in an intrinsic semiconductor. Electrons and holes flow in opposite directions in an electric field, though they contribute to current in the same direction since they are oppositely charged. Hole current and electron current are not necessarily equal in an intrinsic semiconductor, however, because electrons and holes have different effective masses (crystalline analogues to free inertial masses).

The concentration of carriers is strongly dependent on the temperature. At low temperatures, the valence band is completely full making the material an insulator.

Both silicon and germanium are tetravalent, i.e. each has four electrons (valence electrons) in their outermost shell. Both elements crystallize with a diamond-like structure, i.e. in such a way that each atom in the crystal is inside a tetrahedron formed by the four atoms which are closest to it. Each atom shares its four valence electrons with its four immediate neighbours, so that each atom is involved in four covalent bonds.

EXTRINSIC SEMICONDUCTOR

An extrinsic semiconductor is one that has been doped with impurities to modify the number and type of free charge carriers. An extrinsic semiconductor is a semiconductor that has been *doped*, that is, into which a doping agent has been introduced, giving it different electrical properties than the intrinsic (pure) semiconductor.

Doping involves adding dopant atoms to an intrinsic semiconductor, which changes the electron and hole carrier concentrations of the semiconductor at thermal equilibrium. Dominant carrier concentrations in an extrinsic semiconductor classify it as either an n-type or p-type semiconductor. The electrical properties of extrinsic semiconductors make them essential components of many electronic devices.

A pure or intrinsic conductor has thermally generated holes and electrons. However these are relatively few in number. An enormous increase in the number of charge carriers can by achieved by introducing impurities into the semiconductor in a controlled manner.

The result is the formation of an extrinsic semiconductor. This process is referred to as doping. There are basically two types of impurities: donor impurities and acceptor impurities. Donor impurities are made up of atoms (arsenic for example) which have five valence electrons. Acceptor impurities are made up of atoms (gallium for example) which have three valence electrons.

The two types of extrinsic semiconductor

N-TYPE SEMICONDUCTORS

Extrinsic semiconductors with a larger electron concentration than hole concentration are known as n-type semiconductors. The phrase 'n-type' comes from the negative charge of the electron. In n-type semiconductors, electrons are the majority carriers and holes are the minority carriers. N-type semiconductors are created by doping an intrinsic semiconductor with donor.

impurities. In an n-type semiconductor, the Fermi energy level is greater than that of the intrinsic semiconductor and lies closer to the conduction band than the valence band. Arsenic has 5 valence electrons, however, only 4 of them form part of covalent bonds. The 5th electron is then free to take part in conduction. The electrons are said to be the majority carriers and the holes are said to be the minority carriers.

P-TYPE SEMICONDUCTORS

As opposed to n-type semiconductors, p-type semiconductors have a larger hole concentration than electron concentration. The phrase 'p-type' refers to the positive charge of the hole. In p-type semiconductors, holes are the majority carriers and electrons are the minority carriers. P-type semiconductors are created by doping an intrinsic semiconductor with acceptor impurities. P-type semiconductors have Fermi energy levels below the intrinsic Fermi energy level.

The Fermi energy level lies closer to the valence band than the conduction band in a p-type semiconductor. Gallium has 3 valence electrons, however, there are 4 covalent bonds to fill. The 4th bond therefore remains vacant producing a hole. The holes are said to be the majority carriers and the electrons are said to be the minority carriers.

PN JUNCTION :

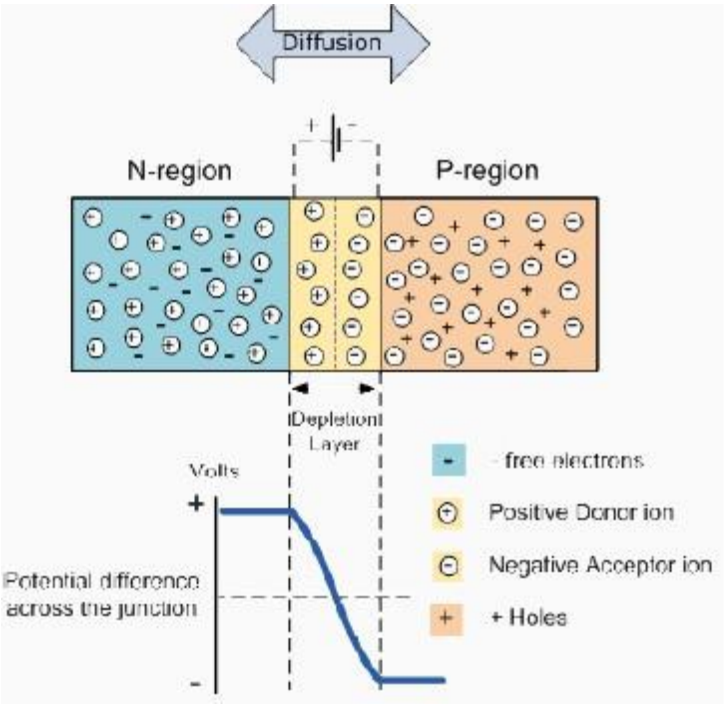
When the N and P-type semiconductor materials are first joined together a very large density gradient exists between both sides of the junction so some of the free electrons from the donor impurity atoms begin to migrate across this newly formed junction to fill up the holes in the P-type material producing negative ions.

