DEPARTMENT OF ELECTRICAL ENGINEERING

GOVERNMENT COLLEGE OF ENGINEERING
KALAHANDI

BHAWANIPATNA

Lecture Notes on Basic Electronics

By

Dr. Deepa Das

Assistant Professor

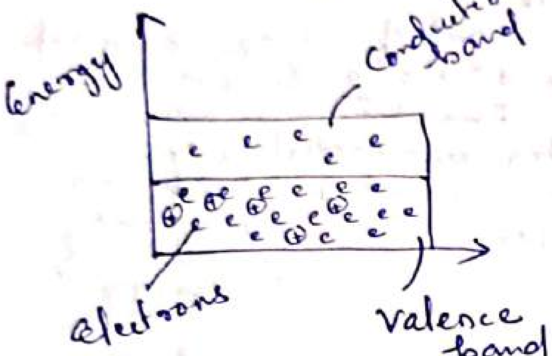
Department of Electrical Engineering

Disclaimer

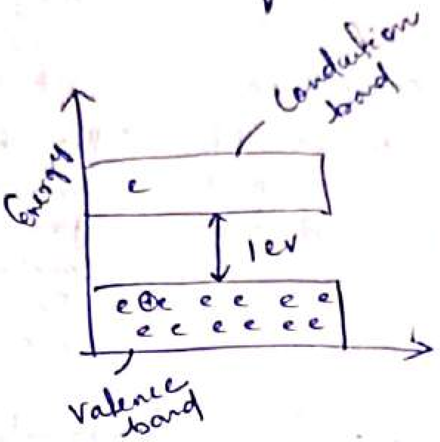
MODULE - I

Classification of Materials

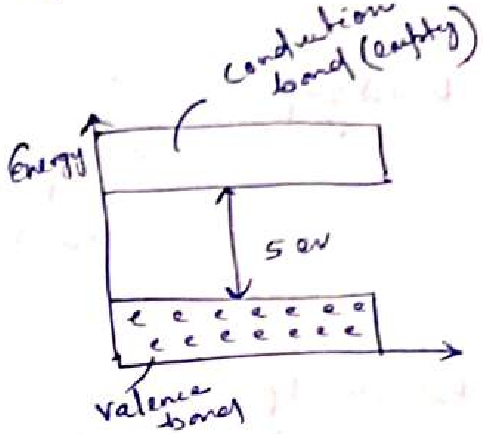
→ The materials are classified based on their Conducting property.



(conductor)
(No forbidden band gap)



(Semiconductor)
(forbidden energy gap ~ 1eV)



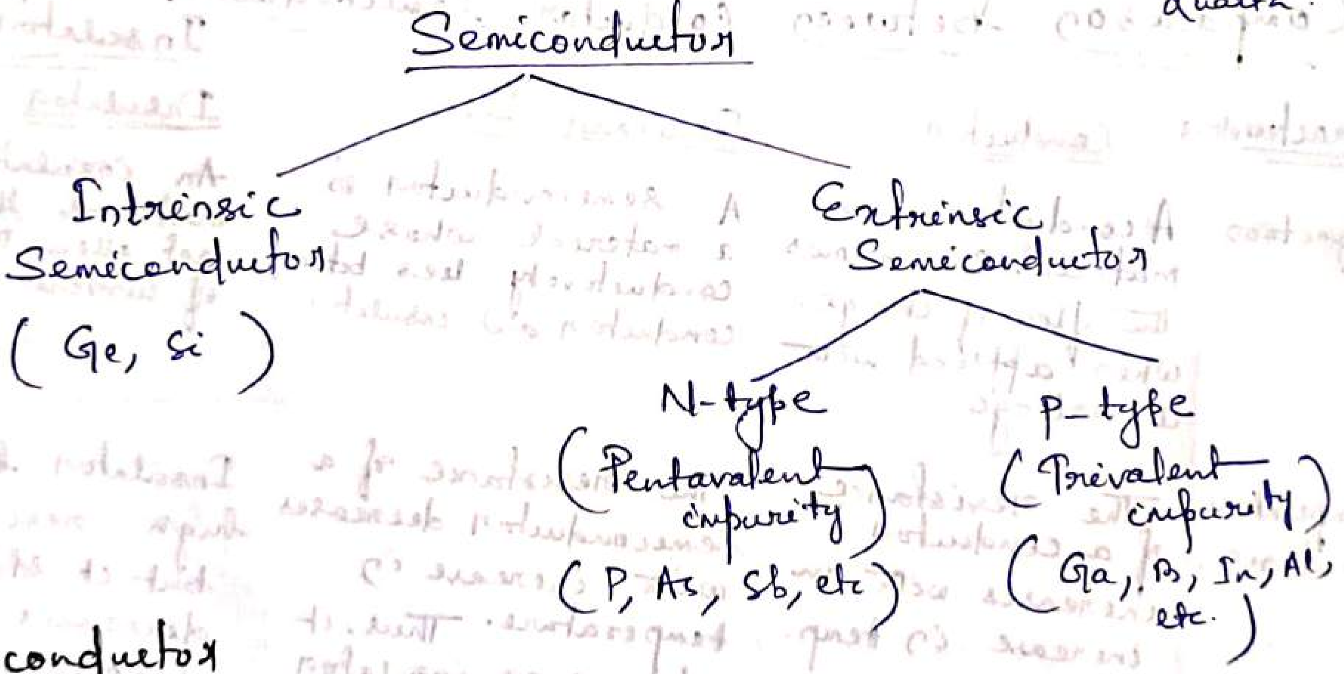
(Insulator)
(forbidden energy gap >~ 5 eV)

Comparison between Conductor, semiconductor and Insulator :

Characteristics	Conductor	Semiconductor	Insulator
1. Definition:	A conductor is a material that allows the flow of charge when applied with a voltage.	A semiconductor is a material whose conductivity lies between conductor and insulator.	An insulator is material that does not allow the flow of current.
2. Temperature dependence:	The resistance of a conductor increases with an increase in temp.	The resistance of a semiconductor decreases with increase in temperature. Thus, it acts as an insulator at absolute zero.	Insulator has ver high resistance but it still decreases with temperature.
3. Conduction:	The conduction in conductors is due to the free electrons in metal bonding.	The conduction in semiconductor is due to the movement of electrons and holes.	There are no free electrons or holes, thus there is no conduction.

