University of Calcutta
Semester 4
PHYSICS
paperPHS-A-CC-4-10-TH (OLD SYLLABUS)

Barrier Formation of p-n junction diode, Static And Dynamic Resistance, Current flow mechanism in Forward and Reverse Biased condition, Derivation of Barrier Potential

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BARRIER FORMATION IN PN JUNCTION DIODE

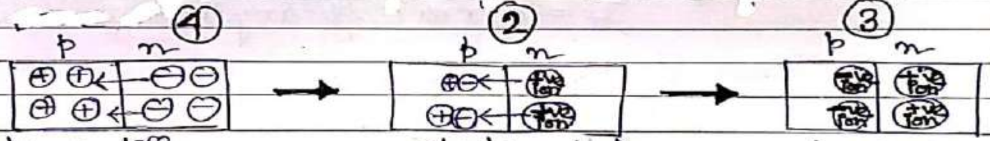
OLD SYLLABUS

PHS-A-CC-4-10-TH

(20)

• Barrier formation in p-n junction diode :-

(1) When a p-n junction is formed, some of the free electron (majority carriers of the n-side) in the n-region diffuse across the junction and combine with the holes (majority carriers of the p-side) to form negative ions. In this way, electrons leave behind positive ions at the n-side.



electrons diffuse through the junction — electron-hole combination and formation of +ve ions. — presence of -ve ion and +ve ion

(2) Thus, at the junction, no mobile charge carrier are present.

(3) Movements of ions are so so large that these +ve and -ve ions acts as a barrier at the junction

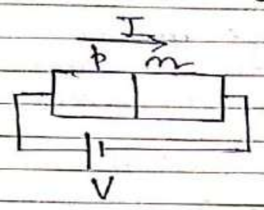
(4) This barrier formed at the junction opposes the flow of e⁻s from n-side and holes from p-side.

(5) These immobile +ve ion and -ve form electric field at the junction.

STATIC
AND
DYNAMIC
POTENTIAL

- Static and Dynamic Resistance :-

- Static Resistance :



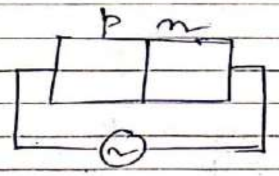
Static resistance can be defined ~~across~~ as the ratio of DC voltage applied across the junction diode to the DC current flowing through the diode.

If V = applied DC voltage
I = current flowing through the diode

then static resistance

$$R_{dc} = \frac{V}{I}$$

- Dynamic Resistance :-



Dynamic Resistance can be defined as the ratio of the change in voltage to the corresponding change in current when AC voltage is applied.

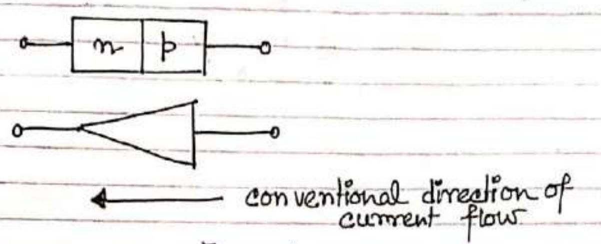
If δV = change in voltage
δI = " " current

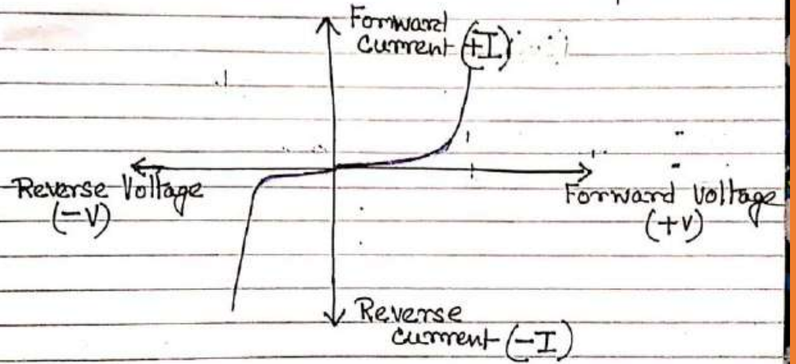
then dynamic resistance

$$R_{ac} = \frac{\delta V}{\delta I}$$

INTRODUCTION OF CURRENT FLOW MECHANISM IN FORWARD AND REVERSE BIASED DIODE

• Current Flow Mechanism in Forward and Reverse Biased Diode :-





① A p-n junction is said to be forward-biased when the positive pole of a battery is connected to the p-side and −ve pole to the n-side of the junction.

