Energy bands in Intrinsic and Extrinsic silicon:

Energy Band Diagram of Conductor, Insulator and Semiconductor:

Now let us come to an important category of materials, which are neither insulators nor conductors. The forbidden gap in such materials is very narrow as shown in Fig. 2.4 (c). Such materials are called semiconductors. The forbidden gap is about 1 eV. In such materials, the energy provided by the heat at room temperature is sufficient to lift the electrons from the valence band to the conduction band. Therefore at room temperature, semiconductors are capable of conduction. But at 0°K or absolute zero (−273°C), all the electrons of semiconductor materials find themselves locked in the valence band. Hence at 0°K, the semiconductor materials behave as perfect insulators. In case of semiconductors, forbidden gap energy depends on the temperature. For silicon and germanium, this energy is given by,

\[
E_G = \begin{align*}
1.21 & - 3.6 \times 10^{-4} \times T \\
0.785 & - 2.23 \times 10^{-4} \times T
\end{align*} \text{ eV (for Silicon)}
\]

\[
E_G = \begin{align*}
0.785 & - 2.23 \times 10^{-4} \times T
\end{align*} \text{ eV (for Germanium)}
\]

where \( T = \text{Absolute temperature in °K} \)

Assuming room temperature to be 27° C i.e. 300° K, the forbidden gap energy for Si and Ge can be calculated from the above equations. The forbidden gap for the germanium is 0.72 eV while for the silicon it is 1.12 eV at room temperature. The silicon and germanium are the two widely used semiconductor materials in electronic devices, as mentioned earlier.

**Key Point**: While calculating \( E_G \), substitute \( T \) in °K.

In intrinsic semiconductor, the probability of finding an electron in the conduction band is zero and the probability of finding a hole in the valence band is zero, at absolute zero i.e. \( T = 0°K \).

Now let \( E_C \) be the lowest energy level in the conduction band while \( E_V \) be the highest energy level in the valence band. As temperature increases, equal number of electrons and holes get generated. Hence probability of finding electron in conduction band and probability of finding hole in valence band is same.

The fermi level in such a case is given by,

\[
E_f = \frac{E_C + E_V}{2}
\]
Thus in the energy band diagram, the fermi level for the intrinsic semiconductor lies at the center of the forbidden energy band. Hence the energy band diagram for intrinsic semiconductor is shown as in the Fig. 2.15.

**Key Point:** The fermi level in the center of forbidden gap indicates equal concentrations of free electrons and holes.

**Fig. 2.15 Energy band diagram for intrinsic semiconductor**

When the impurities are added to the intrinsic semiconductor the allowable energy levels are introduced and material becomes extrinsic semiconductor.

In n-type semiconductor, a donor impurity is added. Each donor atom donates one free electron and there are large number of free electrons, available in the conduction band. The donor energy level corresponding to the donor impurity added is just below the conduction band. This donor level is indicated as $E_D$ and its distance is 0.01 eV below the conduction band in germanium while it is 0.05 eV below the conduction band in silicon. As this distance is very small, even at room temperature, almost all the extra electrons from the donor impurity atoms jump into the conduction band. Hence number of free electrons is very large in case of n-type material. Due to abundant free electrons, the probability of occupying the energy level by the electrons, towards the conduction band is more. This probability is indicated by Fermi level $E_F$. So in n-type material, the fermi
level $E_F$ gets shifted towards the conduction band. But it is below the donor energy level. The overall energy band diagram for n-type material is shown in the Fig. 2.21 (a).

![Energy band diagram for n-type and p-type material](image)

**Fig. 2.21 Energy band diagrams for extrinsic semiconductors**

As against this, in p-type material, acceptor impurity is added. Due to this, large number of holes get created in the valence band. The acceptor energy level corresponding to acceptor impurity gets introduced which is indicated as $E_A$ and is very close to the valence band just above it. At room temperature, the electrons from valence band jump to acceptor energy level, leaving behind the holes in valence band. This shifts the fermi level $E_F$ towards the valence band. It lies above the acceptor energy level. The overall energy band diagram for p-type material is shown in the Fig. (b).

**Key Point**: It must be noted that the doped material is always electrically neutral as the total number of electrons is equal to the total number of protons, after the addition of impurity.

**Carrier transport:**

Any motion of free carriers in a semiconductor leads to a current. This motion can be caused by an electric field due to an externally applied voltage, since the carriers are charged particles. This transport mechanism is carrier drift. Carriers also move from regions where the carrier density is high to regions where the carrier density is low. This carrier transport mechanism is due to the thermal energy and the associated random motion of the carriers. This transport mechanism is carrier diffusion. The total current in a semiconductor equals the sum of the drift and the diffusion current.

As applies an electric field to a semiconductor, the electrostatic force causes the carriers to first accelerate and then reach a constant average velocity, $v$, due to collisions with impurities and lattice vibrations. The ratio of the velocity to the applied field is called the mobility.
Intrinsic semiconductors behave as a perfect insulator at absolute zero temperature. Let us see what happens at room temperature. At room temperature, the number of valence electrons absorb the thermal energy, due to which they break the covalent bond and drift to the conduction band. Such electrons become free to move in the crystal as shown in the Fig. 2.6 (a).

Once the electrons are dislodged from the covalent bonds, then they become free. Such free electrons wander in a random fashion in a crystal. The energy required to break a covalent bond is 0.72 eV for germanium and 1.1 eV for silicon, at room temperature.

When a valence electron drift from valence to conduction band breaking a covalent bond, a vacancy is created in the broken covalent bond. Such a vacancy is called a hole. Whenever an electron becomes free, the corresponding hole gets generated.

So **free electrons and holes get generated in pairs**. The formation of electron-hole pair is shown in the Fig. 2.6 (b) while the corresponding energy band diagram is shown in the Fig. 2.6 (c). Such a generation of electron hole pairs due to thermal energy is called **thermal generation**.

![Fig. 2.6 Thermal generation](image)

The concentration of free electrons and holes is always equal in an intrinsic semiconductor. The hole also serves as a carrier of electricity similar to that of free electron. An **electron is negatively charged particle**. Thus a hole getting created due to electron drift is said to be positively charged.

**Key Point**: Thus in an intrinsic semiconductors both holes as well as free electrons are the charge carriers.
Drift and diffusion currents:

The flow of charge (ie) current through a semiconductor material are of two types namely drift & diffusion. (ie) The net current that flows through a (PN junction diode) semiconductor material has two components:

(i) Drift current  
(ii) Diffusion current

1.9 Drift Current

When a voltage is applied to a semiconductor, the free electrons try to move in a straight line towards the positive terminal of the battery. The electrons, moving towards positive terminal collide with the atoms of semiconductor and connecting wires, along its way. Each time the electron strikes an atom, it rebounds in a random direction. But still the applied voltage make the electrons drift towards the positive terminal. This drift causes current to flow in a semiconductor, under the influence of the applied voltage. This current produced due to drifting of free electrons is called drift current and the velocity with which electrons drift is called drift velocity. Thus drift current means the flow of current due to bouncing of electrons from one atom to another, travelling from negative terminal to positive terminal of the applied voltage.

Key Point: The direction of conventional current is always opposite to the direction of drifting electrons.

This is shown in the Fig. 1.14.

![Fig. 1.14 Drift mechanism causing drift current](image)

When an electric field is applied across the semiconductor material, the charge carriers attain a certain drift velocity \( V_d \), which is equal to the product of the mobility of the charge carriers and the applied Electric Field intensity \( E \):

\[
Drift \text{ velocity } V_d = \text{mobility of the charge carriers} \times \text{Applied Electric field intensity } E
\]

Holes move towards the negative terminal of the battery and electrons move towards the positive terminal of the battery. This combined effect of movement of the charge carriers constitutes a current known as “the drift current “.
Thus the drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

Drift current due to the charge carriers such as free electrons and holes are the current passing through a square centimeter perpendicular to the direction of flow.

\[ J_n = q n \mu_n E \text{ A/cm}^2 \]

\[ J_p = q p \mu_p E \text{ A/cm}^2 \]

Where,  
- \( n \) - Number of free electrons per cubic centimeter.  
- \( p \) - Number of holes per cubic centimeter  
- \( \mu_n \) – Mobility of electrons in cm\(^2\)/Vs  
- \( \mu_p \) – Mobility of holes in cm\(^2\)/Vs  
- \( E \) – Applied Electric filed Intensity in V/cm  
- \( q \) – Charge of an electron = 1.6 x 10\(^{-19}\) coulomb.

1.10 Diffusion Current

This is the current which is due to the transport of charges occurring because of nonuniform concentration of charged particles in a semiconductor.

Consider a piece of semiconductor which is nonuniformly doped. Due to such nonuniform doping, one type of charge carriers occur at one end of a piece of semiconductor. The charge carriers are either electrons or holes, of one type depending upon the impurity used. They have the same polarity and hence experience a force of repulsion between them. The result is that there is a tendency of the charge carriers to move gradually i.e. to diffuse from the region of high carrier density to the low carrier density. This process is called diffusion. This movement of charge carriers under the process of diffusion constitutes a current called diffusion current. This is shown in the Fig. 1.15.

![Diffusion current](image)

Fig. 1.15 Diffusion current

The diffusion current continues till all the carriers are evenly distributed throughout the material. A diffusion current is possible only in case of nonuniformly doped semiconductors while drift current is possible in semiconductors as well as conductors.

**Key Point**: The diffusion current exists without external voltage applied while drift current can not exist without an external voltage applied.

It is possible for an electric current to flow in a semiconductor even in the absence of the applied voltage provided a concentration gradient exists in the material. A concentration gradient exists if the number of either elements or holes is greater in one region of a semiconductor as compared to the rest of the Region. In a semiconductor material the charge carriers have the tendency to move from the region of higher concentration to that of lower concentration of the same type of charge carriers. Thus the movement of charge carriers takes place resulting in a current called diffusion current.
Mobility and Resistivity:

When an electric field \( E \) is applied across a piece of material, the electrons respond by moving with an average velocity called the drift velocity. The electron mobility is defined by the equation:

\[
v_d = \mu E.
\]

where:

- \( E \) or \( \varepsilon \) is the magnitude of the electric field applied to a material,
- \( v_d \) is the magnitude of the electron drift velocity (in other words, the electron drift speed) caused by the electric field, and
- \( \mu \) is the electron mobility.

The hole mobility is defined by the same equation. Both electron and hole mobilities are positive by definition.

A steady state drift speed has been superimposed upon the random thermal motion of the electrons. Such a directed flow of electron constitutes a current. If the concentration of free electrons is \( n \), the current density \( J \) is \( J = n v_e = n e \mu E = \sigma E \) where \( \sigma = n e \mu \) is the conductivity of the metal in \((\text{ohm-meter})^{-1}\). The equation \( J = \sigma E \) is recognized as Ohm’s Law, namely the conduction current is proportional to the applied voltage.

The property called conductivity indicates the ease with which a material can carry the current. Thus more conductivity means that material can carry high current, very easily. The conductivity of a good conductor is high while that of an insulator is low.

In intrinsic semiconductor, very few electron-hole pairs get generated at room temperature. Hence very small current can be constituted, due to the application of voltage to an intrinsic semiconductor. Thus the conductivity of an intrinsic semiconductor at room temperature is very low. Such a low conductivity has very little practical significance.

Due to low conductivity, the intrinsic semiconductors are not used in practice for manufacturing of electronic devices.

In a semiconductor, there are two charged particles. One is negatively charged free electrons while the other is positively charged holes. These particles move in opposite direction, under the influence of an electric field but as both are of opposite sign, they constitute current in the same direction.

For the semiconductor,

\[
\begin{align*}
n & = \text{concentration of free electrons/m}^3 \\
p & = \text{concentration of holes/m}^3 \\
\mu_n & = \text{mobility of electrons in m}^2/\text{V-s} \\
\mu_p & = \text{mobility holes in m}^2/\text{V-s}
\end{align*}
\]

then the current density is given by,

\[
J = (n\mu_n + p\mu_p) \varepsilon E \text{ A/m}^2
\]  

...(1)

This can be obtained from the general expression for \( J \) derived in last section, equation (6).