Characteristics	conductor	Semiconductor	Insulator
4. Conductivity:	The conductors have high conductivity (10^{-7} $\mho$/m), thus they can conduct electrical current easily.	They have intermediate conductivity (10^{-7} $\mho$/m to 10^{-13} $\mho$/m), thus they can acts as insulator and conductor at different conditions.	They have very low conductivity (10^{-13} $\mho$/m), thus they donot allow current flow.
5. Bandgap:	There is no or low energy gap between the conduction and valance band of a conductor.	The band gap of semiconductor is greater than the conductor but smaller than an insulator i.e 1ev.	The band gap in insulator is huge (~5ev), which needs an enormous amount of energy.
6. Resistivity:	Low (10^{-5} Ω/m) eg. silver, copper, Aluminium	Normal (10^{-5} Ω/m to 10^{5} Ω/m) eg. Si, Ge, GaAs, GaAsP, GaN	very high (10^{5} Ω/m) eg. Glass, Rubber, Quartz.

Semiconductor Classification :-



Semiconductor

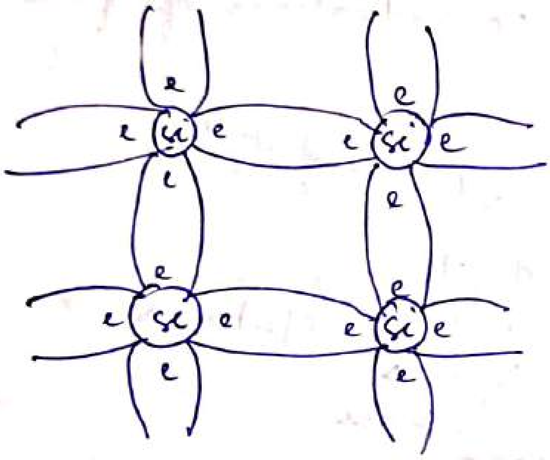
Semiconductor materials may be classified into two classes eg. intrensic (or pure) semiconductors and entrinsic (or impure) semiconductor.

→ An intrinsic semiconductor is one which is made up of the semiconductor material in its extremely pure form.

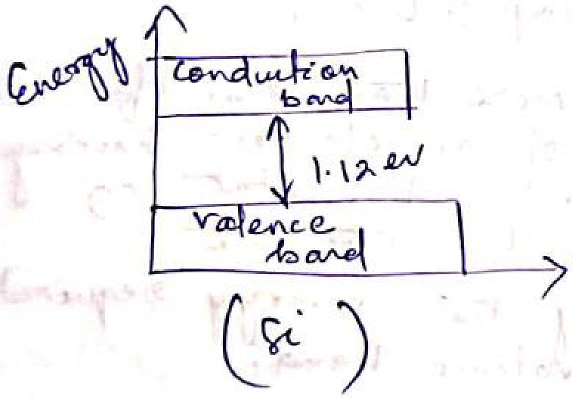
→ A semiconductor is intrinsic when the impurity content is less than one part in 100 milion parts of the semiconductor.

→ Silicon has 14 orbiting electrons and Germanium has 32 electrons.

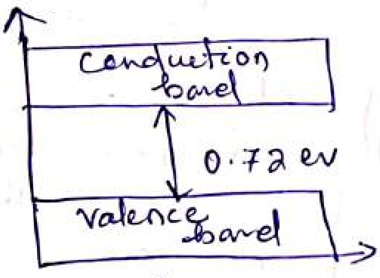
→ for Ge and Si, there are four electrons in the outermost shell which are referred to as valence electrons. Atoms ~~that~~ those have four valence electrons are called tetravalent atom.



→ In a pure Silicon or Germanium crystal, the four valence electrons of one atom form a bonding arrangement with four adjoining atoms. The bonding of atoms, strengthened by the sharing of electrons is called covalent bonding.



(Si)



(Ge)

→ for semiconductors at a temperature of absolute zero, the valence band is usually full and there may be no electrons in the conduction band. Hence, conductivity of intrinsic semiconductors at absolute zero temperature Zero.

→ Since energy required in transferring electrons from valence band to conduction band is more in case of Silicon than that in case of Germanium. So, the conductivity of Silicon will be less than that of Germanium at room temperature.

→ Breaking the covalent bond is equivalent to an electrons from valence band to the conduction band.

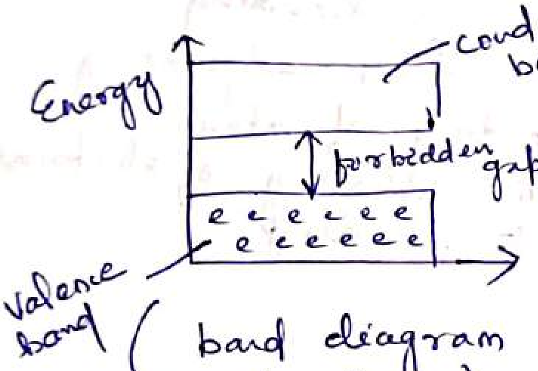
When an electron breaks a covalent bond of an intrinsic semiconductor and moves away, a vacancy is created in the broken covalent bond.

→ The vacancy constitutes a hole and is represented by a small circle.

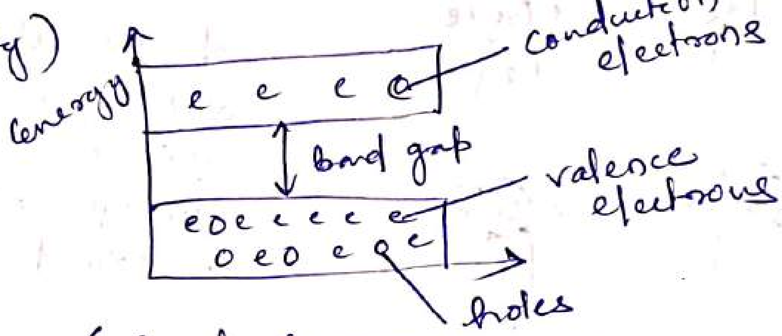
→ free electrons and holes are always generated in pairs.

→ The merging of a free electron and hole is called recombination.

→ With the increase in temperature, concentrations of free electrons and holes increases.



(band diagram at 0°K)



(band diagram at temp > 0°K)

→ The mobility of electrons is more than that of holes because the probability of an electron having the energy required to move to an empty state in the conduction band is much greater than the probability of an electron having the energy required to move to the empty state in valence band.

→ The current due to movement of electrons is greater than that due to the hole drift in the semiconductor

Limitations :

→ The conductivity of an intrinsic semiconductor depends on the surrounding temperature.

At room temperature, it exhibits a low conductivity.

Extrinsic Materials

Intrinsic semiconductor has little current conduction capability at ordinary room temperature.

The electrical conductivity of intrinsic semiconductor can be increased many times by adding very small amount of impurity to it in the process of crystallization. This process is called doping and the doped material is called the impurity or extrinsic semiconductor.