In this situation,

ⓐ barrier potential is reduced

ⓑ a large amount of current will flow across the junction.

② In reverse-bias condition, the +ve pole of the battery is connected to the n-side and

−ve pole to the p-side of a p-n junc.

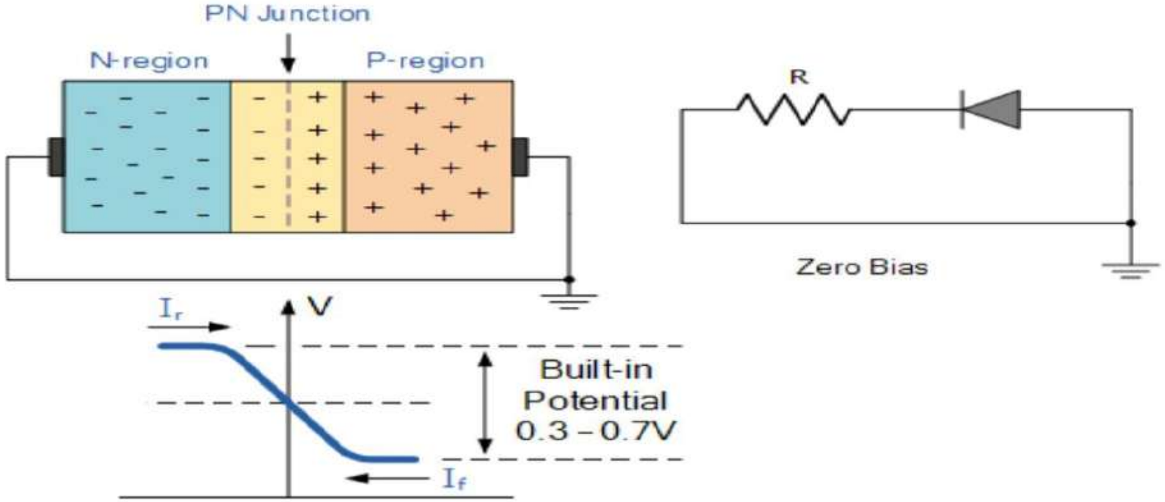
In this case,

ⓐ barrier potential is enhanced.

ⓑ very small current will flow.

ZERO POTENTIAL

Zero Biased PN Junction Diode

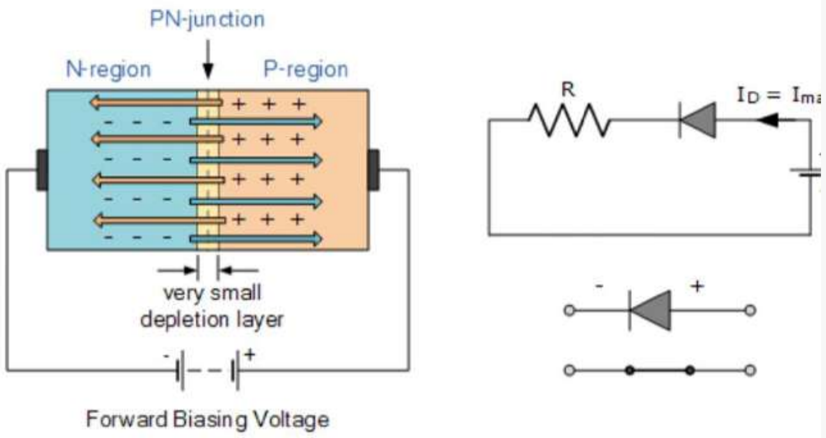


The potential barrier that now exists discourages the diffusion of any more majority carriers across the junction. However, the potential barrier helps minority carriers (few free electrons in the P-region and few holes in the N-region) to drift across the junction.

