PN JUNCTION DIODE, I-V CHARACTERISTICS, ZENER DIODE AND ITS APPLICATIONS, OPTOELECTRONIC DIODES: LED, PHOTO DIODE.

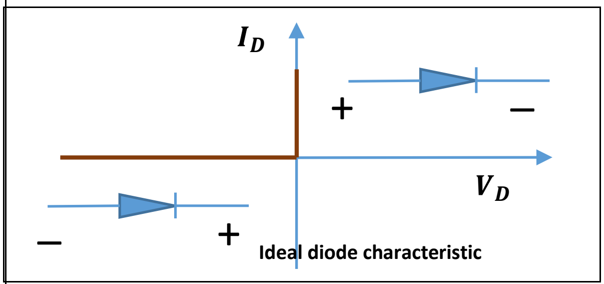
❖ PN junction diode, I-V characteristics

When one side of a single crystal of a semiconductor is doped with donor impurity atoms (diffused impurities with five valance electrons) and the other side of the same crystal with acceptor impurity (diffused impurity with three valance electrons) a p-n junction is formed.

It conducts well when a voltage is applied across the junction with some definite polarities, but it is non-conducting when a voltage is applied across the junction with opposite polarities. Thus it has properties similar to that of vacuum diode. For this a p-n junction is called a semiconductor diode.

Simple by joining a p-type material to an n-type material a p-n junction with useful electrical properties cannot be formed because in this case lattice structure remains discontinuous at the junction. Thus the fabrication of p-n junction requires a highly develop semiconductor technology.

Ideal Diode: Ideally, a diode will conduct current in the direction defined by the arrow in the symbol and act like an open circuit to establish current in opposite direction. In essence: the characteristics of an ideal are those of a switch that can conduct current only one direction. The ideal diode therefore, is a short circuit for their region of conduction.



Real Diode: Practically no real diodes behave perfectly as said earlier diode is also an electronic component with asymmetric conductance; it has low (ideally zero) resistance to current in one direction and high (highly infinite) resistance in other direction. Now since diode is a two terminal device, the application of a voltage across is terminal leaves three possibilities: (i)**NO BIAS (V_D=0 $volt$); (ii) FORWARD BIAS (V_D > 0 $volt$); (iii) REVERSED BIAS (V_D < 0 $volt$).** Each is a condition that will result in a response that the user must clearly understand if the device is to be applied effectively.

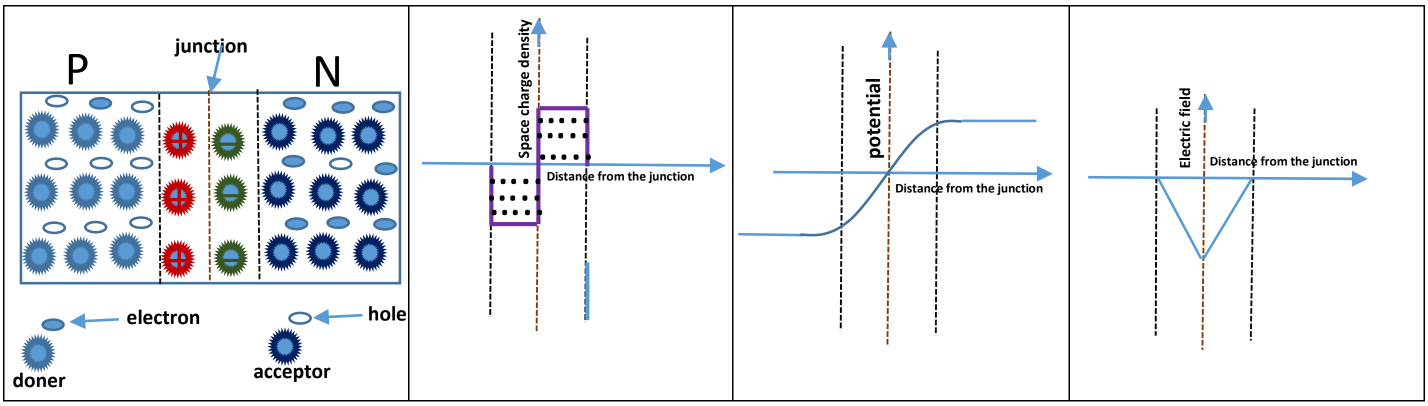
No bias or Open bias of a p-n junction:

Because of difference in carrier concentration as soon as p-n junction is formed electrons from n-side diffuse from p-side and holes from p-side diffuse from n-side. The electrons from n-side after crossing the junction recombine with holes in p-side. Similarly holes from p-side after crossing the junction recombine with free electrons in n-side. As a result the region near the junction which depleted of mobile charges and contains only immobile ionic charges is called **Depletion region** or **space charge region** or **transition region**.