Ge and Si are tetravalent. So, the impurity or doping material may be either pentavalent or trivalent.

Accordingly the impurity introduced may be of two types
<i> Donor type or N-type (N-type semiconductor)
<ii> Acceptor type or p-type (P-type Semiconductor)

N-type extrinsic semiconductor

→ When a small amount of pentavalent impurity, such as Arsenic, Antimony, Bismuth or phosphorous is added to a pure semiconductor crystal, the resultant crystal is called N-type extrinsic semiconductor.

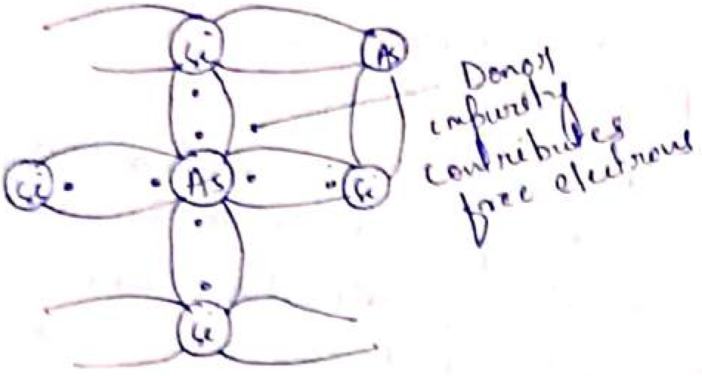
→ When a pentavalent or a donor impurity is added to a tetravalent atom, the impurity atoms form covalent bonds with the silicon.

→ An additional fifth electron due to impurity atom, is unassociated with any particular covalent bond.

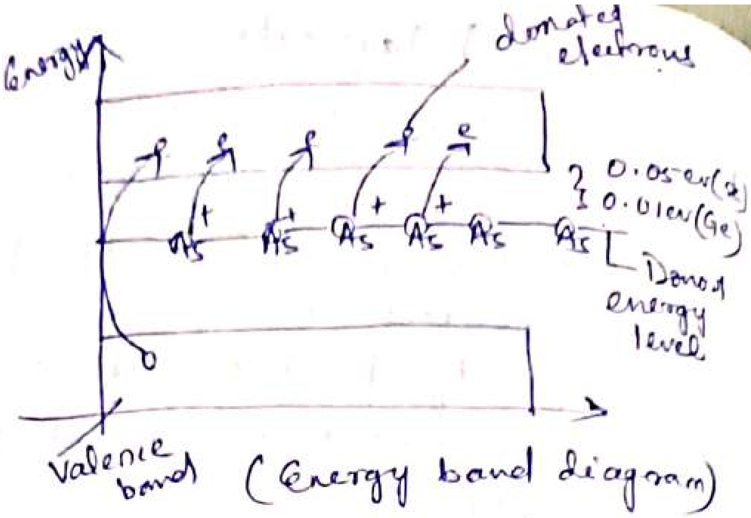
→ This spare electron enters the conduction band of pure semiconductor as a free electron.

→ The pentavalent impurity is called the donor type impurity as it donates one electron to the conduction band of a pure semiconductor.

→ A discrete energy level or donor level appears in the forbidden band with an Eg significantly less than that of the intrinsic material.



(Covalent bond)



(Energy band diagram)

→ The energy required to detach this 5th electron from the atom is of the order of only 0.05eV for Si and 0.01eV for Ge.

→ At room temp in an intrinsic Si material, there is about one free electron for every 10^{12} atoms. If the dosage level is 1 in 10 milion (10^7), the ratio $10^{7}/10^{12} = 10^5$ indicates that the carrier concentration has increased by ratio of 100000 : 1.

→ In an N-type semiconductor, the number of free electrons is more greater than the number of holes. N-type semiconductor has electrons as <u>majority</u> carriers, and the holes as <u>minority</u> carriers. ($n >> h$)

P-type Extrinsic Semiconductor

→ When a small amount of trivalent impurity such as Boron, Gallium, Indium or Aluminium is added to Pure semiconductor crystal, the resulting crystal is called the <u>P-type extrinsic semiconductor</u>.

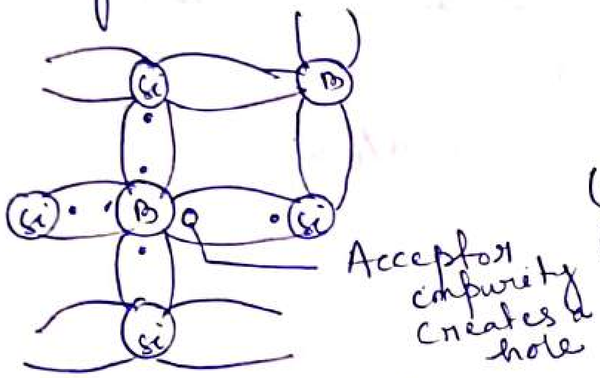
→ When a trivalent impurity is added to Si (or Ge), these impurity atoms form covalent bonds with four surrounding intrinsic semiconductor (Si or Ge atoms), but one bond is left incomplete and gives rise to <u>hole</u>.

→ So, they create hole which can accept electrons.

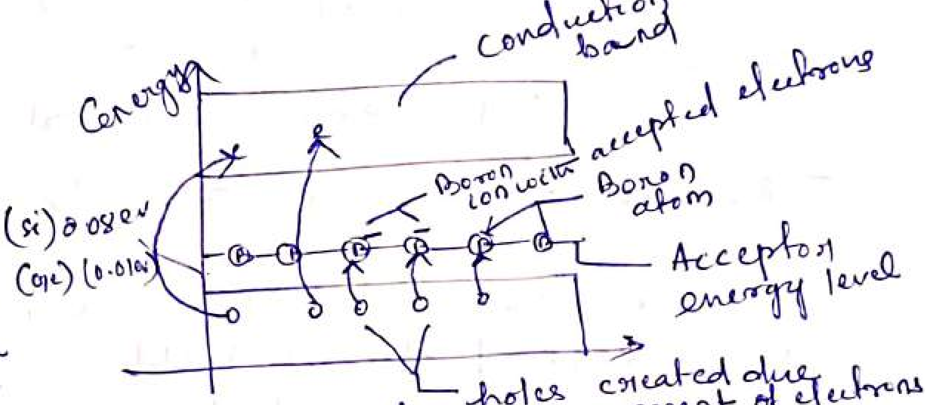
→ These impurities are known as acceptor or p-type impurities.

→ When acceptor or p-type impurities are added to the intrinsic semiconductor, they produce an allowable discrete energy levels which is just above the valence band.