Hence the conductivity for a semiconductor is given by,

\[
\sigma = (n\mu_n + p\mu_p) \varepsilon (\Omega - \text{m}^{-1})
\]  

...(2)
**Generation and Recombination of carriers:**
In the solid-state physics of semiconductors, carrier generation and recombination are processes by which mobile charge carriers (electrons and electron holes) are created and eliminated. Carrier generation and recombination processes are fundamental to the operation of many optoelectronic semiconductor devices, such as photodiodes, LEDs and laser diodes. They are also critical to a full analysis of p-n junction devices such as bipolar junction transistors and p-n junction diodes.

The electron–hole pair is the fundamental unit of generation and recombination, corresponding to an electron transitioning between the valence band and the conduction band where generation of electron is a transition from the valence band to the conduction band and recombination leads to a reverse transition.

Carrier generation describes processes by which electrons gain energy and move from the valence band to the conduction band, producing two mobile carriers; while recombination describes processes by which a conduction band electron loses energy and re-occupies the energy state of an electron hole in the valence band. Recombination and generation are always happening in semiconductors, both optically and thermally, and their rates are in balance at equilibrium.

The product of the electron and hole densities \((n \text{ and } p)\) is a constant \(np = n_i^2\) at equilibrium, maintained by recombination and generation occurring at equal rates. This is called Law of Mass Action. This Law can be applied to both intrinsic and extrinsic semiconductors. When there is a surplus of carriers (i.e., \(np > n_i^2\)), the rate of recombination becomes greater than the rate of generation, driving the system back towards equilibrium. Likewise, when there is a deficit of carriers (i.e. \(np < n_i^2\)), the generation rate becomes greater than the recombination rate, again driving the system back towards equilibrium.

The movement of holes in the valence band is always random and similarly the movement of free electrons in the conduction band is also random. Thermal agitation continues to produce new hole-electron pairs. Occasionally, a free electron approaches a hole and falls into it. This merging of a free electron and a hole is called recombination. After the recombination, an electron-hole pair gets disappeared. Due to recombination the number of charge carriers decreases. The amount of time between the creation and disappearance of a free electron or hole is called the mean life time of the charge carrier.

At any temperature, at any instant, the free electrons and holes, the two types of charge carriers are present in equal numbers. This concentration is called intrinsic concentration. Mathematically this is indicated as,

\[
\begin{align*}
\text{number of free electrons per unit volume} & = n \\
\text{number of holes per unit volume} & = p \\
\text{Intrinsic concentration} & = n_i
\end{align*}
\]

The concentration is measured in the units number per m\(^3\) or per cm\(^3\).
Poisson and continuity equations:
The relationship between potential and charge density is given by Poisson’s equation, 
\[ \frac{d^2V}{dx^2} = \frac{eN_A}{\varepsilon} \], where \( \varepsilon \) is the permittivity of the semiconductor. If \( \varepsilon_r \) is the relative dielectric constant and \( \varepsilon_0 \) is the permittivity of free space, then \( \varepsilon = \varepsilon_r \varepsilon_0 \).

**Continuity Equation**

The carrier concentration in the body of a semiconductor is a function of time and distance. Mathematically, a partial differential equation governs this functional relationship between carrier concentration, time and distance. Such an equation is called continuity equation. The equation is based on the fact that charge can neither be created nor destroyed.

Consider the infinitesimal n type element of volume of area A and length dx as shown in the Fig. 2.27. The average hole concentration is \( p/m^3 \). The current entering the volume at \( x \) is \( I \) and leaving at \( x + dx \) is \( I + dI \). This change in current is because of diffusion.

Hence,

\[ \therefore dI = \text{Number of coulombs per second decreased within the volume} \quad \ldots (1) \]

Now if \( \tau_p \) is the mean life time of the holes then,

\[ \frac{P}{\tau_p} = \text{Holes per second lost by recombination per unit volume} \]

Due to recombination, number of coulombs per second decreased within the given volume is,

\[ = \left( \text{Charge} \right) \times \left( \text{Holes / sec} \right) \times \left( \text{per unit volume} \right) \times \left( \text{Volume} \right) \]

\[ = q \times \frac{P}{\tau_p} \times (A \ dx) = qA \ dx \times \frac{P}{\tau_p} \quad \ldots (2) \]

While let \( g \) is the rate at which electron hole pairs are generated by thermal generation per unit volume. Due to this, number of coulombs per second increases with the volume

\[ = \left( \text{Charges} \right) \times \left( \text{Rate of generation} \right) \times \left( \text{Volume} \right) \]

\[ = q \ g \ A \ dx \quad \ldots (3) \]

Thus the total change in number of coulombs per second is because of three factors as indicated by the equations (1), (2) and (3).
Now due to diffusion the concentration of charge carriers decreases exponentially with the distance.

Total change in holes per unit volume per second is \( \frac{dp}{dt} \). Hence the total change in coulombs per second within the given volume

\[
= q \frac{dp}{dt} \text{ (Volume)} = q A \, dx \, \frac{dp}{dt} \quad \cdots \quad (4)
\]

According to law of conservation of charges,

\[
q A \, dx \, \frac{dp}{dt} = -q \, A \, dx \, \frac{p}{\tau_p} + q \, g \, A \, dx \, - \, dI \quad \cdots \quad (5)
\]

**Key Point**: The negative sign indicates decrease while positive indicates increase in number of coulombs per second.

\[
\therefore \quad \frac{dp}{dt} = -\frac{p}{\tau_p} + g \frac{-dI}{q \, A \, dx} \quad \cdots \quad (6)
\]

But \( J = \frac{1}{A} \) = Current density

\[
\therefore \quad I = JA \text{ i.e. } dI = ADJ \text{ as } A \text{ is constant.}
\]

\[
\therefore \quad \frac{dp}{dt} = -\frac{p}{\tau_p} + g \frac{-1}{q \, dx} \quad \cdots \quad (7)
\]

the total current density \( J \) is due to drift and diffusion current.

\[
\therefore \quad J = -q D_p \frac{dp}{dx} + p q \mu_p E = \text{diffusion + drift} \quad \cdots \quad (8)
\]

where \( E = \text{Electric field intensity within the volume} \).
If the semiconductor is in thermal equilibrium and subjected to no external electric field then hole density will attain a constant value \( p_0 \). Under this condition \( I = 0 \) i.e. \( J = 0 \) and \( \frac{dp}{dt} = 0 \) due to equilibrium. Using in (7),

\[
0 = -\frac{p_0}{\tau_p} + g - o
\]

::

\[
g = \frac{p_0}{\tau_p}
\]  

... (9)

The equation (9) indicates the thermal equilibrium i.e. the rate at which holes are thermally generated just equal to the rate at which holes are lost due to the recombination.

Using (8) and (9) in (7),

\[
\frac{dp}{dt} = \frac{-p - p_0}{\tau_p} + \frac{1}{q} \frac{d}{dx} \left[ -q D_p \frac{dp}{dx} + pq \mu_p E \right]
\]

::

\[
\frac{dp}{dt} = \frac{-p - p_0}{\tau_p} + D_p \frac{d^2 p}{dx^2} - \mu_p \frac{d (pE)}{dx}
\]  

... (10)

This is called equation of conservation of charge or the continuity equation.

As holes in n type material are considered, let us use the suffix \( n \). And as concentration is a function of both time \( t \) and distance \( x \), let us use partial differentiation. Hence the final continuity equation takes the form as,

\[
\frac{\partial p_n}{\partial t} = \frac{(p_n - p_{n0})}{\tau_p} + D_p \frac{\partial^2 p_n}{\partial x^2} - \mu_p \frac{\partial (p_n E)}{\partial x}
\]  

... (11)

Similarly the continuity equation for the electrons in p type material can be written as,

\[
\frac{\partial n_p}{\partial t} = \frac{(n_p - n_{p0})}{\tau_n} + D_n \frac{\partial^2 n_p}{\partial x^2} - \mu_n \frac{\partial (n_p E)}{\partial x}
\]  

... (12)

Let us see the special cases for continuity equation under the condition of zero electric field.
Concentration Independent of Distance and $E = 0$

As concentration is not dependent on $x$ and $E = 0$, the last two terms on right hand side of the continuity equation become zero. Hence equation reduces as,

\[
\frac{dp_n}{dt} = - \frac{(p_n - p_{no})}{\tau_p}
\]

... (13)

This is a differential equation in terms of $p_n$ and the solution of this equation is,

\[p_n - p_{no} = Ke^{-t/\tau_p}\]

where $K = \text{constant}$

Now $\tau_p$ is mean life time but also time constant of the above equation.

**Key Point**: Thus $\tau_p$ can be defined as the time taken by the injected concentration to fall to 36.78% of its initial value.

Concentration Independent of Time and $E = 0$

As concentration is not dependent on $t$ and $E = 0$, the left hand side of continuity equation is zero and last term on right hand side is zero.

\[\frac{\partial p_n}{\partial t} = 0 \quad \text{and} \quad \mu_p \frac{\partial (p_nE)}{\partial x} = 0\]

\[0 = - \frac{(p_n - p_{no})}{\tau_p} + D_p \frac{d^2 p_n}{dx^2}\]

\[\frac{d^2 p_n}{dx^2} = \frac{p_n - p_{no}}{D_p \tau_p}\]

... (14)

But \[\sqrt{D_p \tau_p} = L_p = \text{diffusion length of holes}\]

Hence the solution of the equation (14) takes the form,

\[p_n - p_{no} = K_1 e^{-x/L_p} + K_2 e^{+x/L_p}\]

where $K_1, K_2 = \text{Constants}$

Concentration Varies Sinusoidally with Time and $E = 0$

The injected concentration varies sinusoidally with an angular frequency of $\omega$. The sinusoidal variation is indicated in phasor form as,

\[P_n(x, t) = P_n(x) e^{j\omega t}\]

Substituting in continuity equation with $E = 0$,

\[j\omega P_n(x) = - \frac{P_n(x)}{\tau_p} + D_p \frac{d^2 P_n(x)}{dx^2}\]

i.e.

\[\frac{d^2 P_n}{dx^2} = \left[\frac{1 + j\omega \tau_p}{\tau_p D_p}\right] P_n \]

but \[\tau_p D_p = L_p^2\]

\[\frac{d^2 P_n}{dx^2} = \left[\frac{1 + j\omega \tau_p}{L_p^2}\right] P_n\]

For zero frequency ($\omega = 0$), the equation takes the form as obtained for special case discussed in 2.2.0.2.

Hence a.c. solution for $\omega \neq 0$ can be obtained from d.c. solution by replacing $L_p$ by \[L_p/\sqrt{1 + j\omega \tau_p}\].

Thus continuity equation is the fundamental law governing the flow of charge.
Questions:
1. Discuss the Energy bands in intrinsic and extrinsic silicon.
2. Write notes on carrier transport in semiconductor.
3. Explain Drift and Diffusion current for a semiconductor.
4. With expressions, explain mobility and conductivity of a semiconductor.
5. Describe generation and recombination of carriers.
6. Derive the expression for Continuity equation for a semiconductor.
1.1 P-N Junction

The two type of materials namely p-type and n-type are chemically combined with a special fabrication technique to form a p-n junction. The p-n junction forms a popular semiconductor device called diode. The diode is the basic element of number of electronic circuits. Hence the knowledge of p-n junction and its behaviour is very important in understanding the operation of number of electronic circuits, applications and devices.

1.4 Unbiased P-N Junction

In a given material if the doping is not uniform then at one place large number of charge carriers exist while at other place small number of charge carriers exist. In a high charge carrier concentration area, all charge carriers are of similar type, either electrons or holes and hence start repelling each other. Due to this, charge carriers start moving from high concentration area towards low concentration area, to achieve uniform concentration all over the material. This process is called diffusion and exists when there is nonuniform concentration of charge carriers in the material. In a p-n junction, on n side there are large number of electrons while on p side electrons are minority in number. So there is high concentration of electrons on p side while low concentration of electrons on p side. Hence diffusion starts and electrons start moving from n side towards p side.

Similarly the holes from p side diffuse across the junction into the n-region.

