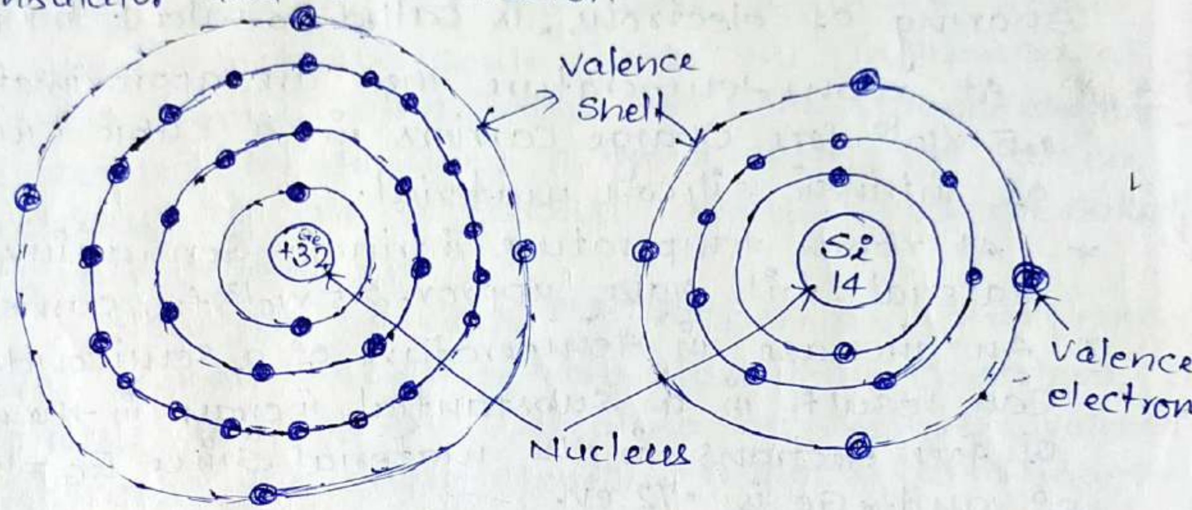
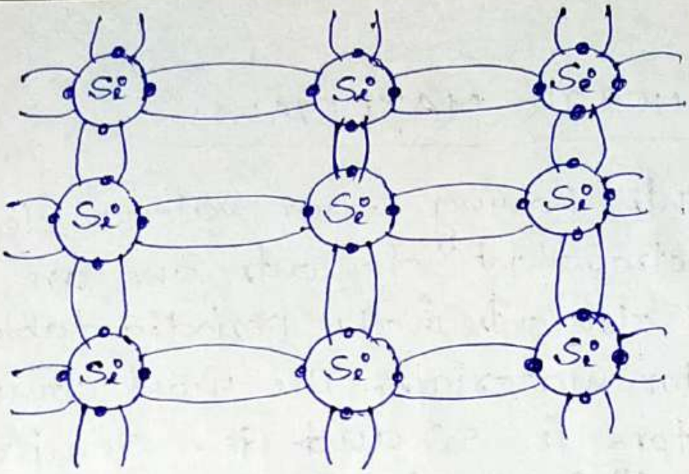
SEMICONDUCTOR MATERIALS -

The elements having four valence electrons are called tetravalent elements and are classified as group IV elements in the periodic table, are called semiconductor materials. The most commonly popular semiconductors is Si and Ge. Semiconductors have conductivity level between extremes of an insulator and a conductor.



(Atomic structure of Ge and Si atom)

* When there are four electrons in the outermost orbit the semiconductor material is referred to as pure or intrinsic semiconductor.
* The characteristics of intrinsic semiconductors can be changed as per the requirement by the process of mixing impurity called doping.
* The characteristics of pure semiconductor can be changed significantly by the application of heat, light, external radiation.
* They are most suitable for consideration in the development of heat and light sensitive devices.



Co-valent-bonding of the silicon atom.

* A bonding of atoms, strengthened by the sharing of electrons, is called co-valent bonding.
* At room temperature there are approximately 1.5×10^{10} free charge carriers in a cubic cm. of intrinsic silicon material.
* At room temperature intrinsic Germanium material will have approx. 2.5×10^{13} free carriers/cm.
* An increase in temperature of a semiconductor can result in a substantial increase in the number of free electrons in the material since $E_G = 1.12$ for Si and for Ge is .72 eV.
* Semiconductor materials such as Ge and Si show a reduction in resistance, with increase in temperature are said to have a negative temperature coefficient. At absolute zero temperature semiconductors behave as perfect insulators. As temperature increases, the electrons acquire thermal energy and some are available as free electrons. Due to increased number of free electrons, the resistance of the semiconductor material decreases, as temperature increases.

ENERGY BAND THEORY -

Each shell of an atom is associated with an energy level. An electron orbiting very close to the nucleus in the first shell is very much tightly bound to the nucleus and possesses only a small amount of energy. Greater the distance of an electron from the nucleus, the greater is its energy. In solids, atoms are brought close together. In such a case, outershell electrons are shared by more than one atom. So these electrons come under the influences of forces from other atoms too. The valence electrons are shared by forming a bond with the valence electrons of an adjacent atom which are called co- valent bond.

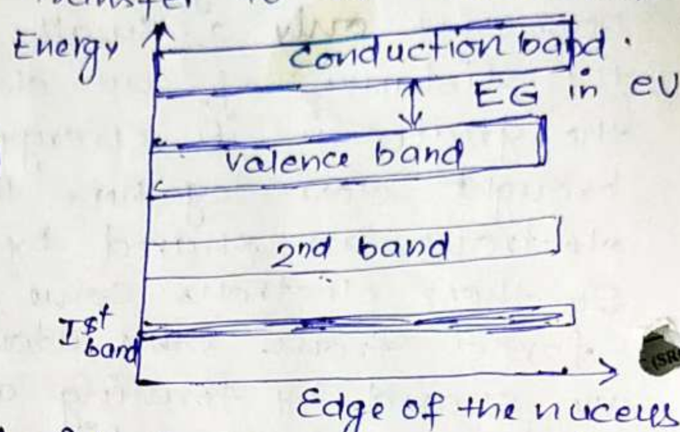
Now the valence electrons possess highest energy level. When such electrons form the co-valent bonds, due to the coupling between the valence electrons, the energy levels associated with the valence electrons merge into each other. This merging forms an energy band.