→ Since ~~or~~ a very small amount of energy (0.08 ev for Si and 0.01 ev for Ge) is required for an electron to leave the valence band and occupy the acceptor energy level, holes are created in the valence band by these electrons.



(Covalent bond structure)



(Energy band diagram)

→ The holes created constitute the large number of carriers in the semiconductor material.

→ Since holes can be said to have a positive charge, acceptor-doped semiconductor material is referred to as <u>p-type semiconductor.</u>

→ In p-type semiconductor, the majority carriers are **holes** while the minority carriers are **electrons**.
(h >> n)

★ N type semiconductor : $\boxed{n >> h}$

★ P type semiconductor : $\boxed{h >> n}$

n = concentration of free electrons
h = concentration of holes in valence band

Movement of charge carriers :-

— There are two mechanisms in which electrons and holes move through a semiconductor.

a. Drift current
b. Diffusion current

Drift current :-

When the movement of charge carriers is under the influence of an applied electric field is termed as drift current.

— The electric current I, defined as the charge flowing per second across any normal plane of the conductor is

$$\boxed{I = enva} \quad (v = \mu_e E)$$

— The current density $\boxed{J = I/a = env \ A/m^2}$

μ_e = electron mobility (m^2/Vs)
E = applied electric field
e = charge of the electron
n = electron density crossing any plane of cross sectional area a.
v = ~~velocit~~ drift velocity of the electron.

Diffusion current :-

Diffusion current occurs when charge carriers diffuse from a point of concentration (charge carriers tend to move from the region of high concentration to the region of lower concentration), to spread uniformly throughout the volume of a piece of material.

→ The process is called the diffusion, and the current due to this process is called the diffusion current.

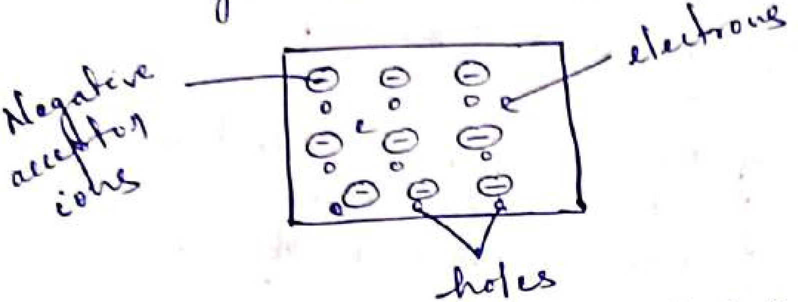
— The current density due to diffusion of electrons and holes are given as

$$\boxed{J_e = eD_e \frac{dn}{dx}} \qquad \boxed{J_h = -eD_h \frac{dp}{dx}}$$

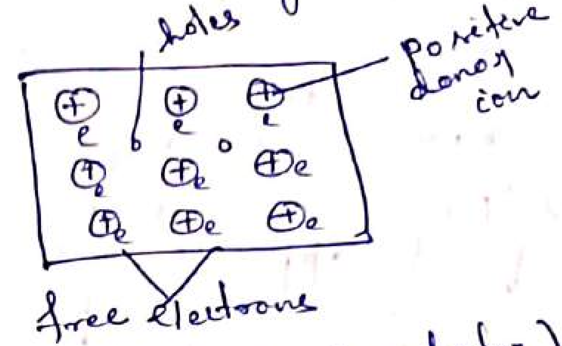
D_e and D_h = Diffusion constant

Semiconductor Diode :-

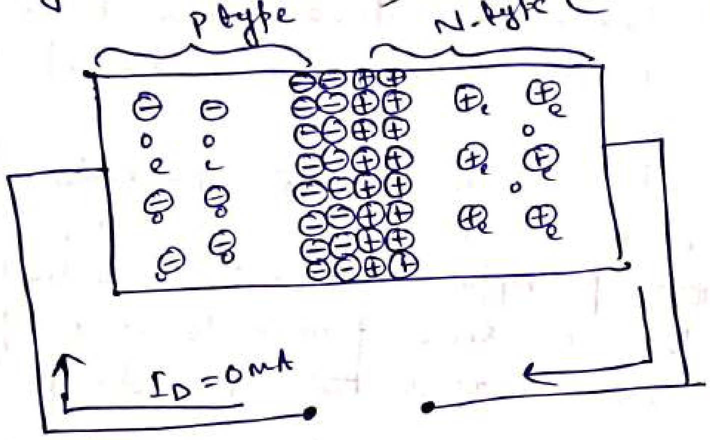
The semiconductor is created by simply joining an N-type material and P-type material together.



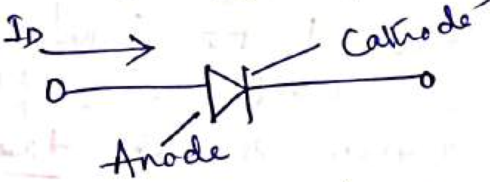
(P- type semiconductor)



(N-type semiconductor)



(P-N junction diode in no-bias condition)



(Symbol of PN junction diode)

- It is a two-terminal device.
- The P-N junction is produced by placing a layer of P-type semiconductor next to the layer of N-type semiconductor. The contact surface is called the P-N junction.
- The P-type semiconductor block has mobile holes and the same number of fixed negative acceptor ions. The N-type semiconductor block has mobile or free electrons and the immobile donor positive ions.

→ On the formation of P-N junction, some of the holes from P- type material tend to diffuse across the boundry into N-type material, and some of the free electrons diffuse into P- type material. This occurs due to concentration gradient. This process is known as diffusion.

→ Due to the displacement of the charges, an electric field appears across the junction. ~~the~~ The electric charges are confined to the neighbourhood of the junction, and consists of immobile ions.

→ The electrons leave positive ions behind them on the N-side. Negative ions are created on the P-side of the junction.

→ The negative potential on the P-side prevents the migration of any more electron from the N-type material to the P-type material. Similarly, the positive potential on the N-side prevents any further migration of holes across the boundary.

→ The initial diffusion of charge carriers creates a barrier potential at the junction.

→ Since the region around the junction is depleted of mobile charges, it is called the depletion region, the space charge region or the transition region.

→ The thickness of the depletion region is of the order of 1 micron (10^{-6}m).

→ The magnitude of barrier potential is of the order (0.3 V for Ge and 0.7 V for Si).

→ Barrier voltage depends on the doping density, electronic charge and temperature.

→ It is found that either Silicon or Germanium diodes, the barrier potential decreases ~~2m~~ 2.5mv for each celsius degree rise in temp.

There are three options available: <u>no bias</u>, <u>forward bias</u> and <u>reverse bias</u>.