The initial diffusion is shown in the Fig. 1.4.

1.4.1 Formation of Depletion Region

As holes enter the n-region, they find number of donor atoms. The holes recombine with the donor atoms. As donor atoms accept additional holes, they become positively charged immobile ions. This happens immediately when holes cross the junction hence number of positively charged immobile ions get formed near the junction on n side.

Atoms on p side are acceptor atoms. The electrons diffusing from n side to p side recombine with the acceptor atoms on p side. As acceptor atoms accept additional electrons, they become negatively charged immobile ions. Such large number of negatively charged immobile ions get formed near the junction on p side. The formation of immobile ions near the junction is shown in the Fig. 1.5.

As more number of holes diffuse on n side, large positive charge gets accumulated on n side near the junction. Eventually the diffusing holes which are positively charged, get repelled due to accumulated positive charge on n side. And the diffusion of holes stops.
Similarly due to large negative charge accumulated on p side, the diffusing electrons get repelled and eventually the diffusion of electrons also stops.

Thus in thermal equilibrium, in the region near the junction, there exists a wall of negative immobile charges on p side and a wall of positive immobile charges on n side. In this region, there are no mobile charge carriers. Such a region is depleted of the free mobile charge carriers and hence called depletion region or depletion layer. The depletion region is also called space-charge region. In equilibrium condition, the depletion region gets widened upto a point where no further electrons or holes can cross the junction. Thus depletion region acts as the barrier.

The physical distance from one side to other side of the depletion region is called width of the depletion region.

Practically width of the depletion region is very small of the order of few microns where 1 micron = 1 × 10^{-6} m.

1.4.2 Barrier Potential

Due to immobile positive charges on n side and negative charges on p side, there exists an electric field across the junction. This creates potential difference across the junction which is called barrier potential, junction potential, built-in potential or cut-in voltage of p-n junction.

![Diagram of p-n junction](image)

**Fig. 1.6 Open circuited p-n junction**

The barrier potential depends on,
1. Type of semiconductor
2. The donor impurity added
3. The acceptor impurity added
4. The temperature
5. Intrinsic concentration

<table>
<thead>
<tr>
<th>Semiconductor material</th>
<th>Symbol</th>
<th>Barrier potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>0.6 V</td>
</tr>
<tr>
<td>Germanium</td>
<td>Ge</td>
<td>0.2 V</td>
</tr>
</tbody>
</table>

The barrier potential is called height of the depletion region and expressed in volts. Symbolically it is denoted as \( V_J \), \( V_o \) or \( V_Y \).
1.4.3 Effect of Doping on Depletion Region

The width of the depletion region depends on the amount of doping on n side and p side. If the two sides are equally doped, the width of the depletion region is equal on both sides as shown in Fig. 1.7 (a). But if n side is heavily doped as compared to p side, then depletion region is observed more on p side as shown in the Fig. 1.7 (b). If p side is heavily doped as compared to n side, then depletion region is observed more on n side as shown in the Fig. 1.7 (c).

(a) Both sides equally doped  (b) n side heavily doped  (c) p side heavily doped  

Fig. 1.7

Key Point: The depletion region penetrates more on the lightly doped side.

1.5 The P-N Junction Diode

The p-n junction forms a popular semiconductor device called p-n junction diode. The p-n junction has two terminals called electrodes, one each from p-region and n-region. Due to the two electrodes it is called diode i.e. diode + electrode.

To connect the n and p-regions to the external terminals, a metal is applied to the heavily doped n and p-type semiconductor regions. Such a contact between a metal and a heavily doped semiconductor is called ohmic contact. Such an ohmic contact has two important properties,

1. It conducts current equally in both the directions.

2. The drop across the contact is very small, which do not affect the performance of the device.

Thus ohmic contacts are used to connect n and p-type regions to the electrodes.

The Fig. 18 (a) shows schematic arrangement of p-n junction diode while the Fig. 1.8 (b) shows the symbol of p-n junction diode. The p-region acts as anode while the n-region acts as cathode. The arrowhead in the symbol indicates the direction of the conventional current, which can flow when an external voltage is connected in a specific manner across the diode.

(a) Two electrodes  (b) Symbol of a diode  

Fig. 1.8
1.5.1 Biasing of P-N Junction Diode

Applying external d.c. voltage to any electronic device is called biasing. As seen, there is no current in the unbiased p-n junction at equilibrium.

**Key Point:** The usefulness of p-n junction lies in the fact that it allows current flow only in one direction, under biased condition.

Depending upon the polarity of the d.c. voltage externally applied to it, the biasing is classified as **Forward biasing** and **Reverse biasing**.

1.5.2 Types of Diodes

When forward current flows under forward biasing, diode gets heated. Hence forward current should not exceed the particular maximum value. Similarly the diode can be damaged due to large reverse voltage applied to it during reverse biasing. This voltage also must be maintained below the particular maximum value. These maximum values are specified in the manufacturer's datasheet.

**Key Point:** Practically the diodes which can carry large forward current and handle large reverse voltage are physically large in size.

The diodes which are small in size can carry low forward current and can handle low reverse voltage. The Fig. 1.9 shows the types of diodes based on forward current carrying and reverse voltage withstanding capacity.

![Diodes Types](image)

**Fig. 1.9 Types of diodes**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Diode</th>
<th>Forward current capacity</th>
<th>Reverse voltage capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Low current</td>
<td>Upto 100 mA</td>
<td>Upto 75 V</td>
</tr>
<tr>
<td>2.</td>
<td>Medium current</td>
<td>Upto 400 mA</td>
<td>Upto 200 V</td>
</tr>
<tr>
<td>3.</td>
<td>Large current</td>
<td>Few amperes</td>
<td>Several hundred volts</td>
</tr>
</tbody>
</table>

Let us see in detail, behaviour of a p-n junction under two biasing conditions.

1.6 Forward Biasing of P-N Junction Diode

If an external d.c. voltage is connected in such a way that the p-region terminal is connected to the positive of the d.c. voltage and the n-region is connected to the negative of the d.c. voltage, the biasing condition is called **forward biasing**. The p-n junction is said to be forward biased.

**Key Point:** Forward biasing means connecting p-region to +ve and n-region to -ve of the battery.
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(a) Forward biasing

(b) Symbolic representation

Fig. 1.10

The Fig. 1.10 (a) shows the connection of forward biasing of a p-n junction. To limit the current, practically a current limiting resistor is connected in series with the p-n junction diode. The Fig. 1.10 (b) shows the symbolic representation of a forward biased diode.

1.6.1 Operation of Forward Biased Diode

When the p-n junction is forward biased as long as the applied voltage is less than the barrier potential, there cannot be any conduction.

When the applied voltage becomes more than the barrier potential, the negative terminal of battery pushes the free electrons against barrier potential from n to p-region. Similarly positive terminal pushes the holes from p to n-region. Thus holes get repelled by positive terminal and cross the junction against barrier potential. Thus the applied voltage overcomes the barrier potential. This reduces the width of depletion region.

As forward voltage is increased, at a particular value the depletion region becomes very much narrow such that large number of majority charge carriers can cross the junction.

The large number of majority carriers constitute a current called forward current. Once the conduction electrons enter the p-region, they become valence electrons. Then they move from hole to hole towards the positive terminal of the battery. The movement of valence electrons is nothing but movement of holes in opposite direction to that of electrons, in the p-region. So current in the p-region is the movement of holes which are majority carriers. This is the hole current. While the current in the n-region is the movement of free electrons which are majority carriers. This is the electron current. Hence the overall forward current is due to the majority charge carriers. The action is shown in the Fig. 1.11. These majority carriers can then travel around the closed circuit and a relatively large current flows. The direction of flow of electrons is from negative to positive of the battery. While direction of the conventional current is from positive to negative of the battery as shown in the Fig. 1.11.

Key Point: The direction of flow of electrons and conventional current is opposite to each other.
1.6.2 Effect on the Depletion Region

Due to the forward bias voltage, more electrons flow into the depletion region, which reduces the number of positive ions. Similarly, flow of holes reduces the number of negative ions. This reduces the width of the depletion region. This is shown in the Fig. 1.12.

![Depletion region](image)

**Fig. 1.12**

**Key Point**: Depletion region narrows due to forward bias voltage.

1.6.3 Effect of the Barrier Potential

Under the influence of applied forward bias voltage, the free electrons get the energy equivalent to the barrier potential so that they can easily overcome the barrier, which is a sort of a hill and cross the junction. While crossing the junction, the electrons give up the amount of energy equivalent to the barrier potential. This loss of energy produces a voltage drop across the p-n junction which is almost equal to the barrier potential.

**Key Point**: The polarities of voltage drop across the p-n junction in forward biased condition are opposite to that of barrier potential but the value is almost equal to the barrier potential.

Due to the internal resistance, there is additional small voltage drop across the diode.

Thus the total voltage drop across a p-n junction diode in a forward biased condition is $V_f$ and it is made up of

1. Drop due to barrier potential.
2. Drop due to internal resistance.

$$V_f = V_T + I_f r_f$$

**Key Point**: The total $V_f$ is of the order of 0.7 V for silicon and 0.3 V for the germanium.

1.6.4 Forward V-I Characteristics of Diode

The response of p-n junction can be easily indicated with the help of characteristics called V-I characteristics of p-n junction. It is the graph of voltage applied across the p-n junction and the current flowing through the p-n junction.

![Forward biased diode](image)

**Fig. 1.13** Forward biased diode

The Fig. 1.13 shows the forward biased diode. The applied voltage is $V$ while the voltage across the diode is $V_f$. The current flowing in the circuit is the forward current $I_f$. The graph of forward current $I_f$ against the forward voltage $V_f$ across the diode is called forward characteristics of a diode.
The forward characteristics of a diode is shown in the Fig. 1.14.

![Forward characteristics of a diode](image)

Fig. 1.14 Forward characteristics of a diode

Basically forward characteristics can be divided into two regions:

1. **Region O to P**: As long as $V_f$ is less than cut-in voltage ($V_f$), the current flowing is very small. Practically this current is assumed to be zero.

2. **Region P to Q and onwards**: As $V_f$ increases towards $V_f$, the width of depletion region goes on reducing. When $V_f$ exceeds $V_f$, i.e. cut-in voltage, the depletion region becomes very thin and current $I_f$ increases suddenly. This increase in the current is exponential as shown in the Fig. 1.14 by the region P to Q.

The point P, after which the forward current starts increasing exponentially is called **knee** of the curve.

**Key Point**: The normal forward biased operation of the diode is above the knee point of the curve, i.e. in the region $P-Q$.

The forward current is the conventional current, hence it is treated as positive and the forward voltage $V_f$ is also treated positive. Hence the forward characteristics is plotted in the first quadrant.

### 1.6.5 Forward Resistance of Diode

The resistance offered by the p-n junction diode in forward biased condition is called **forward resistance**. The forward resistance is defined in two ways:

1) **Static forward resistance**:

This is the forward resistance of p-n junction diode when p-n junction is used in d.c. circuit and the applied forward voltage is d.c. This resistance is denoted as $R_f$ and is calculated at a particular point on the forward characteristics.

Thus at a point E shown in the forward characteristics, the static resistance $R_f$ is defined as the ratio of the d.c. voltage applied across the p-n junction to the d.c. current flowing through the p-n junction.

$$R_f = \frac{\text{Forward d.c. voltage}}{\text{Forward d.c. current}} = \frac{OA}{OC} \text{ at point E}$$

2) **Dynamic forward resistance**:

The resistance offered by the p-n junction under a.c. conditions is called **dynamic resistance**, denoted as $r_f$.

**Key Point**: The dynamic resistance is reciprocal of the slope of the forward characteristics.

Consider the change in applied voltage from point A to B shown in the Fig. 1.14. This is denoted as $\Delta V_f$. The corresponding change in the forward current is from point C to D. It is denoted as $\Delta I_f$. Thus the slope of the characteristics is $\Delta I_f / \Delta V_f$. The reciprocal of the slope is dynamic resistance $r_f$. 