However, because the electrons have moved across the junction from the N-type silicon to the P-type silicon, they leave behind positively charged donor ions (ND) on the negative side and now the holes from the acceptor impurity migrate across the junction in the opposite direction into the region are there are large numbers of free electrons. As a result, the charge density of the P-type along the junction is filled with negatively charged acceptor ions (NA), and the charge density of the N-type along the junction becomes positive. This charge transfer of electrons and holes across the junction is known as diffusion.

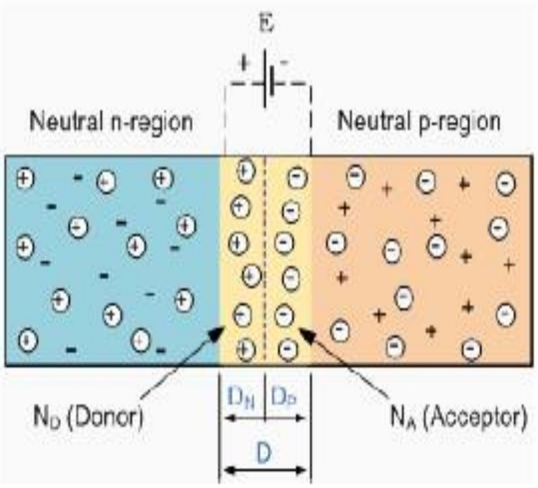
This process continues back and forth until the number of electrons which have crossed the junction have a large enough electrical charge to repel or prevent any more carriers from crossing the junction. The regions on both sides of the junction become depleted of any free carriers in comparison to the N and P type materials away from the junction. Eventually a state of equilibrium (electrically neutral situation) will occur producing a "potential barrier" zone around the area of the junction as the donor atoms repel the holes and the acceptor atoms repel the electrons. Since no free charge carriers can rest in a position where there is a potential barrier the regions on both sides of the junction become depleted of any more free carriers in comparison to the N and P type materials away from the junction. This area around the junction is now called the Depletion Layer.

THE PN JUNCTION

The total charge on each side of the junction must be equal and opposite to maintain a neutral charge condition around the junction. If the depletion layer region has a distance D, it therefore must therefore penetrate into the silicon by a distance of Dp for the positive side, and a distance of Dn for the negative side giving a relationship between the two of Dp.NA = Dn.ND in order to maintain charge neutrality also called equilibrium.



PN JUNCTION DIODE:



As the N-type material has lost electrons and the P-type has lost holes, the N-type material has become positive with respect to the P-type.

Then the presence of impurity ions on both sides of the junction cause an electric field to be established across this region with the N- side at a positive voltage relative to the P-side. The problem now is that a free charge requires some extra energy to overcome the barrier that now exists for it to be able to cross the depletion region junction. This electric field created by the diffusion process has created a "built-in potential difference" across the junction with an open-circuit (zero bias) potential of:

$$E_o = V_T \ln\left(\frac{N_D . N_A}{n_i^2}\right)$$

Where: Eo is the zero bias junction voltage, VT the thermal voltage of 26mV at room temperature, ND and NA are the impurity concentrations and ni is the intrinsic concentration.

A suitable positive voltage (forward bias) applied between the two ends of the PN junction can the free electrons and holes with the extra energy. The external voltage required to overcome this potential barrier that now exists is very much dependent upon the type of semiconductor material used and its actual temperature.