Then an "Equilibrium" or balance will be established when the majority carriers are equal and both moving in opposite directions, so that the net result is zero current flowing in the circuit. When this occurs the junction is said to be in a state of "**Dynamic Equilibrium**".

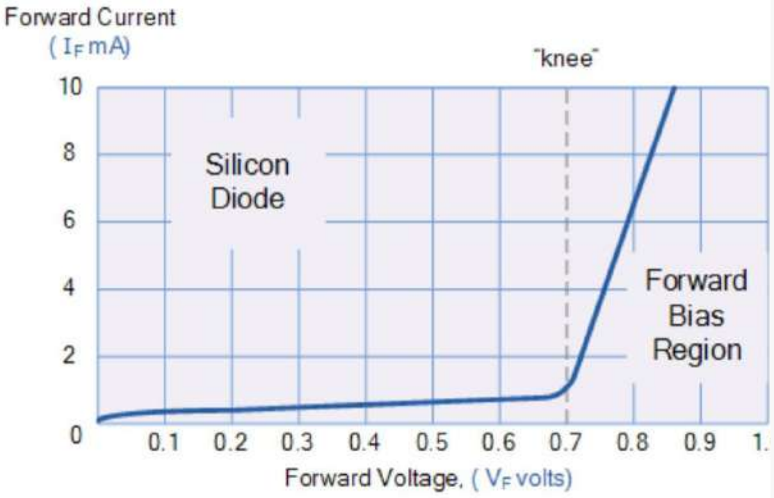
FORWARD BIAS CONDITION

Reduction in the Depletion Layer due to Forward Bias



This condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.7v for silicon junction diodes.

Forward Characteristics Curve for a Junction Diode



The application of a forward biasing voltage on the junction diode results in the depletion layer becomin very thin and narrow which represents a low impedance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the "knee" point.

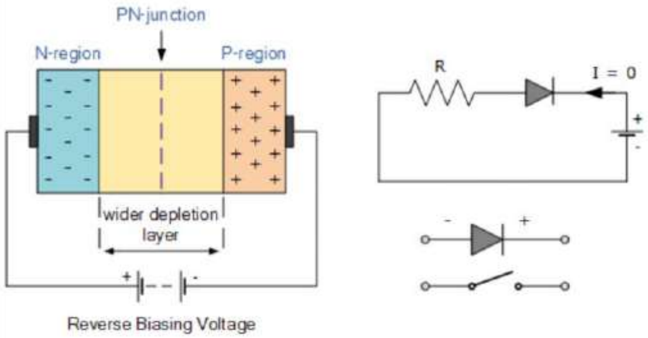
Forward Biased PN Junction Diode

When a diode is connected in a **Forward Bias** condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.

This is because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the "knee" on the static curves and then a high current flow through the diode with little increase in the external voltage as shown below.

REVERSE BIAS CONDITION

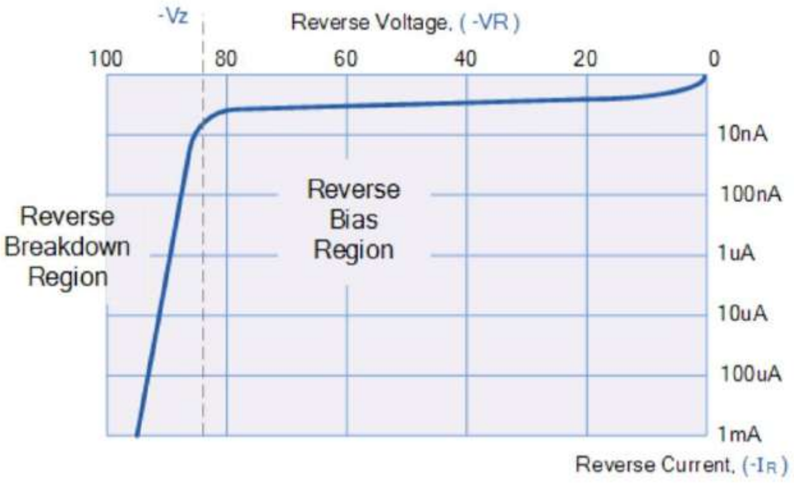
Increase in the Depletion Layer due to Reverse Bias



This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small **leakage current** does flow through the junction which can be measured in micro-amperes, (μA).