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\[
\frac{r_f}{\Delta I_f} = \frac{1}{\left(\Delta I_f / \Delta V_f\right)} = \text{slope of forward characteristics}
\]

Key Point: Generally the value of \( r_f \) is very small of the order of few ohms, in the operating region i.e. above the knee.

1.7 Reverse Biasing of P-N Junction Diode

If an external d.c. voltage is connected in such a way that the p-region terminal of a p-n junction is connected to the negative of the battery and the n-region terminal of a p-n junction is connected to the positive terminal of the battery, the biasing condition is called reverse biasing of a p-n junction.

Key Point: Reverse biasing means connecting p-region to -ve and n-region to +ve of the battery.

The Fig. 1.15 (a) shows the connection of a reverse biasing of a p-n junction while the Fig. 1.15 (b) shows the symbolic representation of a reverse biased diode.

![Diagram of reverse biasing and symbolic representation](image)

**Fig. 1.15**

1.7.1 Operation of Reverse Biased Diode

When the p-n junction is reverse biased the negative terminal attracts the holes in the p-region, away from the junction. The positive terminal attracts the free electrons in the n-region away from the junction. No charge carrier is able to cross the junction. As electrons and holes both move away from the junction, the depletion region widens. This creates more positive ions and hence more positive charge in the n-region and more negative ions and hence more negative charge in the n-region. This is because the applied voltage helps the barrier potential. This is shown in the Fig. 1.16.

![Diagram showing depletion region widening](image)

**Fig. 1.16 Depletion region widens in reverse bias**

Key Point: Reverse biasing increases the width of the depletion region.

As depletion region widens, barrier potential across the junction also increases. However, this process cannot continue for long time. In the steady state, majority current ceases as holes and electrons stop moving away from the junction.
The polarities of barrier potential are same as that of the applied voltage. Due to increased barrier potential, the positive side drags the electrons from p-region towards the positive of battery. Similarly negative side of barrier potential drags the holes from n-region towards the negative of battery. The electrons on p side and holes on n side are minority charge carriers, which constitute the current in reverse biased condition. Thus reverse conduction takes place.

The reverse current flows due to minority charge carriers which are small in number. Hence reverse current is always very small.

**Key Point**: The generation of minority charge carriers depends on the temperature and not on the applied reverse bias voltage. Thus the reverse current depends on the temperature i.e. thermal generation and not on the reverse voltage applied.

For a constant temperature, the reverse current is almost constant though reverse voltage is increased upto a certain limit. Hence it is called reverse saturation current and denoted as $I_0$.

**Key Point**: Reverse saturation current is very small of the order of few microamperes for germanium and few nanoamperes for silicon p-n junction diodes.

The reverse current and its direction is shown in the Fig. 1.17.

![Diagram of reverse biased diode](image)

(a) Flow of minority charge carriers (b) Direction of reverse current

**Fig. 1.17 Reverse biased diode**

The reverse biasing produces a voltage drop across the diode denoted as $V_R$ which is almost equal to applied reverse voltage.

### 1.7.2 Breakdown in Reverse Biased

Though the reverse saturation current is not dependent on the applied reverse voltage, if reverse voltage is increased beyond particular value, large reverse current can flow damaging the diode. This is called reverse breakdown of a diode. Such a reverse breakdown of a diode can take place due to the following two effects,

1. Avalanche effect and 2. Zener effect

#### 1.7.2.1 Breakdown due to the Avalanche Effect

Though reverse current is not dependent on reverse voltage, if reverse voltage is increased, at a particular value, velocity of minority carriers increases. Due to the kinetic energy associated with the minority carriers, more minority carriers are generated when there is collision of minority carriers with the atoms. The collision make the electrons to break the covalent bonds. These electrons are available as minority carriers and get
accelerated due to high reverse voltage. They again collide with another atoms to generate more minority carriers. This is called carrier multiplication. Finally large number of minority carriers move across the junction, breaking the p-n junction. These large number of minority carriers give rise to a very high reverse current. This effect is called avalanche effect and the mechanism of destroying the junction is called reverse breakdown of a p-n junction. The voltage at which the breakdown of a p-n junction occurs is called reverse breakdown voltage. The series resistance must be used to avoid breakdown condition, limiting the reverse current.

1.7.2.2 Breakdown due to the Zener Effect

The breakdown of a p-n junction may occur because of one more effect called zener effect. When a p-n junction is heavily doped the depletion region is very narrow. So under reverse bias conditions, the electric field across the depletion layer is very intense. Electric field is voltage per distance and due to narrow depletion region and high reverse voltage, it is intense. Such an intense field is enough to pull the electrons out of the valence bands of the stable atoms. So this is not due to the collision of carriers with atoms. Such a creation of free electrons is called zener effect which is different than the avalanche effect. These minority carriers constitute very large current and mechanism is called zener breakdown.

Why to avoid reverse breakdown?

1. Large reverse voltage appears across the diode and large current flows through the diode in reverse breakdown condition.
2. So large power gets dissipated which appears in the form of heat at the junction.
3. This increases junction temperature beyond the safe limits and this may damage the diode permanently.

So reverse breakdown must be avoided for conventional diodes.

Some special diodes are manufactured to be operated in the reverse breakdown region and are called zener diodes.

1.7.3 Reverse Characteristics of P-N Junction Diode

The Fig. 1.18 shows the reverse biased diode. The reverse voltage across the diode is $V_R$ while the current flowing is reverse current $I_R$ flowing due to minority charge carriers. The graph of $I_R$ against $V_R$ is called reverse characteristics of a diode.

The polarity of reverse voltage applied is opposite to that of forward voltage. Hence in practice reverse voltage is taken as negative. Similarly the reverse saturation current is due to minority carriers and is opposite to the forward current. Hence in practice reverse saturation current is also taken as negative. Hence the reverse characteristics is plotted in the third quadrant as shown in the Fig. 1.19.
**Key Point:** Typically the reverse breakdown voltage is greater than 50 V for normal p-n junctions.

![Diagram of reverse breakdown voltage and saturation current](image)

**Fig. 1.19**

As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current $I_0$ though reverse voltage is increased. The point A where breakdown occurs and reverse current increases rapidly is called knee of the reverse characteristics.

### 1.7.4 Reverse Resistance of Diode

The p-n junction offers large resistance in the reverse biased condition called reverse resistance. This is also defined in two ways.

1. **Reverse static resistance**:

   This is reverse resistance under d.c. conditions, denoted as $R_r$. It is the ratio of applied reverse voltage to the reverse saturation current $I_0$.

   $$R_r = \frac{QQ}{I_0} = \frac{\text{Applied reverse voltage}}{\text{Reverse saturation current}}$$

2. **Reverse dynamic resistance**:

   This is the reverse resistance under the a.c. conditions, denoted as $r_r$. It is the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

   $$r_r = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{Change in reverse voltage}}{\text{Change in reverse current}}$$

   The dynamic resistance is most important in practice whether the junction is forward or reverse biased.
Complete V-I Characteristics of a Diode

The complete V-I characteristics of a diode is the combination of its forward as well as reverse characteristics. This is shown in the Fig. 1.20.

![Diagram of Diode Characteristics](image)

**Fig. 1.20 Complete V-I characteristics of a diode**

In forward characteristics, it is seen that initially forward current is small as long as the bias voltage is less than the barrier potential. At a certain voltage close to barrier potential, current increases rapidly. The voltage at which diode current starts increasing rapidly is called as cut in voltage. It is denoted by \( V_I \). Below this voltage, current is less than 1 % of maximum rated value of diode current. The cut-in voltage for germanium is about 0.2 V while for silicon it is 0.6 V.

It is important to note that the breakdown voltage is much higher and practically diodes are not operated in the breakdown condition. The **voltage at which breakdown occurs is called reverse breakdown voltage denoted as \( V_{BR} \)**.

**Key Point**: Reverse current before the breakdown is very very small and can be practically neglected.

### 1.8.1 V-I Characteristics of Typical Ge and Si Diodes

The combined forward and reverse characteristics is called V-I characteristics of a diode. As mentioned earlier, the barrier potential for germanium (Ge) diode is about 0.3 V while for Silicon (Si) diode is as about 0.7 V. The potential at which current starts increasing exponentially is also called **Offset potential**, **Threshold potential** or **Firing potential** of a diode. The Fig. 1.21 shows the V-I characteristics of typical Ge and Si diodes.

The reverse saturation current in a germanium diode is about 1000 times more than the reverse saturation current in a silicon diode of a comparable rating. The reverse saturation current \( I_0 \) is of the order of nA for silicon diode while it is of the order of \( \mu A \) for germanium diode. Reverse breakdown voltage for Si diode is higher than that of the Ge diode of a comparable rating.
1.9 V-I Characteristics Equation of a Diode

The mathematical representation of V-I characteristics of diode is called V-I characteristic equation or diode current equation. It gives the mathematical relationship between applied voltage \( V \) and the diode current \( I \). It is given by,

\[
I = I_0 \left[ e^{V/\eta V_T} - 1 \right] A
\]

where
- \( I_0 \) = Reverse saturation current in amperes
- \( V \) = Applied voltage
- \( \eta \) = 1 for germanium diode
  = 2 for silicon diode
- \( V_T \) = Voltage equivalent of temperature in volts.

The factor \( \eta \) is called emission coefficient or ideality factor. This factor takes into account the effect of recombination taking place in the depletion region. The effect is dominant in silicon diodes and hence for silicon \( \eta = 2 \). The range of factor is from 1 to 2.

The voltage equivalent of temperature indicates dependence of diode current on temperature. The voltage equivalent of temperature \( V_T \) for a given diode at temperature \( T \) is calculated as,

\[
V_T = kT \text{ volts}
\]

where
- \( k \) = Boltzmann's constant = \( 8.62 \times 10^{-5} \) eV/°K
- \( T \) = temperature in °K.

At room temperature of 27 °C i.e. \( T = 27 + 273 = 300 \) °K and the value of \( V_T \) is 26 mV, as seen earlier.

The value of \( V_T \) also can be expressed as,

\[
V_T = \frac{T}{k} = \frac{T}{8.62 \times 10^{-5}} = \frac{T}{11600}
\]
**Key Point:** The diode current equation is applicable for all the conditions of diode i.e. unbiased, forward biased and reverse biased.

When unbiased, \( V = 0 \) hence we get,

\[ I = I_0 [e^0 - 1] = 0 \text{ A} \]

Thus there is no current through diode when unbiased.

**Key point:** For forward biased, \( V \text{ must be taken positive and we get current } I \text{ positive which is forward current. For reverse biased, } V \text{ must be taken negative and we get negative current } I \text{ which indicates that it is reverse current.} \)

### 1.9.1 Nature of V-I Characteristics from Equation of Diode

Consider a current equation of diode as,

\[ I = I_0 (e^{V/\eta VT} - 1) \]

Now for a forward biased condition, the bias voltage \( V \) is considered positive and hence exponential index has positive sign. Due to this, \( 1 << e^{V/\eta VT} \) hence neglecting \( 1 \) we get the equation for a forward current as,

\[ I_f = I_0 e^{V/\eta VT} \]

This indicates that once bias voltage exceeds cut in voltage, the forward current increases exponentially. In reverse biased condition, the bias voltage \( V \) is treated negative and due to this exponential index has negative sign. So \( e^{-V/\eta VT} << 1 \), hence neglecting exponential term we get,

\[ \alpha I_R \equiv I_0 (-1) = -I_0 \]

The above equation indicates that under reverse biased condition, the current is reverse saturation current which is negative indicating that it flows in opposite direction to that of forward current and almost constant. Such nature of diode characteristics is already been discussed and it is as shown in Fig. 1.22. The dashed portion represents breakdown region.

![Fig. 1.22 V-I characteristics of p-n junction diode](image)

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As mentioned earlier, $I_0$ is due to minority carriers generated due to thermal energy and hence $I_0$ is temperature dependent. While $V_T$, the voltage equivalent of temperature is $kT$ is also temperature dependent. Hence the forward current which depends on $I_0$ and $V_T$ is also temperature dependent. Hence we can conclude that in all, the entire V-I characteristics of a p-n junction diode depends on the temperature.