The space charge, thus formed, develops an internal electrostatic potential barrier across the junction which tends to prevent further electron and hole diffusion. In equilibrium condition the internal potential barrier becomes high enough to restrain the process of diffusion.

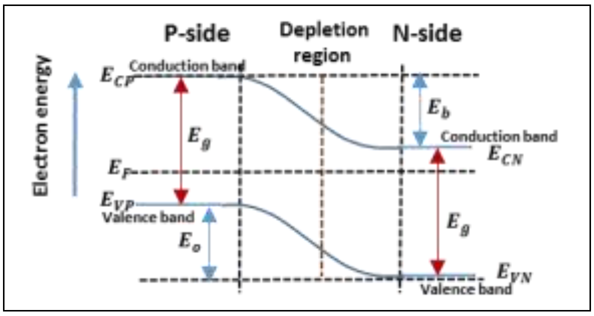
** Note that, because of statistical distribution of velocities there are always a few majority holes which have enough energy to overcome the potential barrier and move from p-side to n-side. The magnitude of (this diffusion) current due flow of majority holes is governed by the height of barrier. In equilibrium the potential barrier is assume as such a height that net current due to movement of holes become zero (As there are also always some minority holes in n-side, because of their random motion move close to the junction can immediately slide down the potential barrier).

Similarly for electrons there will be two types of flow: Minority electrons from p-side to n-side and majority electrons from n-side to p-side. Again at equilibrium these two current counter balance each other and yield current. Thus in an open circuited p-n junction a condition of dynamical equilibrium is set.



Energy band diagram (open circuit): The positive space charge appears on the n-side of the junction and negative space charge on the p-side raise the position of all the energy levels including Fermi levels of the p-side and lower sit on the n-side.

In the energy band diagram we plot the energy of an electron which has a negative charge. Due to charge transfer p-side acquires a negative charge and for this p-bonds are slightly raised relative to the n- bonds. Clearly, in equilibrium condition bond edge E_{CP} in the p-side will be at higher level than the conduction band edge E_{CN} in the side. Similarly the valance band edge E_{VP} in the p-side will be higher level than the valance band edge E_{VN} in the n-side.



Note that, electrostatic potential barrier $V_b = \frac{E_b}{e} = \frac{KT}{e} ln \frac{N_a N_d}{{n_i}^2}$

Q1. On which factors does the height of potential barrier and width of the depletion region depend?

The internal potential barrier V_O across the junction is given by $V_O = \frac{KT}{e} ln \frac{N_a N_d}{{n_i}^2}$

[K =Boltzman constant, T =absolute temp. of the junction, N_a =no. of acceptor impurity atoms, N_d = no. of donor impurity atoms per unit volume, n_i =intrinsic carrier concentration (no. of electrons or holes per unit volume)]

Again the width X_1 of the depletion region in the N-region and the width X_2 in the P-region are given by

$X_1 = \sqrt{\frac{2\epsilon_r \epsilon_0 V_1}{eN_d}}$ And $X_2 = \sqrt{\frac{2\epsilon_r \epsilon_0 V_2}{eN_a}}$ [where $\epsilon_0 = free\ space\ permitivity\ \epsilon_r = dielectic\ constant\ of\ the\ water$

[V_1 =Magnitude of potential rise in the N region V_2 =magnitude of potential fall in the P region]

Hence if $N_a\ or\ N_d$ increase width of the depletion region in the p-side or n-side decreases.

Total width of the depletion region is given by $d = x_1 + x_2 = \sqrt{\frac{2\epsilon_r \epsilon_0 V_0}{e}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$ where $V_0 = V_1 + V_2 = inernal\ potential\ barrier$.