So instead of the presence of widely seperated energy levels, the closely spaced energy levels are present in a solid. which are called energy bands.

* The energy band formed due to merging of energy levels associated with the valence electrons is called Valence band.

* The energy band formed due to merging of energy levels associated with the free electrons is called conduction band.
* Normally, in semiconductors conduction band is empty and valence band is completely filled at 0K.

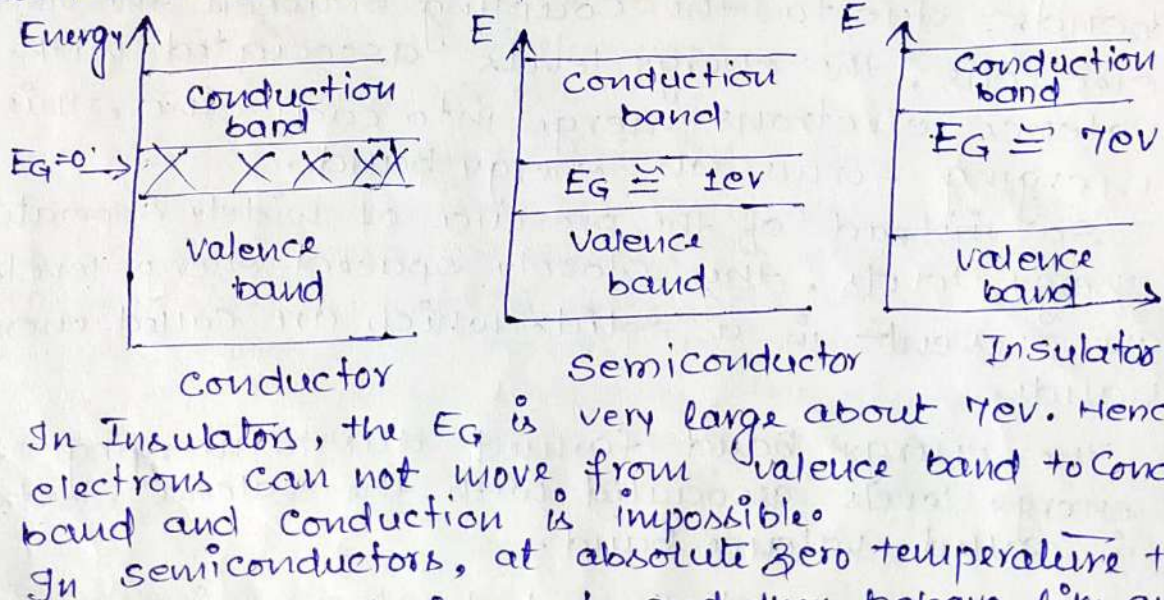
* An energy band which seperates the conduction band and valence band is called forbidden band or forbidden gap, and is denoted by E_G. This E_G represents amount of energy required to be given to valence electrons to transfer to the conduction band.



(Energy-Band diagram)

Classification of Materials On Energy Band diagram.

In conductors, large number of free electrons exist at normal room temperature so $E_G = 0$. The valence and conduction bands overlap.



Conductor   Semiconductor   Insulator

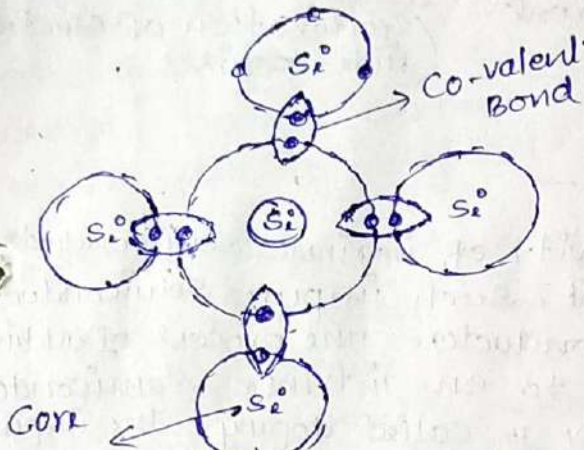
In Insulators, the E_G is very large about 7eV. Hence electrons can not move from valence band to conduction band and conduction is impossible.

In semiconductors, at absolute zero temperature the conduction band is empty and they behave like an insulator. At room temperature some electrons move from valence band to conduction band due to smaller band gap ($\simeq$ 1eV), hence conduction is possible paratially. As temperature increases, large number of free electrons are available resulting increased conductivity.

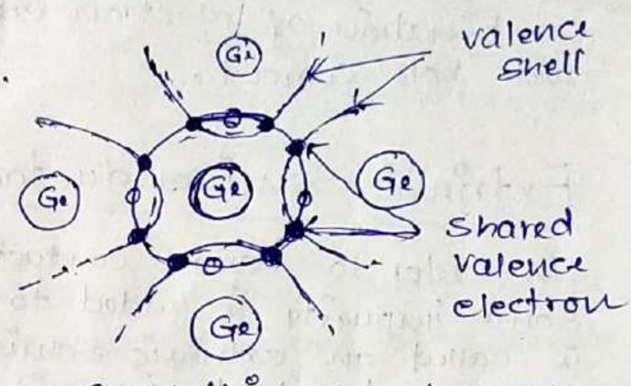
E_G for $Si = 1.12$ eV   for $Ge = .72$ eV

Intrinsic Semiconductor

A sample of semiconductor in its purest form is called an intrinsic semiconductor. The conductivity of intrinsic semiconductor is very poor and practically can not be used for manufacturing of the semiconductor devices.