The diode current equation is applicable for both forward and reverse biased conditions and completely describes the V-I characteristics of p-n junction diode.

Example 1.1: The voltage across a silicon diode at room temperature of 300°K is 0.71 V when 2.5 mA current flows through it. If the voltage increases to 0.8 V, calculate the new diode current.

Solution: The current equation of a diode is

$$ I = I_0 \left( e^{V/\eta V_T} - 1 \right) $$

At 300 °K, $V_T = 26$ mV = $26 \times 10^{-3}$ V

$$ V = 0.71 \text{ V for } I = 2.5 \text{ mA} $$

and $\eta = 2$ for silicon

$$ 2.5 \times 10^{-3} = I_0 \left[ e^{(0.71/2 \times 26 \times 10^{-3})} - 1 \right] $$

$$ I_0 = 2.93 \times 10^{-9} \text{ V} $$

Now $V = 0.8 \text{ V}$, $I_0$ remains same.

$$ I = 2.93 \times 10^{-9} \left[ e^{(0.8/2 \times 26 \times 10^{-3})} - 1 \right] = 0.0141 \text{ A} = 14.11 \text{ mA} $$

Example 1.2: A germanium diode has a reverse saturation current of 3 $\mu$A. Calculate the voltage at which 1% of the rated current will flow through the diode, at room temperature if diode is rated for 1 A.

Solution:

$\eta = 1$ for germanium,

$$ I_0 = 3 \mu\text{A} = 3 \times 10^{-6} \text{ A} $$

Rated current is 1 A, and

$$ I = 1 \% \text{ of rated current} = 0.01 \text{ A} $$

$$ V_T = 26 \text{ mV at room temperature.} $$

Using current equation of a diode,

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

$$ 0.01 = 3 \times 10^{-6} \left[ e^{V/1 \times 26 \times 10^{-3}} - 1 \right] $$

$$ 3333 = e^{V/1 \times 26 \times 10^{-3}} - 1 $$

$$ e^{V/1 \times 26 \times 10^{-3}} = 3334.33 $$

$$ V \left/ 26 \times 10^{-3} \right. = 8.112 $$

$$ V = 0.2109 \text{ V} $$

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Example 1.3: A diode operating at 300 °K at a forward voltage of 0.4 V carries a current of 10 mA. When voltage is changed to 0.42 V, the current becomes twice. Calculate the value of reverse leakage current and $\eta$ for the diode.

Solution:

At $V_1 = 0.4$ V, $I_1 = 10$ mA and at $V_2 = 0.42$ V, $I_2 = 2I_1 = 20$ mA

Now

$\therefore \quad 10 \times 10^{-3} = I_0 \left[ e^{0.4/\eta \times 26 \times 10^{-3}} - 1 \right]$\[1\]

and

$20 \times 10^{-3} = I_0 \left[ e^{0.42/\eta \times 26 \times 10^{-3}} - 1 \right]$\[2\]

In forward bias condition $1 << e^{V/\eta V_T}, \therefore$ neglecting $1$

$10 \times 10^{-3} = I_0 \frac{15.384}{\eta}$ ... (1)

and

$20 \times 10^{-3} = I_0 \frac{16.153}{\eta}$ ... (2)

Dividing the two equations,

$\frac{1}{2} = \frac{e^{15.384/\eta}}{e^{16.153/\eta}}$

$\therefore \quad e^{16.153/\eta} = 2 e^{15.384/\eta}$

Taking natural logarithm of both sides,

$\frac{16.153}{\eta} = \ln 2 + \frac{15.384}{\eta}$

$\frac{1}{\eta} (16.153 - 15.384) = 0.6931$

$\therefore \quad \eta = 1.109$

Solving equation (1) or (2) \[I_0 = 9.45 \text{ nA}\]

Current Components in PN Junction Diode:

1.10 P-N Diode Currents

It is indicated earlier that when a p-n junction diode is forward biased a large forward current flows, which is mainly due to majority carriers. The depletion region near the junction is very very small, under forward biased condition. In forward biased condition holes get diffused into n side from p side while electrons get diffused into p side from n side. So on p side, the current carried by electrons which is diffusion current due to minority carriers, decreases exponentially with respect to distance measured from the junction. This current due to electrons, on p side which are minority carriers is denoted as $I_{np}$. Similarly holes from p side diffuse into n side carry current which decreases exponentially with respect to distance measured from the junction. This current due to holes on n side, which are minority carriers is denoted as $I_{pn}$. If distance is denoted by $x$ then,

$I_{np} (x) = \text{Current due to electrons in p side as a function of } x$

$I_{pn} (x) = \text{Current due to holes in n side as a function of } x$.

At the junction i.e. at $x = 0$, electrons crossing from n side to p side constitute a current, $I_{np} (0)$ in the same direction as holes crossing the junction from p side to n side constitute a current, $I_{pn} (0)$.
Hence the current at the junction is the total conventional current $I$ flowing through the circuit.

\[ \therefore \quad I = I_{pn}(0) + I_{np}(0) \quad \ldots (1) \]

Now $I_{pn}(x)$ decreases on n side as we move away from junction on n side. Similarly $I_{np}(x)$ decreases on p side as we move away from junction on p side.

But as the entire circuit is a series circuit, the total current must be maintained at $I$, independent of $x$. This indicates that on p side there exists one more current component which is due to holes on p side which are the majority carriers. It is denoted by $I_{pp}(x)$ and the addition of the two currents on p side is total current $I$.

\[ I_{pp}(x) = \text{Current due to holes in p side.} \]

Similarly on n side, there exists one more current component which is due to electrons on n side, which are the majority carriers. It is denoted as $I_{nn}(x)$ and the addition of the two currents on n side is total current $I$.

\[ I_{nn}(x) = \text{Current due to electrons in n side.} \]

On p side,
\[ I = I_{pp}(x) + I_{np}(x) \quad \ldots (2) \]

On n side,
\[ I = I_{nn}(x) + I_{pn}(x) \quad \ldots (3) \]

These current components are plotted as a function of distance in the Fig. 1.23.

The current $I_{pp}$ decreases towards the junction, at the junction enters the n side and becomes $I_{pn}$ which further decreases exponentially. Similarly the current $I_{nn}$ decreases towards the junction, at the junction enters the p side and becomes $I_{np}$ which also further decreases exponentially.

**Key Point:** In forward bias condition, the current enters the p side as a hole current and leaves the n side as an electron current, of the same magnitude.

So sum of the currents carried by electrons and holes at any point inside the diode is always constant equal to total forward current $I$. But the proportion due to holes and electrons in constituting the current varies with the distance, from the junction.

**Diode Equation:**

In a p-n junction diode, if the hole concentrations at the edges of the depletion region are $p_p$ and $p_n$ in p and n type of material respectively and if barrier potential is $V_J$ then,

\[ p_p = p_n e^{V_J/V_T} \quad \ldots (2.4) \]
Consider a forward biased p-n junction diode as shown in the Fig. 2.12.

![Diagram of a p-n junction diode](image)

**Fig. 2.12 Forward biased p-n junction diode**

Due to the forward bias voltage \( V \), barrier potential reduces to \( (V_J - V) \).

Though the proportion of holes and electrons in constituting a current through the p-region is changing, the hole concentration throughout the p-region is constant and denoted as,

\[
p_p = \text{hole concentration in p-region} = p_{p0} \quad \ldots \ (2.5)
\]

While the hole concentration at the edge of the depletion region, at \( x = 0 \) is denoted as,

\[
p_n = p_n(0) \quad \ldots \ (2.6)
\]

Substituting in equation (2.4) we get,

\[
p_{p0} = p_n(0) e^{(V_J - V)/V_T} \quad \ldots \ (2.7)
\]

For an open circuited, p-n junction diode the hole concentration on p-side is \( p_{p0} \) while on the n side it is \( p_{n0} \) and we can write,

\[
p_{p0} = p_{n0} e^{V_J/V_T} \quad \ldots \ (2.8)
\]

For open circuit, \( V = 0 \)

Equating equations (2.7) and (2.8) we get,

\[
p_{n0} e^{V_J/V_T} = p_{n0} e^{(V_J - V)/V_T}
\]

\[
\therefore p_{n0} e^{V_J/V_T} = p_{n0} e^{V_J/V_T} \cdot e^{-V/V_T}
\]

\[
\therefore p_{n0} = p_{n0} e^{V/V_T} \quad \ldots \ (2.9)
\]

This equation representing boundary condition is called the law of the junction.

This equation gives the relation between the hole concentration at the edge of the region (just outside of depletion region) i.e. \( p_n(0) \) in terms of minority carrier concentration \( p_{n0} \) far away from the junction and externally applied bias voltage \( V \).

For a large forward bias, the hole concentration \( p_n(0) \) at the junction on n-side becomes very large compared to the thermal equilibrium value \( p_{n0} \).

The discussion is equally applicable for the electron concentration on the p-side as the electrons are minority charge carriers on p-side.

Now the hole current \( I_{p0}(0) \) crossing the junction from p-side to n-side with \( x = 0 \) is given by,
\[ I_{pn}(0) = \frac{A q D_p P_{n0}}{L_p} \left( e^{V/V_T} - 1 \right) \quad ... (2.10) \]

where,
- \( A \) = area of cross-section of junction
- \( D_p \) = diffusion constant for holes
- \( L_p \) = diffusion length for holes

Similarly the electron current \( I_{np}(0) \) crossing the junction from n-side to p-side is given by,

\[ I_{np}(0) = \frac{A q D_n n_{p0}}{L_n} \left( e^{V/V_T} - 1 \right) \quad ... (2.11) \]

where \( L_n \) = diffusion length for electrons.

The total current I at the junction is sum of the above two currents \( I_{pn}(0) \) and \( I_{np}(0) \) as stated in equation (2.1).

\[ \therefore \quad I = I_{pn}(0) + I_{np}(0) \]

\[ \therefore \quad I = \left[ \frac{A q D_p P_{n0}}{L_p} + \frac{A q D_n n_{p0}}{L_n} \right] \left( e^{V/V_T} - 1 \right) \quad ... (2.12) \]

\[ \therefore \quad I = I_0 \left( e^{V/V_T} - 1 \right) \quad ... (2.13) \]

where \( I_0 = \frac{A q D_p P_{n0}}{L_p} + \frac{A q D_n n_{p0}}{L_n} \quad ... (2.14(a)) \)

This is the standard expression for the diode current equation.

The \( I_0 \) represents reverse saturation current.

Another way of representing reverse saturation current \( I_0 \) is,

\[ \therefore \quad I_0 = A q \left[ \frac{D_p}{L_p} P_{n0} + \frac{D_n}{L_n} n_{p0} \right] \quad ... (2.14(b)) \]

Now from law of mass action,

\[ P_{n0} = \frac{n_i^2}{N_D} \]

and

\[ n_{p0} = \frac{n_i^2}{N_A} \]

Substituting in equation (2.14(b)),

\[ I_0 = A q \left[ \frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right] n_i^2 \quad ... (2.14(c)) \]

Throughout the derivation, the generation and the recombination in the depletion region is neglected. Hence to consider its effect, which is more dominant in Si diode, the current equation is modified by introducing a constant \( \eta \) as,

\[ I = I_0 \left( e^{\eta V/V_T} - 1 \right) \quad ... (2.15) \]

The value of \( \eta = 1 \) for Germanium diode, and \( \eta = 2 \) for Silicon diode.

This is the required mathematical expression for the current through diode, representing its V-I characteristics.
1.11 Diode Resistance

We have seen earlier that the dynamic resistance is the reciprocal of the slope of the V-I characteristic of a diode. For the incremental changes in voltage and current we can write,

\[
r = \frac{1}{\text{Slope of graph}} = \frac{1}{\frac{dI}{dV}} \quad \cdots (1)
\]

Now current equation of a diode is given by,

\[
I = I_0 \left( e^{V/nVT} - 1 \right)
\]

\[
\therefore \quad \frac{dI}{dV} = I_0 \left( \frac{1}{V_T} e^{V/nVT} \right)
\]

\[
\therefore \quad \frac{dI}{dV} = \frac{I_0 e^{V/nVT}}{V_T} \quad \cdots (2)
\]

\[
\therefore \quad r = \frac{1}{\frac{dI}{dV}} = \frac{nV_T}{I_0 e^{V/nVT}} \quad \cdots (3)
\]

But from the current equation we can write,

\[
I = I_0 e^{V/nVT} - I_0
\]

\[
\therefore \quad I_0 e^{V/nVT} = I + I_0 \quad \cdots (4)
\]

Substituting in equation (3), we get,

\[
r = \frac{nV_T}{I + I_0} = \text{Dynamic resistance} \quad \cdots (5)
\]

While determining the value of dynamic resistance under forward biased and reverse biased conditions, the general expression, equation (3) is used.