<u>Bias</u> :— The term bias refers to the application of an external voltage across the two terminals of the device to extract a response.

No bias ($V_D = 0$)

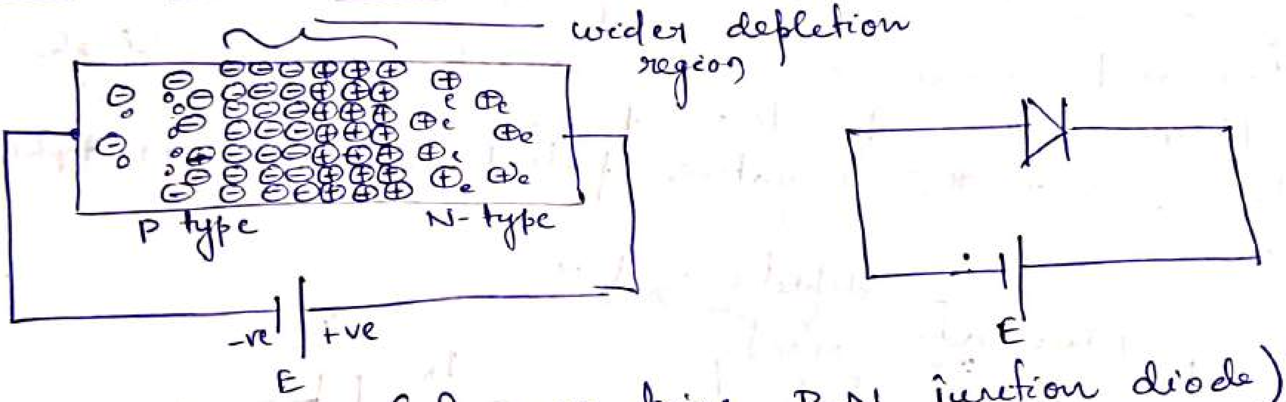
→ The no-bias situation occurs because there is no external voltage applied.

→ The resulting current is 0A.

→ It acts as an ~~ins~~ isolated resistor.

→ In the absence of an applied bias across a semiconductor diode, the net flow of charge in one direction is zero.

Reverse bias condition ($V_D < 0V$)



(Reverse bias P-N junction diode)

→ If an external potential of V is applied across the P-N junction such that the positive terminal is connected to the N type material and the negative terminal is connected to the P-type material, the junction is said to be <u>reverse biased</u>.

→ The number of uncovered positive ions in the depletion region of the N-type material increase due to the large number of free electrons drawn to the positive terminal of the applied voltage.

→ Similarly, the number of uncovered negative ions increase in the P-type material.

→ This results in widening of the depletion region.

→ The barrier potential is increased by the magnitude of the applied bias.

→ With the increased barrier potential, there is no possibility of majority carrier current flow across the junction.

→ The number of minority carriers entering the depletion region will not change, resulting in minority carrier flow vectors of the same magnitude.

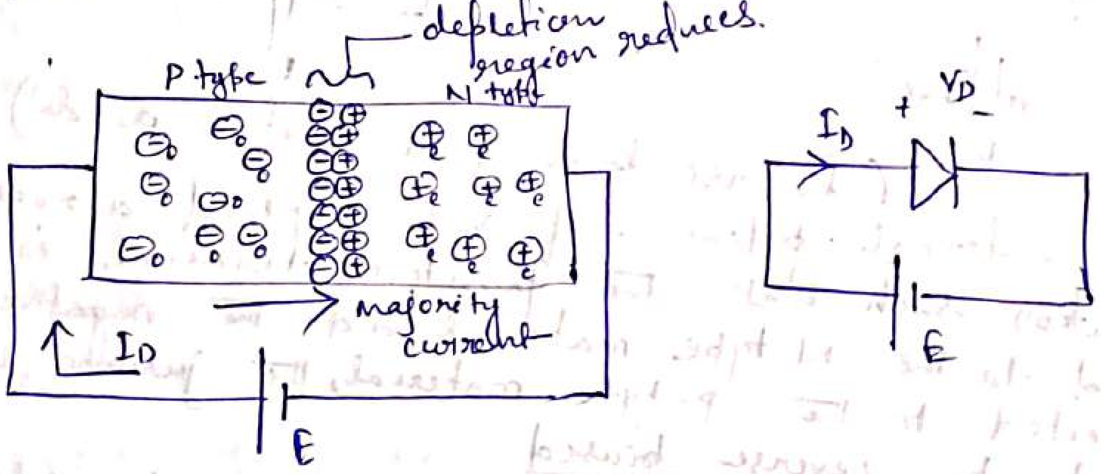
→ The current that exists under reverse-bias conditions is called the reverse saturation current or leakage current, and is represented as I_s.

→ Its value typically in nanoampere range for Si devices.

→ The term saturation means it reaches its maximum level quickly and does not change significantly with increase in the reverse-bias ~~condition~~ potential.

Forward-bias condition ($V_D > 0V$)

A forward bias or "ON" condition is established by applying the positive terminal to the p-type material and the negative potential to the N-type material.



(Forward bias P-N junction)

→ The holes on the P-side being positively charged particles are repelled from the positive bias terminal and driven towards the junction.

→ The electrons on the N-side are repelled from the negative bias terminal and driven towards the junction.

→ The application of a forward-bias potential pressurize electrons in the N-type material and holes in the P-type material to recombine with the ions near the boundary and reduce the width of the depletion region. Hence, barrier potential is reduced.

→ If the applied bias voltage is increased from zero, the barrier potential gets progressively smaller and smaller until it effectively disappears; and charge carriers can easily flow across the junction.

→ Since barrier potential is very small, a small forward voltage is sufficient to eliminate the barrier completely. (junction resistance is zero).