Crystalline structure of Silicon (+14)



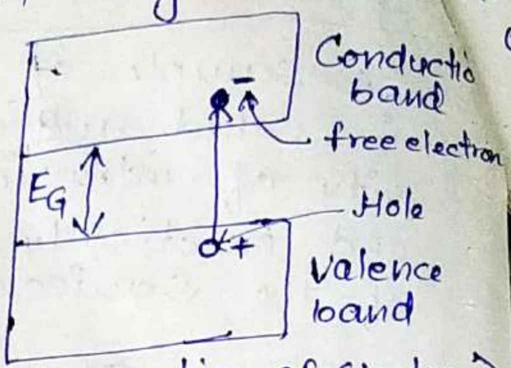
Crystalline structure of Germanium (+32)

* There are four electrons in the valence shell of intrinsic semiconductor. In crystalline structure 4 electrons of an atom share the 4 electrons of an adjacent atom, forming co-valent bonds. Hence the outermost shells of all the atoms are completely filled with 8 electrons and are very stable, and are tightly bound to the nucleus. Hence at, below room temperature, there are no free electrons and conductivity of such intrinsic materials is very poor and they behave as an insulator. Therefore intrinsic semiconductors are not suitable for manufacturing of electronic devices.

Electron-Hole pairs —

When a valence electron absorbs the energy, it leaves the valence band and becomes free and enters in the conduction band. When a valence electron drifts from the valence band, a vacancy is created in the valence band which is denoted as Hole.

The Hole is treated as positively charged. Electron & hole is generated in pairs. Generation of electron hole pairs due to temperature is called thermal generation in semiconductors. In a semiconductor total current is combination of electron current and hole current.



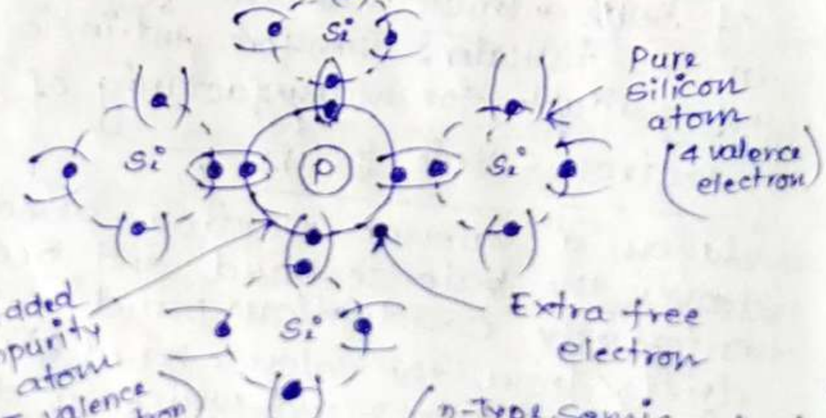
(Generation of Electron Hole pairs)

Extrinsic Semiconductor —

In order to increase conductivity of intrinsic semiconductor some impurity is added to it. Such impure semiconductor is called an extrinsic semiconductor. The process of adding tri or pentavalent impurity to an intrinsic semiconductor to improve its conductivity is called doping. The impurity added is called dopant, and resulting doped semiconductor material is called extrinsic semiconductor. There are two types of impurities used to obtain two different types of extrinsic semiconductors called n-type and p-type.

N-type Semiconductor —

When a pentavalent impurity atom (As, bismuth, P etc) is added to intrinsic semiconductor its each atom donates one free electron and such doping is called donar doping, and referred as n-type semiconductor.



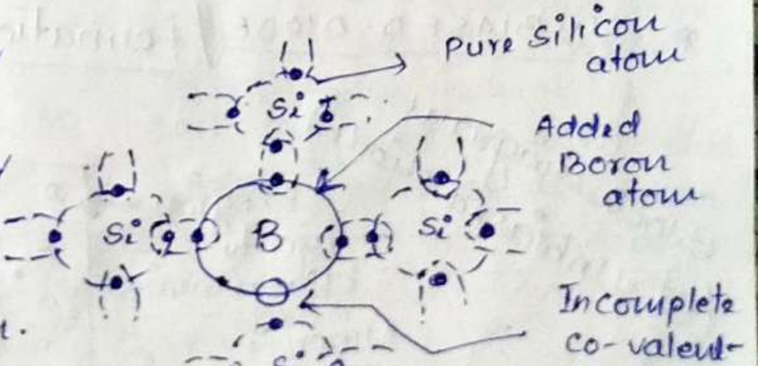
(n-Type semiconductor formation)

The doped phosphorus (P) atom fits in the silicon (IV) crystal in such a way that its four valence electrons form co-valent bonds with four adjacent silicon atoms. Fifth electron of P has no chance to form co-valent bond and hence treated as free electron. Each phosphorus atom added to Si atom donates one free electron which increases the conductivity of n-type semiconductor. The number of free electrons can be controlled by the doping concentration. In n-type semiconductor majority charge carriers are <u>electrons</u> and few <u>holes</u> are available as minority charge carriers. Current in n-type semiconductors are mainly due to majority charge carriers.

<u>p-type Semiconductors</u> -

When a trivalent impurity atom is added to the crystal of pure semiconductor, its each atom creates one hole (vacancy of an electron) which is ready to accept an electron, hence is called <u>acceptor impurity</u>. On adding trivalent atom Boron in silicon crystal, its three valence electrons form co-valent bonds with the three adjacent atoms of silicon and there be shortage of one electron to form fourth co-valent bond. Thus each Boron atom added into silicon crystal creates a <u>Hole</u>' which is ready to accept an electron.

In p-type semiconductor current is mainly due to holes. The number of holes can be controlled by the impurity concentration. Along with Holes as majority charge carriers <u>few electrons</u> are also available as <u>minority charge carriers</u>.

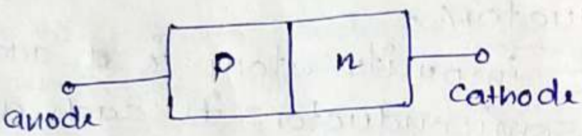


(p-type Semiconductor)

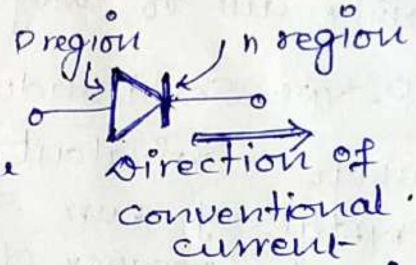
(Di + electrode)

P-N Junction Diode –

When P and N type semiconductors are chemically combined with each other, a popular semiconductor device is formed called p-n junction diode. Diode has two electrodes. The p-region acts as anode and n region as cathode. The arrowhead in the symbol indicates the direction of conventional current, which can flow when an external voltage is connected in a specific manner across the diode.