**Key Point:** For forward biased condition treat \( V \) positive while for reverse biased condition treat \( V \) as negative, while using the expression.

The following example will clear the use of the generalised expression in calculating forward and reverse dynamic resistance.

**Example 1.4:** For a germanium diode, the reverse saturation current is 2 \( \mu \text{A} \) at a reverse voltage of 0.26 \( V \). Calculate forward and reverse dynamic resistance values if forward biased voltage is also 0.26 \( V \), at room temperature.

**Solution:**

The given values are

\( I_0 = 2 \mu \text{A} \), \( V = +0.26 \text{ V} \) for forward biased, \( V = -0.26 \text{ V} \) for reverse biased.

\( \eta = 1 \) for germanium, \( V_T = 26 \text{ mV} \) at room temperature.

\[
r_f = \frac{nV_T}{I_0 e^{V/nVT}} = \frac{1 \times 26 \times 10^{-3}}{2 \times 10^{-6} \times e^{0.26/1 \times 26 \times 10^{-3}}}
\]

\[
= 0.5901 \ \Omega \quad \text{Forward dynamic resistance}
\]

and

\[
r_r = \frac{nV_T}{I_0 e^{V/nVT}} = \frac{1 \times 26 \times 10^{-3}}{2 \times 10^{-6} \times e^{-0.26/1 \times 26 \times 10^{-3}}}
\]

\[
= 286.34 \ \text{M}\Omega \quad \text{Reverse dynamic resistance}
\]
1.12 Temperature Dependence of Diode Characteristics

It has been mentioned earlier that the reverse saturation current $I_0$ depends on temperature while $V_T$ is voltage equivalent of temperature is also temperature dependent. The diode current involving $I_0$ and $V_T$ is hence temperature dependent.

**Key Point:** The overall diode characteristics depends on the temperature.

The dependence of $I_0$ on temperature $T$ is given by,

$$I_0 = K T^m e^{-V_{G0}/kT}$$  \hspace{1cm} (1)

where $K$ = Constant independent of temperature (Not the Boltzmann’s constant.)

$m = 2$ for Ge and 1.5 for Si

and $V_{G0}$ = Forbidden energy gap = 0.785 V for Ge and 1.21 V for Si

Now as temperature increases, the value of $I_0$ increases and hence the diode current increases. To keep diode current constant it is necessary to reduce the applied voltage $V$ of the diode.

Let us calculate, with what rate the applied voltage must be changed in order to keep the diode current constant. For a constant diode current, $\frac{dI}{dT} = 0$. So we have to calculate such a change in voltage for which $\frac{dI}{dT} = 0$.

A diode current is given by the equation,

$$I = I_0 (e^{V/kT} - 1)$$

For a forward current, neglecting 1 we get,

$$I = I_0 e^{V/kT}$$  \hspace{1cm} (2)

Substituting equation (1) in equation (2) we get,

$$I = K T^m e^{-V_{G0}/kT} \cdot e^{V/kT}$$

$$\therefore I = K T^m e^{(V-V_{G0})/kT}$$  \hspace{1cm} (3)

as $V_T = kT$ where $k$ is Boltzmann’s constant,

$$I = K T^m e^{(V-V_{G0})/kT}$$  \hspace{1cm} (4)

Now for constant diode current, $\frac{dI}{dT} = 0$ hence differentiating equation (4) with respect to $T$,

$$\therefore \frac{dI}{dT} = K \left[ m T^{m-1} e^{(V-V_{G0})/kT} + T^m e^{(V-V_{G0})/kT} \cdot \frac{d}{dT} \left( \frac{V-V_{G0}}{kT} \right) \right]$$

$$\therefore \frac{dI}{dT} = K e^{(V-V_{G0})/kT} \left[ m T^{m-1} + \frac{T^m}{kT} \cdot \frac{d}{dT} \left( \frac{V-V_{G0}}{T^2} \times \frac{1}{kT} \right) \right]$$

$$\therefore \frac{dI}{dT} = K e^{(V-V_{G0})/kT} \left[ \frac{m T^{m-1}}{T} - \frac{T^m}{kT^2} \cdot \frac{d}{dT} \left( \frac{V-V_{G0}}{T} \right) \right]$$
Note that, $V_{G0}$ is forbidden energy gap at $0\,^\circ\text{K}$ and hence constant from differentiation point of view.

Taking $T^m$ outside and $(\eta k T^2)$ as L.C.M. we get,

\[ \frac{dI}{dT} = k e^{(V-V_{G0})/\eta k T} \times T^m \left[ \frac{m\eta k T}{\eta k T^2} \right] \]

\[ \Rightarrow \frac{dI}{dT} = K e^{(V-V_{G0})/\eta k T} \times \frac{T^m}{\eta k T^2} \left[ m\eta k T \left( T \frac{dV}{dT} - (V - V_{G0}) \right) \right] \]

Replacing $kT = V_T$ we get,

\[ \Rightarrow \frac{dI}{dT} = K e^{(V-V_{G0})/\eta V_T} \times \frac{T^{m-1}}{V_T} \left[ m\eta V_T \left( T \frac{dV}{dT} - (V - V_{G0}) \right) \right] \] ... (5)

Now $\frac{dI}{dT} = 0$ for constant diode current hence equating the equation (5) to zero we get,

\[ m\eta V_T + T \frac{dV}{dT} - (V - V_{G0}) = 0 \]

\[ \Rightarrow \frac{T \frac{dV}{dT}}{V_T} = V - V_{G0} - m\eta V_T \] ... (7)

\[ \Rightarrow \frac{dV}{dT} = \frac{V - (V_{G0} + m\eta V_T)}{T} \] ... (8)

This is the required change in voltagz necessary to keep diode current constant.

Hence for germanium, at cut-in voltage $V = V_T = 0.2\,\text{V}$ and with $m = 2$, $\eta = 1$, $T = 30\,^\circ\text{K}$ and $V_{G0} = 0.785\,\text{V}$ in equation (8) we get,

\[ \frac{dV}{dT} = \frac{0.2 - (0.785 + 2 \times 1 \times 26 \times 10^{-3})}{300} = -2.12\,\text{mV/}^\circ\text{C} \text{ for Ge} \] ... (9)

The negative sign indicates that the voltagz must be reduced at a rate of $2.12\,\text{mV}$ per degree change in temperature to keep diode current constant.

Similarly for Si we get,

\[ \frac{dV}{dT} = -2.3\,\text{mV/}^\circ\text{C} \text{ for Si} \] ... (10)

**Key Point:** Practically the value of $\frac{dV}{dT}$ is assumed to be $-2.5\,\text{mV/}^\circ\text{C}$ for either Ge or Si at room temperature.

Thus,

\[ \frac{dV}{dT} = -2.5\,\text{mV/}^\circ\text{C} \]

The negative sign indicates that $dV/dT$ decreases with increase in temperature.

The temperature dependence of $I_0$ for Si and Ge diodes is shown in the Fig. 1.24 (a) and (b).
The temperature dependence is approximately same for both the types of diodes. It can be seen that at high temperatures, Ge diode produces excessively large reverse current while for Si diode the $I_0$ is much smaller. So for rise in temperature from 25 °C to 90 °C the $I_0$ increases to 100 μA for Ge diode while it increases to only some tenths of μA for Si diode.

![Graphs showing temperature dependence of reverse current for Ge and Si diodes](image)

**Fig. 1.24 Temperature dependence of $I_0$**

The equation (8) represents dependence of forward voltage on temperature. It contains two terms. The term $\frac{V}{T}$ is due to dependence of $V_T$ on temperature while the other negative term is due to temperature dependence of $I_0$ and does not depend on voltage $V$ across the diode. The equation states that for increasing $V$, $\frac{dV}{dT}$ becomes less negative and reaches zero at $V = V_{G0} + m \eta V_T$. The practical diodes show such behaviour in the operating region.

### 1.12.1 Effect of Temperature on Reverse Saturation Current

Let us now study by what rate $I_0$ changes with respect to temperature. Consider equation (1) again,

$$I_0 = KT^m e^{-V_{G0}/\eta V_T}$$

Taking logarithm of both sides we get,

$$\ln (I_0) = \ln (KT^m e^{-V_{G0}/\eta V_T})$$

$$\Rightarrow \ln (I_0) = \ln K + \ln T^m - \frac{V_{G0}}{\eta V_T}$$

$$\Rightarrow \ln (I_0) = \ln K + m \ln T - \frac{V_{G0}}{\eta V_T}$$

Using $V_T = kT$,

$$\Rightarrow \ln (I_0) = \ln K + m \ln T - \frac{V_{G0}}{\eta k T}$$

... (11)

Differentiating this equation with respect to $T$ we get,

$$\Rightarrow \frac{d \ln (I_0)}{dT} = \frac{m}{T} - \frac{V_{G0}}{\eta k T^2} \left( - \frac{1}{T^2} \right)$$

$$= \frac{m}{T} + \frac{V_{G0}}{\eta k T^2}$$

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Replacing $kT = V_T$,
\[ \frac{d [\ln I_0]}{dT} = \frac{m}{T} + \frac{V_G}{V_T} \] ...
\( (12) \)

For germanium, substituting the values of various terms at room temperature we get,
\[ \frac{d [\ln I_0]}{dT} = \frac{2}{300} + \frac{0.785}{1 \times 300 \times 26 \times 10^{-3}} = 0.11 \text{ per } ^\circ\text{C} \]

This indicates that $I_0$ increases by 11% per degree rise in temperature.

For silicon, we get,
\[ \frac{d [\ln I_0]}{dT} = 0.08 \text{ per } ^\circ\text{C} \]

This indicates that $I_0$ increases by 8% per degree rise in temperature.

**Key Point:** But experimentally it is found that the reverse saturation current $I_0$ increases by 7% per $^\circ\text{C}$ change in temperature for both silicon and germanium diodes. If at $T \ ^\circ\text{C}$ is 1$\mu\text{A}$ then at $(T + 1) \ ^\circ\text{C}$ it becomes 1.07 $\mu\text{A}$ and so on. From this it can be concluded that reverse saturation current approximately doubles i.e. $1.07^{10}$ for every $10 \ ^\circ\text{C}$ rise in temperature.

The equations (8) and (12) explain the overall temperature dependence of diode characteristics.

**Mathematical Interpretation:** The above result can be mathematically represented as,
\[ I_{02} = \left( \frac{T_2 - T_1}{2 \times 10} \right) I_{01} = \left( \frac{\Delta T}{2 \times 10} \right) I_{01} \] ...
\( (13) \)

where
- $I_{02}$ = Reverse saturation current at $T_2$
- $I_{01}$ = Reverse saturation current at $T_1$

Thus the equation (13) is easy to use, than using equation (1), to obtain the effect of temperature on $I_0$.

**1.12.2 Effect of Temperature on Diode**

The temperature has following effects on the diode parameters,

1. The cut-in voltage decreases as the temperature increases. The diode conducts at smaller voltages at large temperature.

2. The reverse saturation current increases as temperature increases.

This increase in reverse current $I_0$ is such that it doubles at every 10 $^\circ\text{C}$ rise in temperature. Mathematically,
\[ I_{02} = 2^{(\Delta T/10)} I_{01} \]

where
- $I_{02}$ = Reverse current at $T_2 \ ^\circ\text{C}$
- $I_{01}$ = Reverse current at $T_1 \ ^\circ\text{C}$
- $\Delta T = (T_2 - T_1)$

3. The voltage equivalent of temperature $V_T$ also increases as temperature increases.

4. The reverse breakdown voltage increases as temperature increases.

This is shown in the Fig. 1.25. (See Fig. 1.25 on next page.)
Example 1.5: Find the factor by which the reverse saturation current of a silicon diode will get multiplied when the temperature is increased from 27 °C to 82 °C.