The general characteristic of a semiconductor diode is referred to as Schockley's equation for the forward- and reverse-bias regions.

$$\boxed{I_D = I_S\left(e^{V_D/\eta V_T} - 1\right)}$$

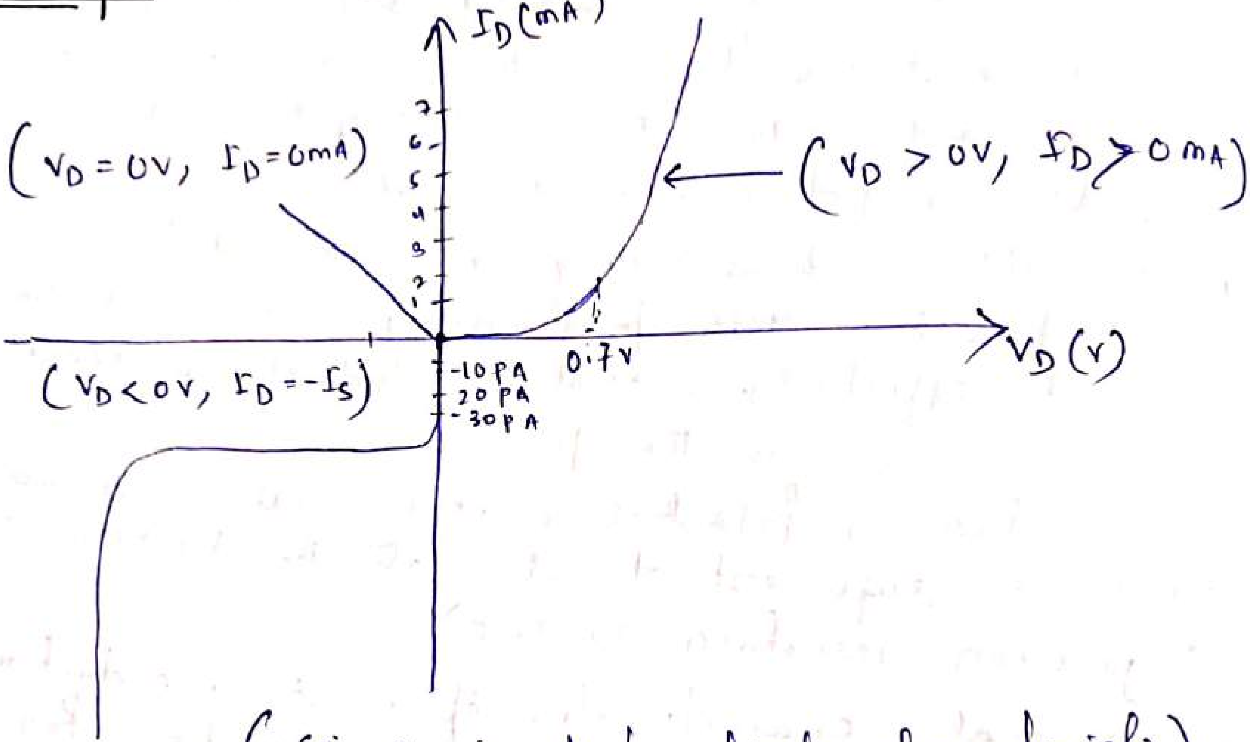
I_D = forward current
I_S = Reverse saturation current
V_D = Applied forward-bias voltage across the diode
η = ideality factor. It is a function of the operating conditions and physical construction. It has range between 1 and 2.
($\eta = 1$ is assumed unless it is mentioned)

The voltage V_T is called the thermal voltage, and is determined by

$$\boxed{V_T = \frac{KT}{q}}$$

K = Boltzmann's constant = 1.38×10^{-23} J/K
T = Absolute temp = 273 + temp in °C
q = charge of electron = 1.60×10^{-19} C

Volt - Ampere characteristics of P-N junction diode



(Si semiconductor diode characteristic)

→ The graph plotted between the potential difference across the P-N junction and the circuit current is known as volt-ampere characteristic of a P-N junction.

→ When $V_D = 0V$, the potential barrier at the junction does not allow the flow of current, so circuit current is zero.

$$V_D = 0\,V$$

$$I_D = I_S\left(e^{V_D/\eta V_T} - 1\right)$$

Substituting $V_D = 0V$ in the above equation

$$I_D = I_S(e^0 - 1) = I_S(1-1) = 0\,mA.$$

→ With forward bias to the P-N junction, the forward current flows until the forward voltage exceeds the junction barrier potential (0.3V for Ge and 0.7V for Si).

→ As the forward voltage is increased to the knee voltage, the barrier potential is progressively reduced to zero.

Beyond the knee voltage, the potential barrier is completely eliminated, forward current increases.

For positive value of V_D

$$\boxed{I_D \cong I_S e^{V_D/\eta V_T}}$$

→ For negative values of V_D, the exponential term drops very quickly below the level 1, and the resulting equation for I_D is

$$\boxed{I_D \cong -I_S}$$

→ The reverse current is made up of minority charge carriers.

→ When temp of the semiconductor material is increased, the additional thermal energy causes more electrons to break away from the atoms. This creates more hole-electron pairs, and generates more minority charge carriers. Thus, reverse saturation current increases with the increase in the junction temperature.

→ Reverse saturation current approximately doubles for each 10° C rise in temp in case of Ge and for each 12° C rise in temp in case of Si.

Some important terms

Breakdown voltage :- Under normal reverse voltage, a very little reverse current flows through a P-N junction. On increasing the reverse voltage, a point may reach at which junction breaks down with sudden rise in reverse current. Breakdown voltage is defined as the reverse voltage at which P-N junction breaks down with sudden rise in reverse current.

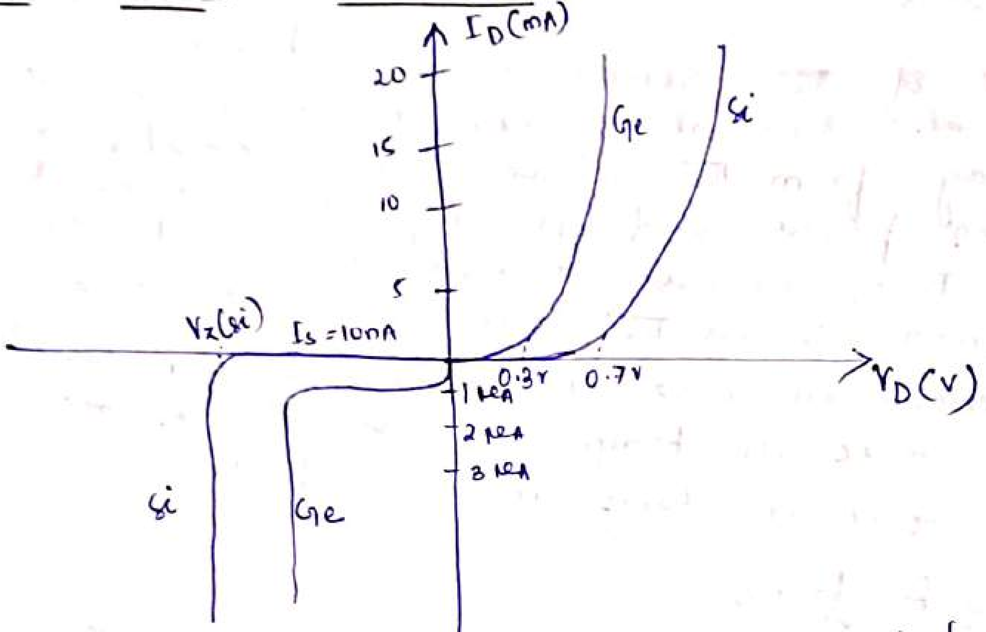
Knee voltage :- The forward voltage at which the current through the junction starts increasing rapidly, is called the knee voltage or the cut-in voltage.