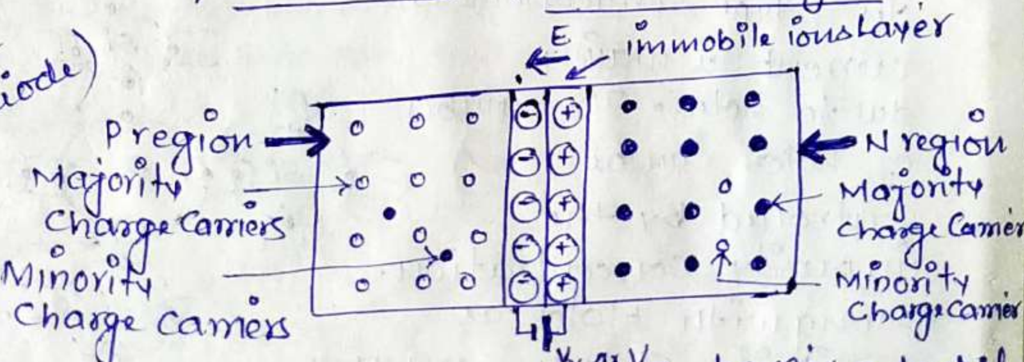
(Block diagram of Diode)



(Symbol of Diode)

Diode allows current flow in one direction under biased condition. Depending upon the polarity of the d.c. voltage externally applied to it, diode can be forward biased or reverse biased.

* UNBIASED DIODE / Formation of Depletion Region



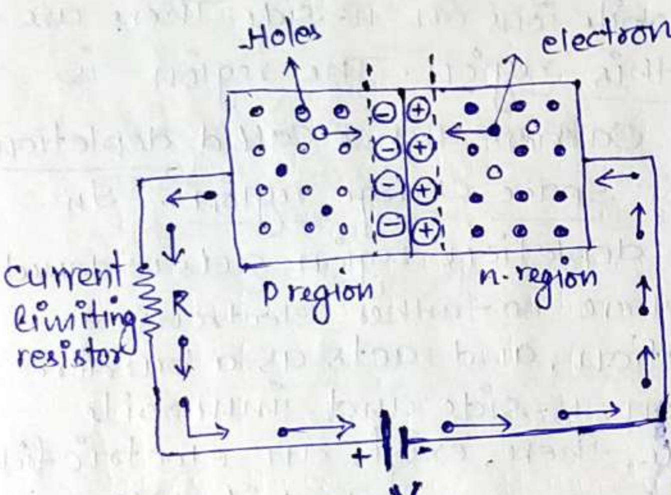
(Block diagram of Unbiased diode)

In a given material if the doping is not uniform, charge carriers start moving from high concentration area towards low concentration area, to achieve uniform concentration all over the material. This process is known as diffusion.

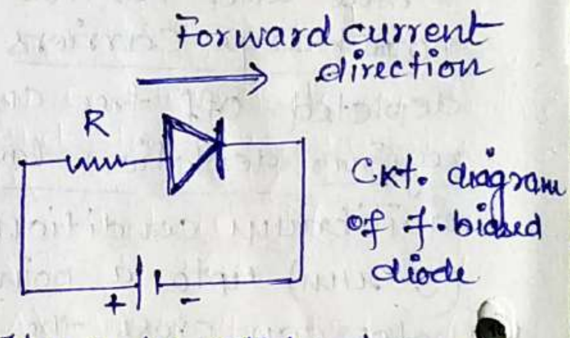
on p-side there are large number of holes while on n-region there are large number of free electrons. Hence, initially overall P-N junction acts as nonuniformly doped material. When P-type and n-type materials are chemically combined with a special fabrication technique, electrons start moving from n-side towards p side and holes from p side diffuse into n-side.
The free electrons diffusing from n-side towards p-region, recombine with the holes of the atom. Due to gain of additional negatively charged free electrons, these atoms become negative immobile ions, near the junction in p-region. Similarly a thin layer of positive immobile ions near the junction in n-region is formed. Thus there exists a wall near the junction with negative immobile ions on P side and positive immobile ions on n-side. There are no charge carriers in this region. The region is depleted off free charge carriers hence called depletion region, depletion layer or space charge region. In equilibrium condition, the depletion region gets widened (μ um) upto a point where no further electrons or holes can cross the junction, and acts as a barrier. Due to immobile (+)ions on n-side and immobile negative ions on p-side, there exists an electric field across the junction. This creates potential difference across the depletion region known as barrier potential, junction potential, built-in potential or cut-in voltage of p-n junction denoted as V_γ or V_T.
The barrier potential depends on
(a) Type of semiconductor
(b) donor or acceptor impurity added.
(c) Temperature
value of V_γ for $Si = .6V$ & for $Ge = .2V$

Forward Biasing of p-n Junction diode

when an external d.c. voltage is connected in such a way that p-region is connected to positive of the external d.c. voltage and n-region to negative of the external d.c. voltage then the junction is said to be forward biased. As soon as connection is made, holes are repelled by the positive terminal of battery and electrons by the negative terminal of battery resulting that, both the electrons and holes are driven towards the junction where they recombine. The large number of movement of majority charge carriers through the junction constitutes a large current flow (mA) in the semiconductor. The junction offers low resistance and width of depletion region reduces in the forward biased condition.

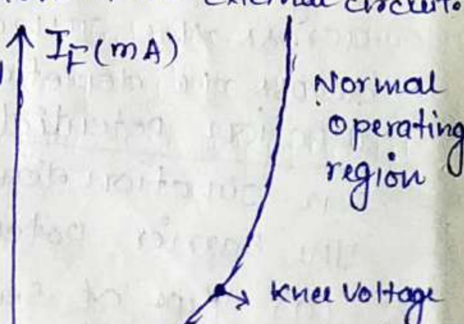


(Block diagram of p-n junction diode)



" It may be noted that though there is movement of both electrons and holes inside the crystal, only free electrons move in the external circuit."