Solution: Let us use the equation (1) which gives dependance of \( I_0 \) on temperature,

\[
I_0 = K T^m e^{-V_G0/\eta V_T} \quad \ldots \quad (1)
\]

Now at \( T = T_1 = 27 \, ^{\circ}C = 300 \, ^{\circ}K, \ V_T = 26 \, mV \)

While at \( T = T_2 = 82 \, ^{\circ}C = 355 \, ^{\circ}K, \ V_T = kT = 8.62 \times 10^{-5} \times 355 \approx 30.6 \, mV \)

where \( k = \) Boltzmann’s constant \( = 8.62 \times 10^{-5} \, eV/^\circ K \)

\[
\therefore \quad (I_0)_1 = K \ (T_1)^m e^{-V_G0/\eta V_{T1}}
\]

and \( (I_0)_2 = K \ (T_2)^m e^{-V_G0/\eta V_{T2}} \)

For silicon, \( \eta = 2, \ m = 1.5, \ V_{G0} = 1.21 \, V \)

\[
\therefore \quad \frac{(I_0)_1}{(I_0)_2} = \frac{(300)^{1.5} e^{-1.21/2 \times 26 \times 10^{-3}}}{(355)^{1.5} e^{-1.21/2 \times 30.6 \times 10^{-3}}} = 0.0235
\]

\[
\therefore \quad (I_0)_2 = 42.54 \ (I_0)_1
\]

Initial reverse saturation current gets multiplied by 42.54 when temperature changes from 27 °C to 82 °C.

Instead of using equation (1), let us use equation (13),

\[
I_{02} = \left( \frac{\Delta T}{10} \right) I_{01} = \left( \frac{82 - 27}{10} \right) I_{01} = 2.55 I_{01} = 45.25 I_{01}
\]

The factor is 45.25 and approximately same as calculated above.

Key Point: While solving examples, use approximate result to study the effect of temperature on reverse saturation current.

---

![Fig. 1.25 Effect of temperature on diode](image-url)
Example 1.6: The reverse saturation current of a germanium diode is 100 µA at room temperature of 27 °C. Calculate the current in forward biased condition, if forward bias voltage is 0.2 V at room temperature. If temperature is increased by 20 °C, calculate the reverse saturation current and the forward current, for same forward voltage, at new temperature.

Solution: At $T_1 = 27 ^\circ C = 300 ^\circ K$, $V_T = 26 \text{ mV}$

$$(I_0)_1 = 100 \mu A, V = 0.2 \text{ V}$$

$$I = I_0 \left( e^{V/NT} - 1 \right)$$

$$.\therefore I = 100 \times 10^{-6} \left[ e^{0.2/0.26 \times 10^{-3}} - 1 \right] = 219.04 \text{ mA}$$

This is forward current at room temperature.

Using the approximate result,

$$(I_0)_2 = 2^{T_2-T_1/10} \times (I_0)_1 = 2^{20/10} \times (I_0)_1 \hspace{1cm} T_2 - T_1 = 20 ^\circ C$$

$$= 4 \times 100 = 400 \mu A$$

New reverse current at $27 + 20 = 47 ^\circ C$ is 400 µA. So for $V = 0.2 \text{ V}$, the new forward current can be calculated using current equation of diode.

$$V_T \text{ at } T_2 = 47 + 273 = 320 ^\circ K = kT = 8.62 \times 10^{-5} \times 320$$

$$= 27.584 \text{ mV}$$

$$.\therefore I = I_0 \left( e^{V/NT} - 1 \right) = 400 \times 10^{-6} \left[ e^{0.2/0.27584 \times 10^{-3}} - 1 \right]$$

$$= 563.158 \text{ mA}$$

Example 1.7: A p-n junction germanium diode has a reverse saturation current of 0.10 µA at the room temperature of 27 °C. It is observed to be 30 µA, when the room temperature is increased. Calculate the new room temperature.

Solution:

Let $(I_0)_1$ be the reverse saturation current at $T_1$

and $(I_0)_2$ be the reverse saturation current at $T_2$

$$.\therefore (I_0)_1 = 10 \mu A \text{ and } (I_0)_2 = 30 \mu A$$

Now

$$(I_0)_2 = (2^{\Delta T/10}) \times (I_0)_1$$

$$.\therefore 30 \times 10^{-6} = (2^{\Delta T/10}) \times 10 \times 10^{-6}$$

$$.\therefore (2^{\Delta T/10}) = 3$$

$$.\therefore \frac{\Delta T}{10} \ln 2 = \ln 3$$

$$.\therefore \Delta T = 15.8496$$

$$.\therefore T_2 - T_1 = 15.8496$$

$$.\therefore T_2 = 15.8496 + 27$$

$$= 42.849 ^\circ C \hspace{1cm} \ldots \text{New temperature}$$
2.34 Transition Capacitance ($C_T$)

Consider a reverse biased p-n junction diode as shown in the Fig. 2.55.

Fig. 2.55 Transition capacitance in reverse biased condition

As seen earlier, when a diode is reverse biased, reverse current flows due to minority carriers. Majority charged particles i.e. electrons in n-region and holes in p-region move away from the junction. This increases the width of the depletion region. The width of the depletion region increases as reverse bias voltage increases. As the charged particles move away from the junction there exists a change in charge with respect to the applied reverse voltage. So change in charge $dQ$ with respect to the change in voltage $dV$ is nothing but a capacitive effect. Such a capacitance which comes into the picture under reverse biased condition is called transition capacitance, space-charge capacitance, barrier capacitance or depletion layer capacitance and denoted as $C_T$. The magnitude of $C_T$ is given by the equation,

$$C_T = \frac{dQ}{dV} \quad \text{... (A)}$$

This capacitance is very important as it is not constant but depends on the magnitude of the reverse voltage.

2.34.1 Derivation of Expression for Transition Capacitance

Consider a p-n junction diode, the two sides of which are not equally doped. Impurity added on one side is more than the other. Assume that p-side is lightly doped and n-side is heavily doped. As depletion region penetrates lightly doped side, the most of depletion region is on p-side as it is lightly doped as shown in the Fig. 2.56.

Fig. 2.56 Unequally doped p-n junction diode
It can be further assumed that concentration of acceptor impurity on p-side ($N_A$) is much less than the concentration of donor impurity on n-side ($N_D$). Hence the width of depletion region on n-side is negligibly small compared to width of depletion region on p-side. Hence the entire depletion region can be assumed to be on the p-side only.

The relationship between potential and charge density is given by Poisson's equation as,

$$\frac{d^2 V}{dx^2} = \frac{q N_A}{\varepsilon} \quad \ldots \ (1)$$

where \(x\) = the distance measured from the junction.

and \(\varepsilon\) = the permittivity of the semiconductor.

\(\varepsilon = \varepsilon_0 \varepsilon_r\) \quad \ldots \ (2)

where \(\varepsilon_0\) = permittivity of free space

\[= \frac{1}{36 \pi \times 10^9} = 8.849 \times 10^{-12} \text{ F/m}\]

and \(\varepsilon_r\) = relative permittivity of the semiconductor

= 16 for germanium

= 12 for silicon

Note: In Poisson's equation, the concentration of lightly doped side is used. If we assume that n-type is lightly doped compared to p-type then as $N_D$ less than $N_A$, Poisson's equation modifies to,

$$\frac{d^2 V}{dx^2} = \frac{q N_D}{\varepsilon}$$

Integrating equation (1) w.r.t. \(x\) we get,

$$\int \frac{d^2 V}{dx^2} \, dx = \int \frac{q N_A}{\varepsilon} \, dx$$

\[\therefore \quad \frac{dV}{dx} = \frac{q N_A x}{\varepsilon} \quad \ldots \ (3)\]

Assume constant of integration as zero.

Now \(\frac{dV}{dx}\) is the electric field intensity over the region 0 to \(W\) over which depletion region is spreaded.

\[\therefore \quad E = \frac{q N_A x}{\varepsilon} \quad \ldots \ (4)\]

where \(E\) is electric field intensity.

To get the potential, integrating equation (3) we get,

$$\int \frac{dV}{dx} \, dx = \int _0^W \frac{q N_A}{\varepsilon} x \, dx$$

\[\therefore \quad V = \frac{q N_A W^2}{2 \varepsilon} \quad \ldots \ (5)\]

At \(x = W\), \(V = V_B\) which is barrier potential
Now barrier potential is the difference between internally developed junction potential and externally applied bias voltage.

\[ V_B = V_J - V \] \hspace{2cm} \ldots (6)

where \( V_B \) is barrier potential and \( V \) must be taken as negative for reverse bias.

Substituting in equation (5) we get,

\[ V_B = \frac{q N_A}{\varepsilon} \frac{W^2}{2} \] \hspace{2cm} \ldots (7)

From the above equation it can be observed that,

\[ W \propto \sqrt{V_B} \] \hspace{2cm} \ldots (8)

The width of barrier i.e. depletion layer increases with applied reverse bias.

If \( A \) is the area of cross-section of the junction, then net charge \( Q \) in the distance \( W \) is

\[ Q = \text{Number of charged particle} \times \text{charge on each particle} \]

\[ Q = [N_A \times \text{Volume}] \times q \]

\[ Q = N_A A W q \] \hspace{2cm} \ldots (9)

Now differentiating equation (7) with respect to \( V \),

\[ 1 = \frac{1}{2} \frac{N_A q}{\varepsilon} \frac{dW}{dV} \cdot 2 W \]

\[ \frac{dW}{dV} = \frac{\varepsilon}{q N_A W} \] \hspace{2cm} \ldots (10)

Now differentiating equation (9),

\[ \frac{dQ}{dV} = N_A A q \frac{dW}{dV} \]

\[ = N_A A q \frac{\varepsilon}{q N_A W} \]

\[ \frac{dQ}{dV} = \frac{\varepsilon A}{W} \] \hspace{2cm} \ldots (11)

But \( \frac{dQ}{dV} \) is the transition capacitance \( C_T \) hence

\[ C_T = \frac{\varepsilon A}{W} \] \hspace{2cm} \ldots (12)

Now from equation (6) we know that \( V_B = V_J - V \) and for reverse bias \( V \) is negative. Hence for reverse biased condition we get \( V_B = V_J + V \) where \( V \) is applied reverse biased voltage. So as reverse biased voltage increases, \( V_B \) increases. From equation (8), we can conclude that the width of depletion layer increases as reverse bias increases. Increasing width \( W \), decreases the transition capacitance \( C_T \). Hence transition capacitance \( C_T \) decreases as the reverse bias voltage increases.

\[ C_T \propto \frac{1}{W} \] \hspace{2cm} \ldots (13)
As the reverse biased applied to the diode increases, the width of the depletion region (W) increases. Thus the transition capacitance \( C_T \) decreases. In short, the capacitance can be controlled by the applied voltage. The variation of \( C_T \) with respect to the applied reverse bias voltage is shown in the Fig. 2.57.

As reverse voltage is negative, graph is shown in the second quadrant. For a particular diode shown, \( C_T \) varies from 80 pF to less than 5 pF as \( V_R \) changes from 2 V to 15 V.

It can be observed that \( V_B = V_I - V \) where,

\[

V_I = \text{Internally developed junction potential}
\]

\[

V = \text{Applied reverse bias voltage}
\]

**Key Point:** For reverse bias, \( V \) is negative hence \( V_B = V_I + V \) for reverse bias. Thus barrier potential increases and hence width of depletion layer increases as reverse bias increases.

### 2.36 Diffusion Capacitance

During forward biased condition, another capacitance comes into existence called diffusion capacitance or storage capacitance, denoted as \( C_D \).

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

\[
C_D = \frac{dQ}{dV}
\]  \( \ldots (1) \)

The diffusion capacitance can be determined by the expression

\[
C_D = \frac{\tau I}{\eta V_T}
\]  \( \ldots (2) \)

where \( \tau \) = mean life time for holes.