One final point, if the reverse bias voltage Vr applied to the diode is increased to a sufficiently high enough value, it will cause the diode's PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below.

Reverse Characteristics Curve for a Junction Diode



Sometimes this avalanche effect has practical applications in voltage stabilising circuits where a series limiting resistor is used with the diode to limit this reverse breakdown current to a preset maximum value thereby producing a fixed voltage output across the diode. These types of diodes are commonly known as Zener Diodes and are discussed in a later tutorial.

Reverse Biased PN Junction Diode

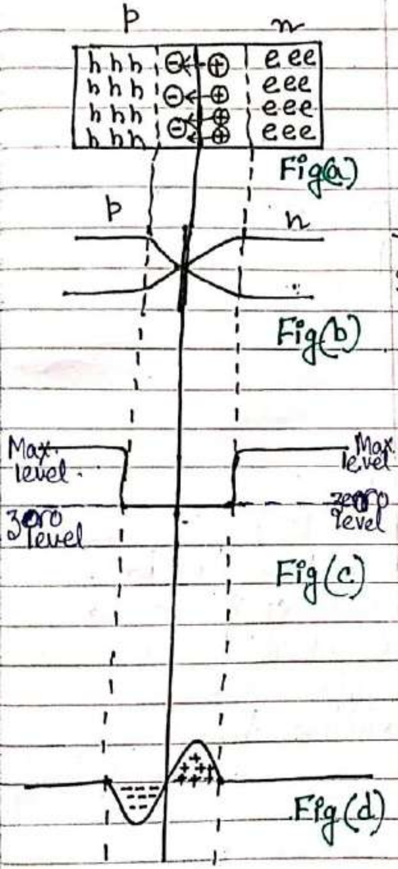
When a diode is connected in a **Reverse Bias** condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.

The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.

The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

SCHEMATIC DIAGRAM OF UNBIASED PN JUNCTION

• SCHEMATIC DIAGRAM OF UNBIASED-PN JUNCTION

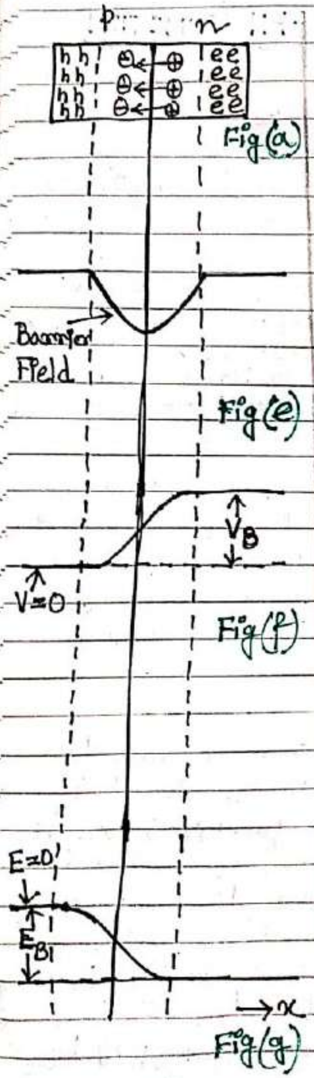


The +ve and -ve ions generate an electric field across the junction directed from n-side to p-side.

The variation of concentrations of donors and acceptors are shown. It is clear that both the concentrations are minimum at the junc. due to barrier potential

The mobile charge concentration is zero at the junc due to the presence of barrier potential and both concentration are high for donor as well as acceptor.

In the depletion region, the immobile charge density is zero at the junction, then it increases and reaches to its maximum level and finally decrease. This is because after barrier potential boundary the acceptor as well as donor concentration will be max.



This fig (e) explains the expression (3) of next page at the jun

V(x) is -ve in eqn (4)
V(x) is zero at the p-side and slowly increase near the barrier junction of the p-side. On the n-side, V(x) becomes max. This gives the highest barrier potential V_B.