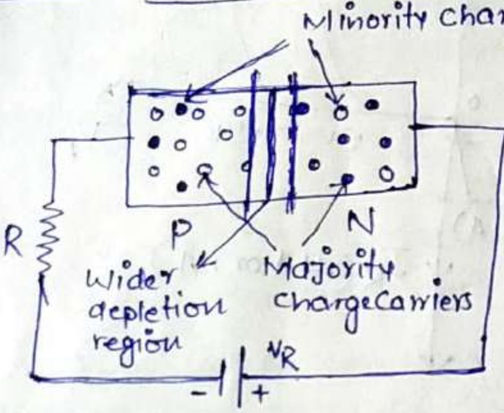
V-I characteristic of Forward biased Diode



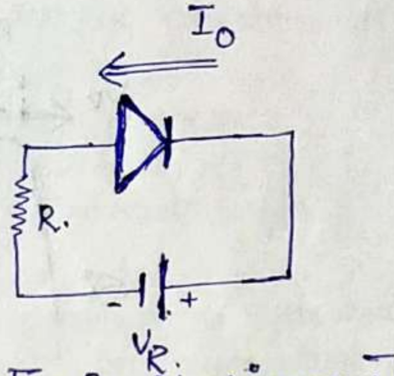
Forward current rises exponentially with the applied forward voltage. beyond a threshold voltage (·7V for Si and ·3V for Ge). For $V_F < V_{Th}$ current flow is negligible. If forward voltage is increased beyond a certain safe value, it will produce an extremely large current which may destroy the junction due to overheating. Ge diode can stand temperatures around 100°C whereas

Si diodes can function upto 175°c.

Reverse Biased P-N Junction –



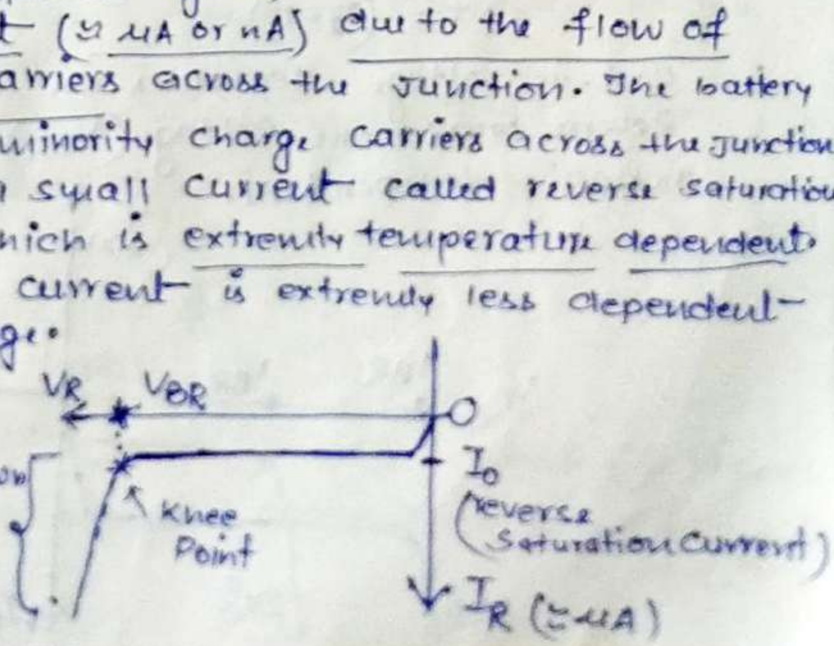
[Block diagram of Reverse biased p-n junction diode]



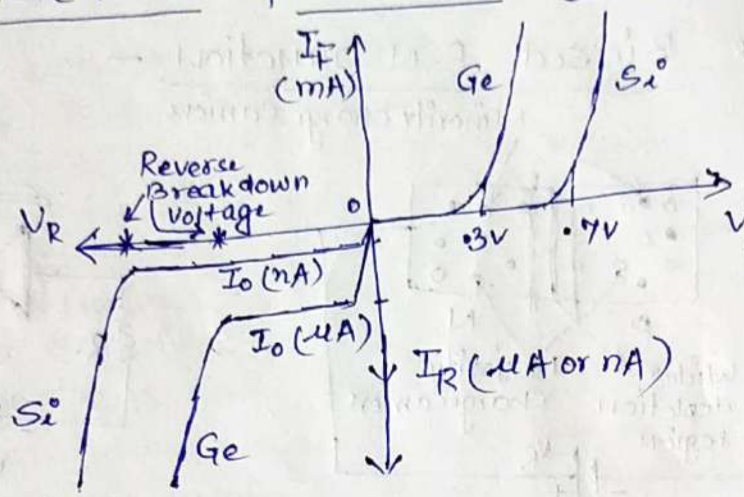
[circuit diagram of P-n junction diode]

When p-region of diode is connected to the ~~positive~~ negative terminal of battery and n-region to the positive terminal of battery (V_R) the junction is said to be reverse biased. In this case, holes are attracted by the negative terminal of battery and electrons by positive terminal, so that both holes and electrons (majority charge carriers) move away from the junction. Since there is no electron-hole combination, no current flows due to majority charge carriers and junction offers high resistance (wider depletion region). Yet there is small amount of current ($\simeq \mu A$ or nA) due to the flow of minority charge carriers across the junction. The battery drives these few minority charge carriers across the junction thereby producing a small current called reverse saturation current. I_0 or I_s, which is extremly temperature dependent. Reverse saturation current is extremly less dependent upon reverse voltage.

(Characteristics of Reverse Biased p-n junction diode)



V-I Characteristics of Si and Ge Diode –



Reverse breakdown voltage (V_{BR}) for Si diode is higher than that of the Ge diode. The cut-in voltage for Germanium (Ge) diode is 0.3V while for silicon diode is 0.7V.