So diffusion capacitance is proportional to the current. For forward biased condition, the value of diffusion capacitance is of the order of nano farads to micro farads while transition capacitance is of the order of pico farads. So \( C_D \) is much larger than \( C_T \).

However in forward biased condition, \( C_D \) appears in parallel with the forward resistance which is very very small. Hence the time constant which is function of product of the forward resistance and \( C_D \) is also very small for ordinary signals.

**Key Point:** Hence for normal signals \( C_D \) has no practical significance but for fast signals \( C_D \) must be considered.
The graph of $C_D$ against the applied forward voltage is shown in the Fig. 2.60.

\[ \begin{align*}
C_{nF \text{ or } \mu F} & \\
0 & \rightarrow \text{Forward bias} \\
0 & \rightarrow 0.25 \\
0.5 & \rightarrow V
\end{align*} \]

**Fig. 2.60** Diffusion capacitance versus applied forward biased voltage

### 2.36.1 Derivation of Expression for Diffusion Capacitance

In a p-n junction, the total current at the junction ($x = 0$) is given by,

\[ I = I_{pn}(0) + I_{np}(0) \quad \text{A} \quad \text{(3)} \]

where

- $I_{pn}(0) = \text{Current due to holes diffusing from p to n side}$
- $I_{np}(0) = \text{Current due to holes diffusing from n to p side}$

For simplicity assume that the one side say p side is heavily doped with respect to other. Hence $I_{np}(0)$ is negligible compared to $I_{pn}(0)$.

\[ I = I_{pn}(0) \quad \text{(4)} \]

For the diffusion current, the current density is given by,

\[ J_p(x) = -q D_p \frac{dp_n}{dx} \quad \text{(5)} \]

where

- $D_p = \text{Diffusion constant}$
- $\frac{dp_n}{dx} = \text{Concentration gradient (Change in concentration with respect to x)}$

Now

\[ J = \text{Current density} = \frac{\text{Current}}{\text{area}} = \frac{I}{A} \]

\[ I_p(x) = -q A D_p \frac{dp_n}{dx} \quad \text{(6)} \]

where

- $A = \text{Area of cross-section}$

Now for a p-n junction,

\[ p_n(x) = p_n(0)e^{-x/L_p} \quad \text{(7)} \]

where

- $L_p = \text{Diffusion length for holes}$

**Key Point:** This $L_p$ is related to the diffusion constant $D_p$ such that $L_p = \left( D_p \tau \right)^{\frac{1}{3}}$ where $\tau = \text{mean life time of charge carrier}$. 

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Differentiating (7),
\[
\frac{dp_n(x)}{dx} = p_n(0)e^{-\frac{q}{L_p}x}\left(-\frac{1}{L_p}\right)
\]
... (8)

Using in (6),
\[
I_p(x) = -q A D_p p_n(0)e^{-\frac{q}{L_p}x}\left(-\frac{1}{L_p}\right)
\]
\[
\therefore I_p(x) = q A \frac{D_p}{L_p} p_n(0)e^{-\frac{q}{L_p}x}
\]
... (9)

At \(x = 0\), \(I_p(0) = I\) hence using \(x = 0\) in equation (9),
\[
I = \frac{q A D_p p_n(0)}{L_p}
\]
... (10)
\[
\therefore p_n(0) = \frac{IL_p}{q A D_p}
\]
... (11)

Now the excess minority charge \(Q\) exists only on the \(n\) side and given by,
\[
Q = \int_0^\infty A q p_n(0)e^{-\frac{q}{L_p}x}dx
\]
\[
= \left[ A q p_n(0)e^{-\frac{q}{L_p}x}\right]_0^\infty = -A q L_p p_n(0)[e^{-\infty} - (e^0)]
\]
\[
\therefore Q = -A q L_p p_n(0)(-1) = A q L_p p_n(0)
\]
... (12)

Using (11) in (12),
\[
Q = \frac{A q L_p I L_p}{q A D_p} = \frac{L_p^2}{D_p} I
\]

But \(\frac{L_p^2}{D_p} = \tau\) = mean life time
\[
\therefore Q = \tau I
\]
... (13)

Now
\[
C_D = \frac{dQ}{dV} = \frac{dQ}{dl} \cdot \frac{dl}{dV}
\]
... (14)

From (13), \(\frac{dQ}{dl} = \tau\)
... (15)

From diode current equation,
\[
I = I_o(e^{\frac{V}{nV_T}} - 1) \approx I_o e^{\frac{V}{nV_T}} \text{ (neglecting 1)}
\]
\[
\therefore \frac{dI}{dV} = I_o e^{\frac{V}{nV_T}} \cdot \frac{1}{nV_T} = \frac{1}{\eta V_T}
\]
... (16)

Using (15) and (16) in (14),
\[
C_D = \frac{\tau I}{\eta V_T}
\]

This is the required expression for diffusion capacitance.
Key Point: The diffusion capacitance is negligibly small in reverse biased condition. It is very large compared to transition capacitance.

Though diffusion capacitance is large, the time constant \( r_f C_D \) is very small as \( r_f \), the forward resistance of diode is very small.

\[
\tau = r_f C_D = \text{Diode time constant}
\]

The time constant means the mean lifetime of the minority carriers.

4.12 ENERGY BAND STRUCTURE OF OPEN CIRCUITED PN JUNCTION

Consider that a PN junction has P-type and N-type materials in close physical contact at the junction on an atomic scale. Hence, the energy band diagrams of these two regions undergo relative shift to equalise the Fermi level. The Fermi level \( E_F \) should be constant throughout the specimen at equilibrium. The distribution of electrons or holes in allowed energy states is dependent on the position of the Fermi level. If this is not so, electrons on one side of the junction would have an average energy higher than those on the other side, and this causes transfer of electrons and energy until the Fermi levels on the two sides get equalised. However, such a shift does not disturb the relative position of the conduction band, valence band and Fermi level in any region. Equalisation of Fermi levels in the P and N materials of a PN junction is similar to equalisation of levels of water in two containers on being joined together.

Fig. 4.13 Energy band structure
The energy band diagram for a PN junction is shown in Fig. 4.13, where the Fermi level $E_F$ is closer to the conduction band edge $E_{cn}$ in the N-type material while it is closer to the valence band edge $E_{vp}$ in the P-type material. It is clear that the conduction band edge $E_{cp}$ in the P-type material is higher than the conduction band edge $E_{cn}$ in the N-type material. Similarly, the valence band edge $E_{vp}$ in the P-type material is higher than the valence band edge $E_{vn}$ in the N-type material. As illustrated in Fig. 4.13, $E_1$ and $E_2$ indicate the shifts in the Fermi level from the intrinsic conditions in the P and N materials respectively. Then the total shift in the energy level $E_0$ is given by

$$E_0 = E_1 + E_2 = E_{cp} - E_{cn} = E_{vp} - E_{vn}$$

This energy $E_0$ (in eV) is the potential energy of the electrons at the PN junction, and is equal to $qV_0$, where $V_0$ is the contact potential (in volts) or contact difference of potential or the barrier potential.

Contact difference of potential A contact difference of potential exists across an open circuited PN junction. We now proceed to obtain an expression for $E_0$. From Fig. 4.13, we find that

$$E_F - E_{vp} = \frac{1}{2} E_G - E_1 \quad (4.6)$$

$$E_{cn} - E_F = \frac{1}{2} E_G - E_2 \quad (4.7)$$

Combining Eqs (4.6) and (4.7), we get

$$E_0 = E_1 + E_2 = E_G - (E_{cn} - E_F) - (E_F - E_{vp}) \quad (4.8)$$

We know that

$$np = N_C N_V e^{-E_G/kT} \text{ and}$$

$$np = n_i^2 \text{ (Mass-action law)}$$

From the above equations, we get

$$E_G = kT \ln \frac{N_C N_V}{n_i^2} \quad (4.9)$$

We know that for N-type material $E_F = E_C - kT \ln \frac{N_C}{N_D}$. Therefore, from this equation, we get

$$E_{cn} - E_F = kT \ln \frac{N_C}{n_n} = kT \ln \frac{N_C}{N_D} \quad (4.10)$$

Similarly for P-type material $E_F = E_V + kT \ln \frac{N_V}{N_A}$. Therefore, from this equation, we get

$$E_F - E_{vp} = kT \ln \frac{N_V}{p_p} = kT \ln \frac{N_V}{N_A} \quad (4.11)$$
Substituting from Eqs (4.9), (4.10) and (4.11) into Eqn. (4.8), we get

\[ E_0 = kT \left[ \ln \frac{N_C N_V}{n_i^2} - \ln \frac{N_C}{N_D} - \ln \frac{N_V}{N_A} \right] \]

\[ = kT \ln \left[ \frac{N_C N_V}{n_i^2} \times \frac{N_D}{N_C} - \frac{N_D}{N_V} \right] \]

\[ = kT \ln \frac{N_D N_A}{n_i^2} \quad (4.12) \]

As \( E_0 = qV_o \), then the contact difference of potential or barrier voltage is given by

\[ V_o = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2} \]

In the above equations, \( E_s \) in electron volts and \( k \) is in electron volt per degree Kelvin. The contact difference of potential \( V_o \) is expressed in volt and is numerically equal to \( E_0 \). From Eqn. (4.12) we note that \( E_o \) (hence \( V_o \)) depends upon the equilibrium concentrations and not on the charge density in the transition region.

An alternative expression for \( E_0 \) may be obtained by substituting the equations of

\[ n_n = N_D, \quad p_n = \frac{n_i^2}{N_D}, \quad n_n \quad p_p = n_i^2, \quad p_p = N_A \quad \text{and} \quad n_p = \frac{n_i^2}{N_A} \]

into Eqn. (4.12). Then we get

\[ E_0 = kT \ln \frac{p_{po}}{p_{no}} = kT \ln \frac{n_{no}}{n_{po}} \quad (4.13) \]

where subscript 0 represents the thermal equilibrium condition.

**PN DIODE APPLICATIONS**

An ideal PN junction diode is a two terminal polarity sensitive device that has zero resistance (diode conducts) when it is forward biased and infinite resistance (diode does not conduct) when reverse biased. Due to this characteristic the diode finds number of applications as given below.

(i) rectifiers in d.c. power supplies
(ii) switch in digital logic circuits used in computers
(iii) clamping network used as d.c. restorer in TV receivers and voltage multipliers
(iv) clipping circuits used as wave shaping circuits used in computers, radars, radio and TV receivers
(v) demodulation (detector) circuits.

The same PN junction with different doping concentration finds special applications as follows:

(i) detectors (APD, PIN photo diode) in optical communication circuits
(ii) Zener diodes in voltage regulators
(iii) varactor diodes in tuning sections of radio and TV receivers
(iv) light emitting diodes in digital displays
(v) LASER diodes in optical communications
(vi) Tunnel diodes as a relaxation oscillator at microwave frequencies.
Questions:
1. What is a PN Junction? Explain the formation of depletion layer in a PN junction.
2. Discuss current components in a PN junction diode.
4. Derive the Diode Current Equation.
5. Write notes on Diode Resistance.
6. Describe the Temperature Dependence of PN Junction Diode on VI Characteristics.
7. Determine the value of forward current in the case of a PN junction diode, with \( I_o = 10\mu A, V_f = 0.8V \) at \( T = 300^\circ K \). Assume Silicon Diode.
8. How does the reverse saturation current of PN junction diode vary with temperature? Explain.
9. Find the factor by which the reverse saturation current of a silicon diode will get multiplied when the temperature is increased from \( 27^\circ C \) to \( 82^\circ C \).
10. What is transition capacitance? Derive the expression for transition capacitance of a PN Junction Diode.
11. Mention the importance of Diffusion capacitance. Derive the expression for Diffusion capacitance of a PN Junction Diode.
12. Draw and explain the energy band diagram of PN Junction Diode.
13. Calculate the dynamic forward and reverse resistance of PN Junction silicon diode when the applied voltage is \( 0.25V \) at \( T = 300^\circ K \) with given \( I_o = 2\mu A \).