Hence value of the height of the potential barrier hence width of the depletion layer depends on the-

(i) The donor and acceptor impurity concentration on the both side of p-n junction.
(ii) Temperature.
(iii) The nature of the semiconductor.

Q2. "The barrier potential across a p-n junction diode cannot be measure simply by placing a volt meter across the diode terminal"-explain.

To show a reading a small amount of current must flow through the ckt. It causes Joule heating in the circuit. Since there is no external source of energy it must causes simultaneous cooling of p-n junction which contradicts the principle of thermodynamics, according to which it is impossible to derive work by cooling a body below its equilibrium temp. Thus no current can pass through the circuit and voltmeter shows zero reading.

Actually the barrier potential is balanced by the metal-to-semiconductor contract potentials in the circuit.

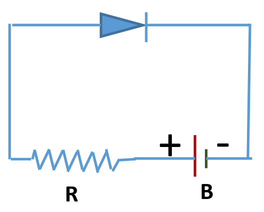
Forward Bias:

When the positive terminal of a battery is connected to the p-region and the negative terminal to the n-region, so that the potential difference acts in opposition to the internal potential barrier, the junction is said to be forward biased.

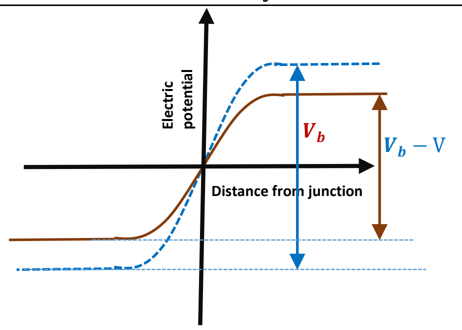
Under the forward bias condition the applied positive potential repels the holes in the p-region towards the junction and the applied negative potential repels the electrons in the n-region also towards the junction. As a result the positive donor ions and the negative acceptor ions within the depletion region regain electrons and holes respectively consequently the depletion region and the internal potential barrier disappears if applied potential difference is more than internal potential difference.

Therefore under the action of the forward potential difference the majority carriers i.e. electron from n-region and holes from p-region flows across the junction, the number of electrons in the n-region always remain constant because the source of the external potential difference compensates for loss of electrons in the n-region (as electrons moves towards the positive terminal of the battery from crystal).

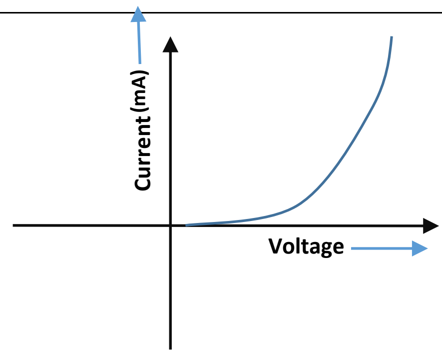
Note that: in p-region the current is mostly carried by holes and in n-region the current is mostly carried by electrons. But in the external circuit the total current is due to flow of electrons only.



Forward biased P-N junction



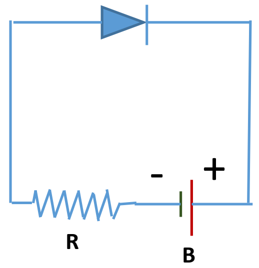
Forward bias reduced the potential



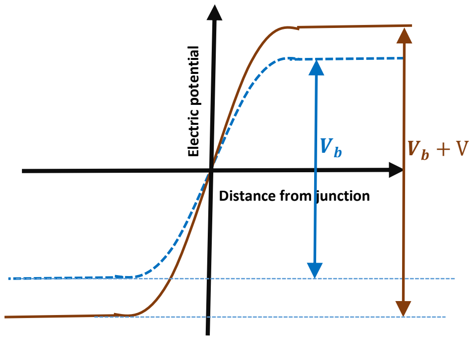
Reverse Bias:

If the polarity of the applied voltage (V) is such that p-side becomes negative and n-side becomes positive, the height of the intrinsic potential barrier is increase to $V_b + V$. The junction is then said to be reverse biased. The increased barrier height makes the current due to flow of majority carriers negligible. Minority carriers moves down the potential barrier and hence their motion is not affected by the barrier height. They constitute a small current in the reverse direction, called reverse saturation current.