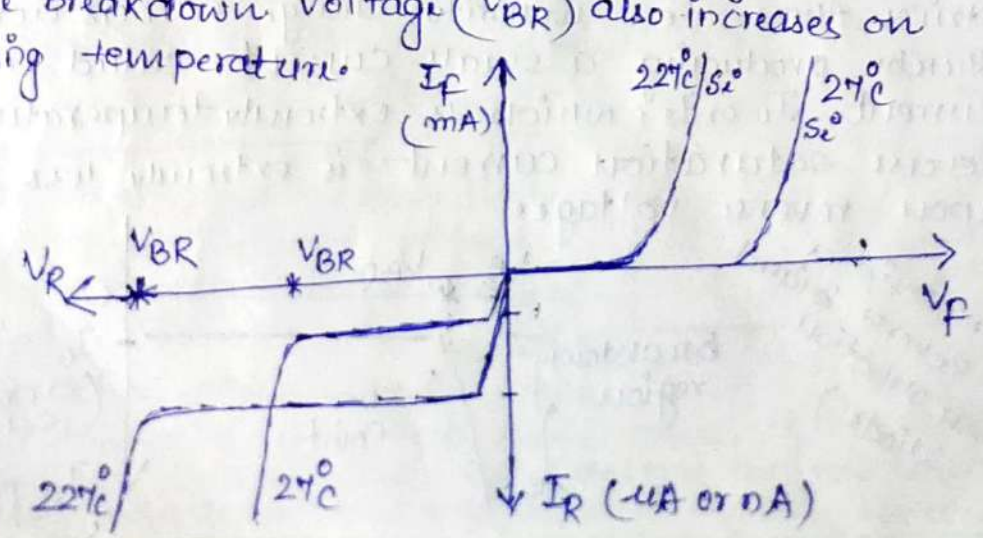
Effect of Temperature on : DIODE –

1. The reverse saturation current doubles for every 10°C rise in temperature.

$$I_{O2} = 2^{\frac{\Delta T}{10}} \cdot I_{O1}$$

where I_{O2} → Reverse saturation current at T_2 temperature
I_{O1} → Reverse saturation current at T_1 Temp.
$\Delta T = (T_2 - T_1)$

2. Cut-in voltage decreases on increasing temperature.
3. Reverse breakdown voltage (V_{BR}) also increases on increasing temperature.



Diode current Equation -

The relationship between applied voltage V and the diode current I is exponential and is mathematically given by the equation called diode current equation. It is expressed by

$$I = I_0 \left[e^{\frac{V}{\eta V_T}} - 1 \right] \text{ Ampere}$$

where I_0 is the reverse saturation current in A

$\eta = 1$ for Ge and 2 for Si

V_T = Voltage equivalent of temperature in volts and indicates dependence of diode current on temperature.

$$V_T = KT$$

where K = Boltzmann Constt $= 8.62 \times 10^{-5}$ eV/°K

and T is temperature in °K.

At room temperature of 27°C $T = 273 + 27 = 300$°K

and $V_T = 8.62 \times 10^{-5} \times 300 \cong 26$ mV

and $V_T = \frac{T}{\frac{1}{K}} = \frac{T}{11600}$.

Nature of V-I characteristics of Diode from current Equation.

In forward biased condition V must be taken positive and we get forward current which is also positive.

Diode current equation is $I = I_0 \left(e^{\frac{V}{\eta V_T}} - 1 \right) A$

In forward biased condition $V = +V_F$, hence exponential term is positive. Due to this $e^{\frac{V_F}{\eta V_T}} >>>> 1$.

hence neglecting 1 we get the equation for the forward current as,

$$I_F = I_0 \, e^{\frac{V_F}{\eta V_T}}$$

which indicates that once bias voltage (V_F) exceeds cut-in voltage, the forward current increases exponentia

In reverse biased condition, the bias voltage V is treated negative and due to this exponential term has negative sign. So $e^{\frac{-V_R}{\eta V_T}} <<<< 1$, hence neglecting exponential term w.r. to 1, we get the reverse current.

$$I_R = -(I_0) = -I_0$$ which is reverse saturation current. Negative sign indicates that current is flowing in opposite direction.

In unbiased condition since applied voltage $V=0$, hence current flowing through diode is zero.

Resistance of Diode —

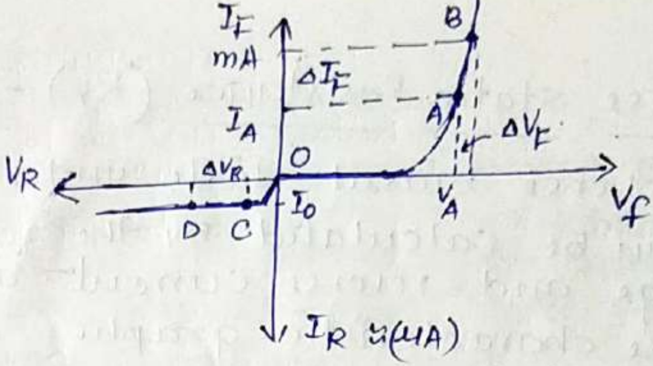
Due to the nonlinear shape of characteristic curve the resistance level of diode is variable. The resistance offered by the diode in forward biased condition is called forward resistance.

Static forward resistance — This is resistance offered by a forward biased diode used in d.c. circuits. This resistance is denoted by R_f and is calculated at a particular point on the forward characteristic graph.

$$R_f = \frac{V}{I} \text{ at point A}$$

Dynamic Forward Resistance (r_f) It is resistance offered by a forward biased diode used in a.c. circuits. It is measured by taking the ratio of average value of voltage and current between two points on the forward characteristic graph.

$$r_f = \frac{\Delta V_F}{\Delta I_F} \text{ between A and B pts.}$$



Generally, the value of r_f is very small of the order of few ohms in the normal operating region.
The dynamic forward resistance can also be obtained as

$$r_f' = \frac{26\,mV}{I_F} \ll r_f$$

This gives resistance only for the junction and does not include d.c. resistance of semiconductor material, hence is slightly smaller than r_f.

$$r_f = \frac{\Delta V_F}{\Delta I_f} = \frac{1}{\left(\frac{dI}{dV}\right)}.$$

$\therefore \; I = I_0\left(e^{\frac{V}{\eta V_T}} - 1\right)$ hence $\frac{dI}{dV} = I_0\left[\frac{1}{\eta V_T} e^{\frac{V}{\eta V_T}}\right]$

$$\frac{dI}{dV} = \frac{I_0 e^{\frac{V}{\eta V_T}}}{\eta V_T}, \quad r_f = \frac{dV_f}{dI_f} = \frac{\eta V_T}{I_0 e^{\frac{V}{\eta V_T}}}$$

$\therefore \; I = I_0 e^{\frac{V}{\eta V_T}} - I_0$ or $I + I_0 = I_0 e^{\frac{V}{\eta V_T}}$

$$\boxed{r_f = \frac{\eta V_T}{I + I_0}}$$ is mathematical expression for dynamic resistance.