Maximum forward current :- It is the highest instantaneous forward current that a P-N junction can conduct without damage to the junction.

Peak Inverse voltage (PIV) :- It is the maximum reverse voltage that can be applied to the P-N junction without damage to the junction. If the reverse voltage across the junction exceeds its PIV, the junction may get destroyed owing to excessive heat.

Maximum power rating :- It is the maximum power that can be dissipated at the junction without any damage to it.

Silicon versus Germanium



(Comparison of Si and Ge semiconductor diodes)

★ Silicon is preferred over Germanium.

a. **Small reverse leakage current** :- The leakage current of the silicon crystal is less than the Germanium crystal. The reverse current in the Silicon is in the order of the nano amperes, whereas the reverse current in the Germanium is in the order of microamperes.

b. **Good temperature stability** :- Temperature stability is defined as the performance of semiconductor devices with a change in the operating temperature.
Silicon can be used for applications in which the temperature may rise to about 200°C whereas Germanium has a much lower maximum rating (100°C).

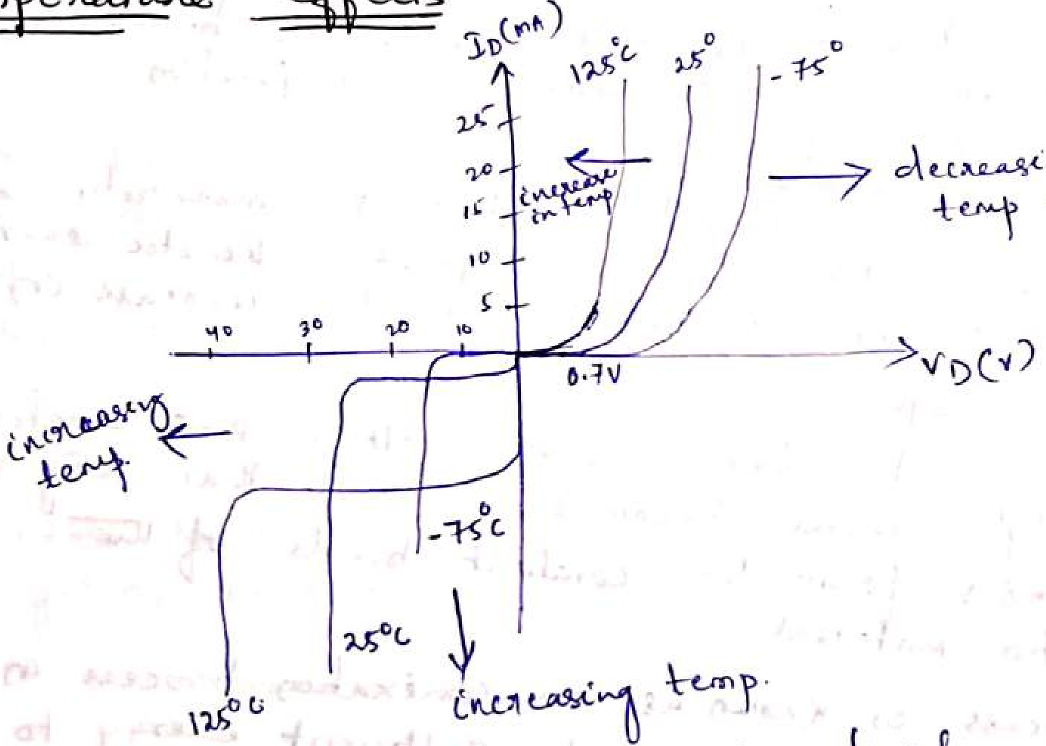
c. High peak inverse voltage (PIV) :- Silicon diodes have higher PIV. and PIV ratings for Silicon can be in the neighbourhood of 1000V, whereas the maximum value for Germanium is closer to 400V.

d. Large forward current :- Silicon is the most suitable for high current applications because it has a very high forward current in a range of ten amps or even more.

2. Good for high power applications :- Silicon-based semiconductor devices can deliver high power up to 50 watts.

Cost-effective :- Silicon is abundantly available on the earth's surface. Silicon is cheaper than Germanium. Germanium is a rare material that is typically found in copper, lead and silver deposits.

Temperature Effects



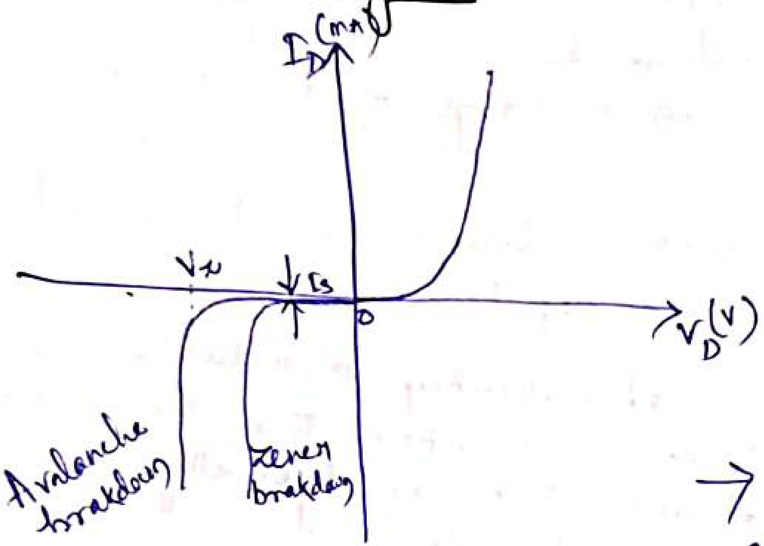
(variation of Si diode characteristics with temp change)

→ In the forward-bias region the characteristics of a silicon diode shift to the left at a rate of 2.5mV per centigrade degree increase in temperature.

→ In the reverse-bias region the reverse saturation current of a Si diode doubles for every 10°C rise in temperature.

→ The reverse breakdown voltage of a semiconductor diode increases or decreases with temperature depending on the zener potential.

Zener Regions



(Zener region)

→ The reverse-bias potential that results in the dramatic change in characteristics is called zener potential and is given as the symbol V_Z.

→ The breakdown voltage depends on the width of the depletion region, depends on the doping level.