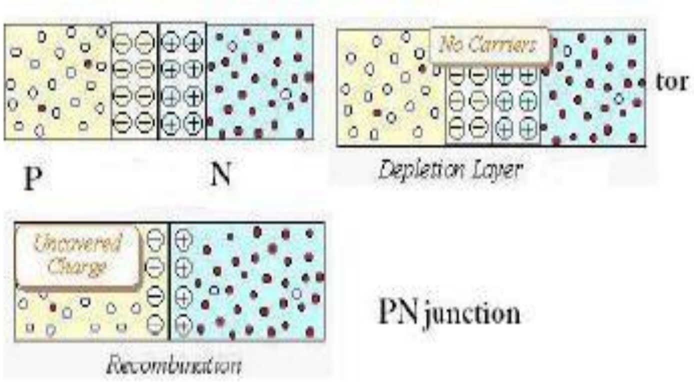
Typically at room temperature the voltage across the depletion layer for silicon is about 0.6 - 0.7 volts and for germanium is about
0.3 - 0.35 volts. This potential barrier will always exist even if the device is not connected to any external power source.

The significance of this built-in potential across the junction, is that it opposes both the flow of holes and electrons across the junction and is why it is called the potential barrier. In practice, a PN junction is formed within a single crystal of material rather than just simply joining or fusing together two separate pieces.

Electrical contacts are also fused onto either side of the crystal to enable an electrical connection to be made to an external circuit. Then the resulting device that has been made is called a PN junction Diode or Signal Diode.

DEPLETION LAYER PN JUNCTION

If one side of crystal pure semiconductor Si(silicon) or Ge(Germanium) is doped with acceptor impurity atoms and the other side is doped with donor impurity atoms , a PN junction is formed as shown in figure.P region has high concentration of holes and N region contains large number of electrons.



As soon as the junction is formed, free electrons and holes cross through the junction by the process of diffusion. During this process , the electrons crossing the junction from N- region into P-region , recombine with holes in the P-region very close to the junction. Similarly holes crossing the junction from the P-region into the N-region, recombine with electrons in the N-region very close to the junction. Thus a region is formed, which does not have any mobile charge very close to the junction. This region is called the depletion layer of pn junction.

In this region, on the left side of the junction, the acceptor atoms become negative ions and on the right side of the junction, the donor atoms become positive ions as shown in figure.

FUNCTION OF DEPLETION LAYER OF PN JUNCTION

An electric field is set up, between the donor and acceptor ions in the depletion layer of the pn junction .The potential at the N-side is higher than the potential at P-side. Therefore electrons in the N- side are prevented to go to the lower potential of P-side. Similarly, holes in the P-side find themselves at a lower potential and are prevented to cross to the N-side. Thus, there is a barrier at the junction which opposes the movement of the majority charge carriers. The difference of potential from one side of the barrier to the other side of the barrier is called potential barrier. The potential barrier is approximately 0.7V for a silicon PN junction and 0.3V for germanium PN junction. The distance from one side of the barrier to the other side is called the width of the barrier, which depends on the nature of the material.

CURRENT EQUATION:

To derive the expression for the total current as function of applied voltage (neglect the barrier width)

When diode is forward biased, holes injected from the p to n material. The concentration p_n of holes in the n-side is increased above equilibrium value p_{no}

$$I = I_o\,[e^{(V/\eta V_T)} - 1]$$

where

I – diode current

I_o – diode reverse saturation current at room temperature

V – external voltage applied to the diode

Ƞ - a constant, 1 for Ge and 2 for Si

V_T = kT/q = T/11600, thermal voltage

K – Boltzmann‘s constant (1.38066x10^-23 J/K)

q – charge of electron (1.6x10^-19 C)

T – temperature of the diode junction

At room temperature (T=300 K), V_T = 26mV. Substituting this value in current equation,

$$I = I_o[e^{(40\,V/\eta)} - 1]$$

For germanium diode,

$I = I_o\,[e^{40V} - 1]$since Ƞ =1 for Ge

For silicon diode,

since Ƞ =2 for Si. $I = I_o[e^{20V} - 1]$

If the value of applied voltage is greater than unity, then the equation of diode current for germanium,

$$I = I_o\,(e^{40V})$$

and for silicon,

$$I = I_o\,(e^{20V})$$

when the diode is reverse biased, its current equation may be obtained by changing the sign of voltage V. Thus diode current with reverse bias is

$$I = I_o\,[e^{(-V/\eta V_T)} - 1]$$

If $V >> V_T$ then the term $e^{(-V/\eta VT)} << 1$ therefore I=Io termed as reverse saturation current, which is valid as long as the external voltage is below the breakdown value.