Reverse Resistance of Diode – Resistance offered by p-n junction diode in reverse biased condition is called reverse resistance of diode. The value of reverse resistance is large.

Reverse static Resistance (R_r) - This is the resistance of reverse biased diode under d.c. conditions. It can be calculated by the ratio of reverse voltage and reverse current at any point on reverse characteristic graph.

$$R_r = \frac{V_R}{I_0} \text{ at point C}$$

Reverse dynamic resistance (r_r) -

This is the resistance of reverse-biased diode under a.c. conditions (used in a.c. circuits). It is calculated by the ratio of incremental change in the reverse voltage to the corresponding change in reverse current.

$$r_r = \frac{\Delta V_R}{\Delta I_R} \text{ between C \& D pts.}$$

$$= \frac{\Delta V_R}{I_0}$$

Example - The reverse saturation current of a silicon diode is 3nA at 27°C. Calculate

(I) Reverse saturation current at 82°C?

(II) Forward current at 82°C if applied voltage is 0.25 V.

Soln:

(I) $I_{01} = 3nA$ at $27°C$ $T_2 = 82°C$

$$\Delta T = 82 - 27 = 55°C$$

$$I_{02} = 2^{\left(\frac{\Delta T}{10}\right)} \times I_{01} = 2^{\left(\frac{55}{10}\right)} \times 3 = 135.764 \text{ nA}$$

(II) $V = 0.25V$, $I_{02} = 135.764$ nA at $82°C$

$$I_f = I_0\left(e^{\frac{V}{\eta V_T}} - 1\right) = 135.764 \times 10^{-9}\left[e^{\left(\frac{.25}{2 \times .0306}\right)} - 1\right]$$

$$V_T = \frac{T}{11600} = \left(\frac{82+273}{11600}\right) = .0306\text{ V} \quad \eta = 2 \text{ for si}$$

$$= 7.934\ \mu A$$

P-n Junction diode Capacitance–

In the semiconductor diode, there are two capacitive effects to be considered. In the reverse biased diode we have the transition or depletion region capacitance (C_T), whereas in the forward biased diode we have diffusion or storage capacitance (C_D).

Transition Capacitance (C_T) – when a p-n junction is reverse biased, the depletion region acts like an insulator or as dielectric material. The P and N regions of diode have less resistance and acts as the plates of capacitor. Therefore, reverse biased diode acts as parallel plate capacitor. This junction capacitance is called transition or space charge capacitance (C_T). Mathematically, transition capacitance is determined by formula.

$$C_T = \frac{\epsilon A}{d} \simeq 40-80 \text{ PF}$$

where $\epsilon = \epsilon_0 \epsilon_r$

ϵ_0 = ~~relative~~ permittivity of free space

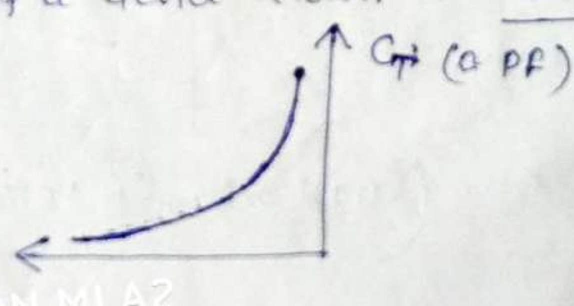
ϵ_r = relative permittivity of semiconductor material.

= 16 for Ge & 12 for Si

A = Area of cross section

d = width of depletion Layer.

Since, thickness of depletion layer depends on amount of reverse bias. On increasing reverse potential transition capacitance decreases. This property of variable capacitance possessed by a reverse biased P-n junction is used in construction of a device known as Varicap or Varactor.



Diffusion Capacitance — (C_D)

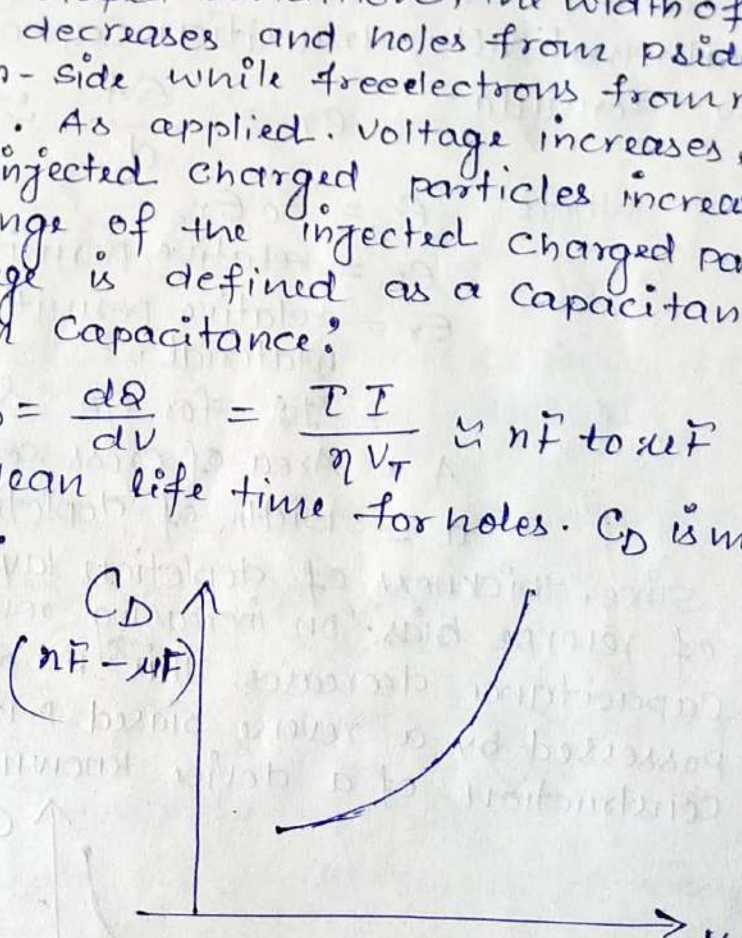
The capacitive effect is also present when the junction is forward biased. It is called diffusion capacitance to account for the time delay in moving charges across the junction by diffusion process. Due to this fact, this capacitance can not be identified in terms of dielectric and plates. It varies directly with the magnitude of forward current.