V(x) is -ve in eqn (4)
charge of electron = -e

$$\therefore E_B = (-e)(-V_B)$$
$$= eV_B \quad \text{—(5)}$$

$E_B \rightarrow +ve$

This field leads to moving from n-type to p-type semiconductor

If ρ = immobile /uncovered charge density at the junction.

V = electrostatic potential at a distance x from an origin

ϵ = permittivity of the semiconductor,

then Poisson's equation can be written as,

$$\frac{d^2V}{dx^2} = -\rho/\epsilon \quad \text{—— (1)}$$

Integrating this equation, we can get,

Barrier Field $F = -\frac{dV}{dx} = -\int \frac{d^2V}{dx^2}\,dx$

$$= -\int (-\rho/\epsilon)\,dx$$

$$= +\int_{x_0}^{x} \rho/\epsilon\,dx \quad \text{—— (2)}$$

- at $x = x_0$ $F = 0$.
- as x increases, F increases.

} Condition (3) Explanation in Fig (e)

Thus the electrostatic potential at a point can be written as,

$$V(x) = -\int_{x_0}^{x} F\,dx \quad \text{—— (4)}$$

This potential increases in the n-side to give a potential barrier V_B which prevents further diffusion of carriers across the junction } Condition (4) Explanation in Fig (f)

V_B = barrier potential.

e = charge,

then Energy $E_B = eV_B$. —— (5)

This energy E_B transfer an electron from n-side to the p-side — This is called Barrier Energy.

Since the charge of an electron being negative, the plot of the potential energy E_B of an electron is obtained by multiplying V_B by $-e$ and is shown in Fig (g)

Explanation in Fig (g)

EXPRESSION FOR BARRIER POTENTIAL

- **EXPRESSION FOR BARRIER POTENTIAL**

N_A = concentration of the acceptors.
N_D = " " " donors
n_i = intrinsic carrier concentration.

- For p-side ⇒

hole concentration $= N_A = p_{p_0}$ —(6).
electron " $= \frac{n_i^2}{N_A} = n_{p_0}$ —(7)

p_{p_0} → hole concentration p-side at 0-bias.

n_{p_0} → electron concentration p-side at 0-bias

• For n-side ⟹

donor concentration = $N_D = n_{no}$ (8)

hole " = $n_i^2/N_D = p_{no}$ — (9)

n_{no} ⟶ donor concentration n-side at 0-bias

p_{no} ⟶ hole concentration n-side at 0-bias

If V_B = barrier potential,
K_B = Boltzmann const
T = absolute temp.

then
$$\exp\left(\frac{-eV_B}{K_BT}\right) = \frac{n_{po}}{n_{no}} = \frac{p_{no}}{p_{po}} \quad —(10).$$

EXTRA NOTE

~~For~~ Considering p-n junction diode,
the total electron/donor concentration
= donor concentration in n-side + electron concentration in p-side.
$= n_{no} + n_{po}$ (eqn. 8 + eqn 7)
$$= N_D + \frac{n_i^2}{N_A} \quad —(11).$$

putting this from eqn (11) in eqn (10).
$$e^{-eV_B/K_BT} = \frac{n_{po}}{n_{no}} = \frac{n_i^2/N_A}{N_D}$$

$$e^{\frac{-eV_B}{K_BT}} = \frac{n_i^2}{N_AN_D}$$

or, $$\frac{-eV_B}{K_BT} = \ln\frac{n_i^2}{N_AN_D}$$

or, $$\frac{eV_B}{K_BT} = \ln\frac{N_AN_D}{n_i^2}$$

or, $$\boxed{V_B = \left(\frac{K_BT}{e}\right)\ln\frac{N_AN_D}{n_i^2}}$$

∵ $\left(\frac{K_BT}{e}\right)$ = ~~conventional~~ const

∴ $V_B \propto \ln\frac{N_AN_D}{n_i^2}$.

or, **Barrier Potential ∝ Dopant concentrations**

~~As V_B increases~~

As N_A, N_D increases ⟶ V_B increases.