There are two mechanisms by which breakdown can occur at a reverse-biased P-N junction.

a Avalanche Breakdown:-

→ In the reverse biased condition, the minority carriers flowing through the junction acquire a kinetic energy $\left(W_K = \frac{1}{2}mv^2\right)$ which increases with the increase in reverse voltage.

→ At a sufficiently high reverse voltage the kinetic of minority carriers becomes so large that they knock out electrons from the covalent bonds of the semiconductor material.

→ This process is known as an ionization process in which the valence electrons absorb sufficient energy to leave the parent atom.

→ As a result of collision, the liberated electrons liberate more electrons and the current becomes very large leading to the breakdown of the crystal structure.

→ This phenomenon is called the avalanche breakdown.

→ Junction that experiences breakdown above 5V is caused by avalanche effect.

→ The avalanche breakdown occurs in lightly doped junctions, which produces wide depletion layer.

→ With increase in junction temperature, avalanche breakdown voltage increases.

→ Avalanche diodes have a positive temperature coefficient.

b. Zener breakdown :-

→ Under a very high reverse voltage, the depletion region expands and the potential barrier increases leading to a very high electric field across the junction.

→ The electric field breaks some of the covalent bonds of the semiconductor atoms leading to a large number of free minority carriers, which suddenly increase the reverse current.

→ This is called zener effect.

→ The breakdown occurs at a particular and constant value of reverse voltage called the zener breakdown voltage.

→ The zener breakdown occurs in heavily doped junction with narrow depletion layers.

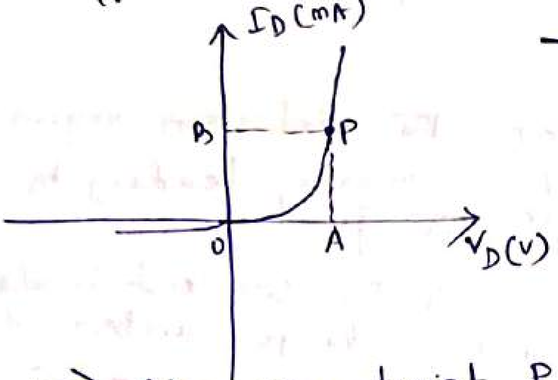
→ With increase in junction temperature, zener breakdown voltage decreases. Hence, the zener diodes have a negative temperature coefficients.

Resistance Levels :-

→ A forward biased diode conducts easily whereas a reverse - biased diode restrains the flow of current.

→ So, a diode has low forward resistance.

DC or static resistance



→ Let R_D is the resistance offered by a diode to the direct current I_D. It is simply the ratio of the dc voltage across the diode to the direct current flowing through it.

→ At any point P on the V-I characteristic of the diode, the voltage across the diode is OA and the corresponding current is OB.

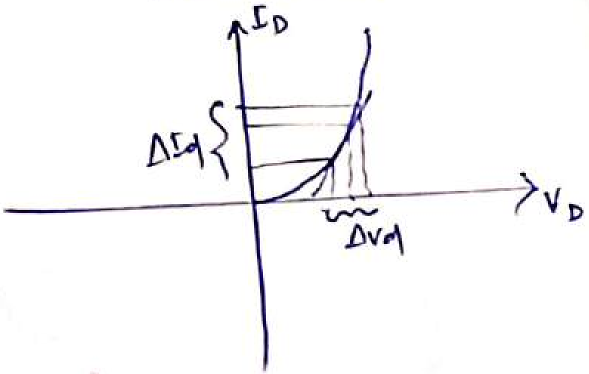
Hence, dc resistance $R_D = \frac{V_D}{I_D} = \frac{OA}{OB}$

→ Thus ~~are~~ at any point on the V-I characteristic of the diode, the dc or static resistance R_D is equal to the reciprocal of the slope of the line joining the operating point to the origin.

AC or Dynamic Resistance

→ r_d is the resistance offered by a diode to the changing forward current.

→ With no applied varying signal, the point of operation would be the Q point determined by the applied dc levels.



→ The designation Q- point is derived from the word quiescent, which means 'still' or 'unvarying'.

→ r_d is the ac resistance which is the reciprocal of the change in voltage and current.

$$\boxed{r_d = \frac{\Delta V_d}{\Delta I_d}}$$

→ The steeper the slope, the lower is the value of ΔV_d for the same change in ΔI_d and the lower is the resistance.

$$I_D = I_S\left(e^{V_D/\eta V_T} - 1\right)$$

$$\frac{dI_D}{dV_D} = \frac{d}{dV_D}\left[I_S\left(e^{V_D/\eta V_T} - 1\right)\right]$$

$$\frac{dI_D}{dV_D} = \frac{1}{\eta V_T}\left(I_D + I_S\right)$$

In general, $I_D >> I_S$ in the vertical-slope section of the characteristics

$$\frac{dI_D}{dV_D} \cong \frac{I_D}{\eta V_T}$$

Hence, $r_d = \frac{dV_D}{dI_D} = \frac{\eta V_T}{I_D}$ $\quad \boxed{r_d = \frac{\eta V_T}{I_D}}$

At room temperature $(T = 300\,K)$

$$V_T = \frac{KT}{q} = \frac{(1.38 \times 10^{-23}\ J/K) \times 300\,K}{1.6 \times 10^{-19}\ C} = 25.875\ m$$

$$\cong 26\ mV$$

Substituting $\eta = 1$ and $V_T \cong 26\ mV$

$$\boxed{r_d = \frac{26\,mV}{I_D}}$$

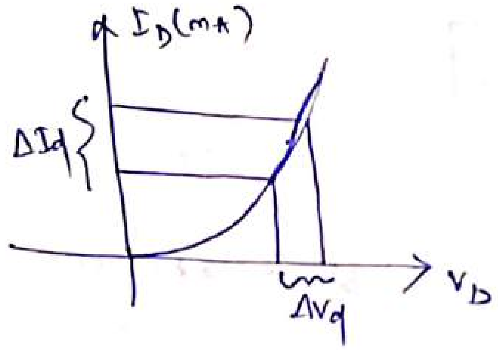
Actually diode ac or dynamic resistance for forward bias is slightly different from that obtained from the above equation. This is because of bulk and contact resistance of the semiconductor device.

Hence, $$\boxed{r_d' = \frac{26\,mV}{I_D} + r_B}$$

→ The factor r_B can change from typically 0.1Ω for high power devices to 2Ω for some low-power, general purpose diodes.

Average AC resistance

If the input signal is sufficiently large to produce a board swing, the resistance associated with the device for this region is called the average ac resistance.



$$r_d = \frac{\Delta V_d}{\Delta I_d}\bigg|_{pt\ to\ pt}.$$