It is seen that when a forward biased p-n junction is suddenly reverse biased, a reverse current flows which is large initially but gradually decreases to the level of saturation current I_0. This effect can be linked to the discharging current of a capacitor. Since the number of charge carriers left in depletion layer is proportional to forward current.

In forward biased condition, the width of depletion region decreases and holes from p side get diffused in n-side while free electrons from n-side move into p-side. As applied voltage increases, concentration of injected charged particles increases. This rate of change of the injected charged particles with applied voltage is defined as a capacitance called diffusion capacitance:

$$C_D = \frac{dQ}{dV} = \frac{\tau I}{\eta V_T} \simeq nF \text{ to } \mu F$$

where τ = Mean life time for holes. C_D is much larger than C_T.



(Graph between C_D verses V_F)

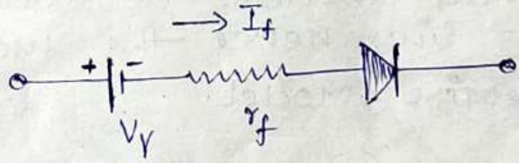
Circuit Models of a Diode —

The diode is required to be replaced by the equivalent circuit in many practical circuits, for the analysis purpose. Such an equivalent circuit of a diode is called circuit Model of a diode. There are three different methods of replacing diode by its circuit model, which are

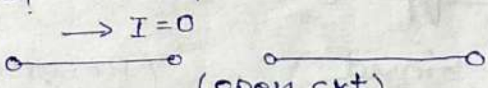
1. Practical diode Model.
2. Ideal diode Model
3. Piecewise linear Model.

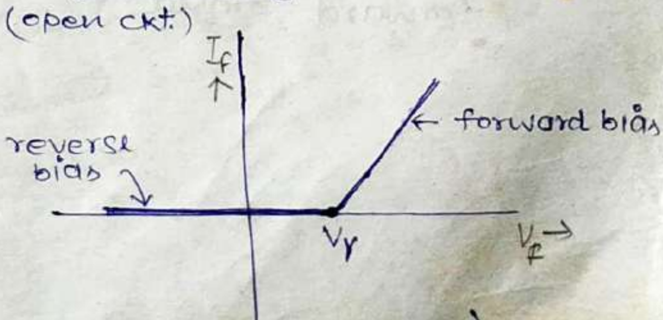
Practical diode Model. —

In forward biased diode the total voltage drop across the diode is V_f, which consists of drop due to barrier potential which is almost equal to cut-in voltage V_γ and the drop across the internal forward resistance r_f of the diode. In reverse biased condition, since reverse saturation current is very small and practically neglected, Hence reverse biased diode is practically assumed to be open circuit. Thus practical diode model consists of a battery equal to cut-in voltage and the forward resistance in series with an ideal diode in forward biased condition.



In reverse biased condition it is open circuited.

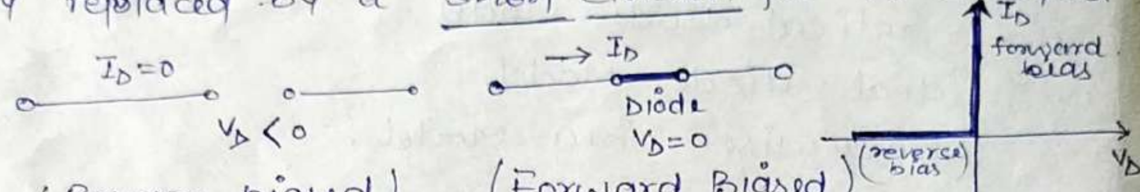




(V-I characteristics)

2. Ideal Diode Model —

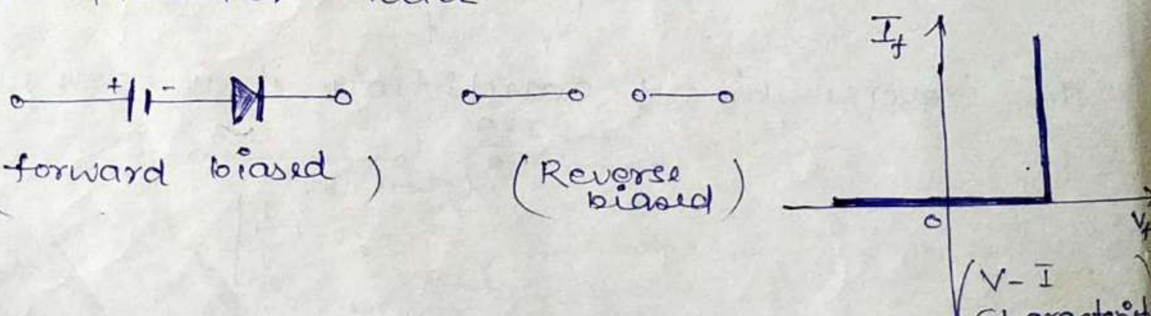
In many cases, as the forward resistance of diode is small and cut-in voltage is also small, the diode is assumed to be an ideal diode. In Ideal diode, it is assumed that it start conducting instantaneously when applied voltage V_D is just greater than zero and the drop across the conducting diode is zero. So conducting diode can be ideally replaced by a short circuit for the analysis.



(Reverse biased) (Forward Biased)

3. Piecewise Linear Model of Diode —

In this model, the forward resistance of diode is neglected and diode is assumed to conduct instantaneously when applied forward voltage V is equal to cut-in voltage V_r. And then it is assumed that current increases instantaneously giving straight line nature of V-I characteristics. In the reversed biased condition when $V < 0$, the diode does not conduct at all and is open circuited. As the method models the diode with the pieces of straight lines hence the model is named as Linear piecewise Model.



(forward biased) (Reverse biased) (V-I Characteristics)