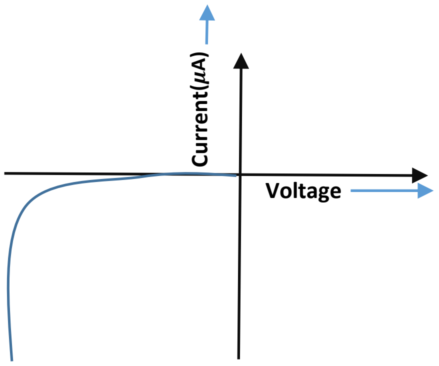
** Thus a p-n junction allows easy flow of charge in one direction but restrains the flow in the opposite direction. It indicates that a p-n junction can act as rectifying element for conservation of a.c into d.c.



Reversed biased P-N junction



reversed bias increase the potential



Q3. (a) Draw a Schematic diagram of the energy band diagram of an open circuited p-n junction.

(b) Draw a Schematic diagram of the energy band structure of F.B and R.B p-n junction.

(c) Explain its action as a rectifier from band diagram.

When a F.B voltage V is applied to the junction, the energy barrier is lowered to the value (E-eV) as a result a good number of electrons from conduction band of n-side diffuse into p-side where they recombine with holes. This gives rise to a large component of diffusion current.
But when a R.B voltage V is applied to the junction, the energy barrier is raised to the value (E_b+eV). Now very few electrons in the conduction band of n-side and holes in the valence band of p-side will have enough energy to surmount the increased barrier, hence diffusion current is negligibly small in a reverse bias.
This means that the junction can be used as a rectifying element to convert a.c into d.c.

Q4. Write down the relationship between current and voltage in p-n junction diode, and explain the variation of current with voltage.

The current flowing through a p-n junction can be approximated by the relation, $I = I_0\left(e^{\frac{eV}{\eta kT}} - 1\right)$.......(i)

[Where I_0= reverse saturation current, V=applied voltage in volt, k=Boltzmann const., T=junction temp., e=charge of electron, η=a dimension less parameter having value between 1 & 2]

If the forward voltage V is large compared with $\frac{kT}{e}$ than the above relation can be written as $I = I_0 \exp\left(\frac{eV}{\eta kT}\right)$. This shows that forward current increases exponentially with applied voltage. For a reverse biased p-n junction V is negative. If its magnitude is very large compared with $\frac{kT}{e}$ the current $I \approx I_0$.

Q5. Define cut in voltage.

In practical Si and Ge diodes it is found that the forward current does not assume significant value unless the forward biased exceeds certain threshold voltage V_v, called cut in voltage.
The existence of V_v can be explained from the intrinsic potential barrier V_b existing across the junction. The current through the diode becomes applicable when the forward voltage exceeds V_b. Thus V_v is equal to the forward voltage for which the effective barrier vanishes. $V_v = 0\cdot 2 - 0\cdot 3\ for\ Ge$ & $V_v = 0\cdot 6 - 0\cdot 7\ for\ Si.$
Note that cut in voltage V_v depends upon doping concentration as well as temperature.

Q6. What do you mean by static and dynamical resistance of a diode? How does the dynamical resistance vary with current and temperature?

The ratio of applied voltage and to the current is known as static or d.c resistance of a diode is $r_{d.c} = \frac{V}{I}$.
If the resistance offered by the diode to flow of steady current. Since diode is non-linear device its d.c resistance varies with current.
The resistance offered by the diode to the varying component of current is called dynamic or incremental resistance. If is given by the reciprocal of the slope of current voltage characteristic curve at the operating point. Thus $r_{a.c} = \frac{dV}{dI}$.

Now we have $I = I_0\left(e^{\frac{eV}{\eta kT}} - 1\right)$ then $\frac{dV}{dI} = \frac{e}{\eta kT} e^{\frac{eV}{\eta kT}}(I + I_0) \approx \frac{eI}{\eta kT}$ when $r_{a.c} = \frac{dV}{dI} = \frac{\eta kT}{eI}$

[kT/e=thermal voltage=$26mV$ room temp.]

As $k = 1.38 \times 10^{-23} J/K, e = 1.6 \times 10^{-9} c, T = 300K$

$\therefore r_{a.c} = \frac{26\eta}{I}$ **[Here I is in mA]**