P-N Junction Diode

What is Semiconductor?

1.Semiconductor is a class of materials whose resistivity falls in between the resistivity of metals and insulators. At 0K , a pure semiconductor behaves like an insulator

2.The electronic properties of semiconductors can be tuned finely by adding suitable level of desired impurity. This property of the semiconductor made it possible for the wide scale application in electronic circuit.

3.Semiconductors are used as devices such as diodes, photodiodes, semiconductor lasers, transistors, solar cells, various integrated circuits, etc.

4.The semiconductor devices replaced the huge size of vacuum tubes.

5.The resistivity of semiconducting materials are generally in the range of 10^{-3} Ω cm to 10^{8} Ω cm.

6.Semiconductors have energy band structure with valence and conduction bands separated by a gap. The energy gap in semiconductors is generally less than 2.5 eV. Because of relatively small band gap, the electrons can be thermally excited from the valence band to the conduction band at room temperature and contribute for electrical conductivity.

Classification of Semiconductor:

There are two types of semiconductors

1. Intrinsic
2. Extrinsic Semiconductors

- A pure or intrinsic semiconductor crystal made up of single type of elements without any impurity or lattice defect is called intrinsic semiconductor. At 0K an intrinsic SC behaves like an insulator.

- Extrinsic semiconductors are obtained by doping the intrinsic materials with appropriate impurities. There are two type of extrinsic semiconductors namely P-type and N-type. In P-type holes are the majority charge carriers and in N-type electrons are the majority charge carriers.

Diffusion of Charge Carriers

- When excess carriers are generated non uniformly in a semiconductor, the electron and hole concentrations vary with position in the sample. As a result there is a diffusion of charge carriers from the region of high concentration to the region of low concentration. The two basic process of current conduction in a semiconductor are diffusion due to carrier gradient and drift in an electric field.
- Diffusion occurs due to random thermal motion and scattering from the lattice and impurities.
- A pulse of excess electrons injected at x=0 at t=0 spreads out with time as shown in the following figure. Initially, the excess electrons are concentrated at x=0, as time goes on the electrons diffuse to

region of lower concentration until the concentration, $n(x)$ is a constant.

n(x) can be determined by choosing an arbitrary distribution function as shown in Fig.2. the curve is divided into segments of equal mean free path, I. n(x) is evaluated at the centre of each segment.

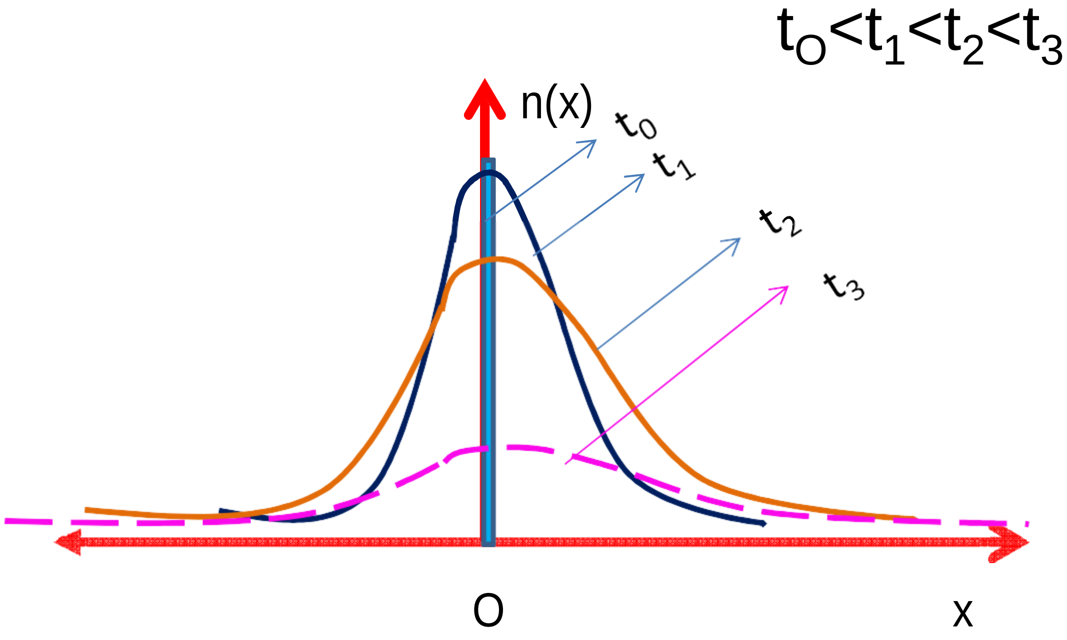


Fig.1 distribution of charge carriers

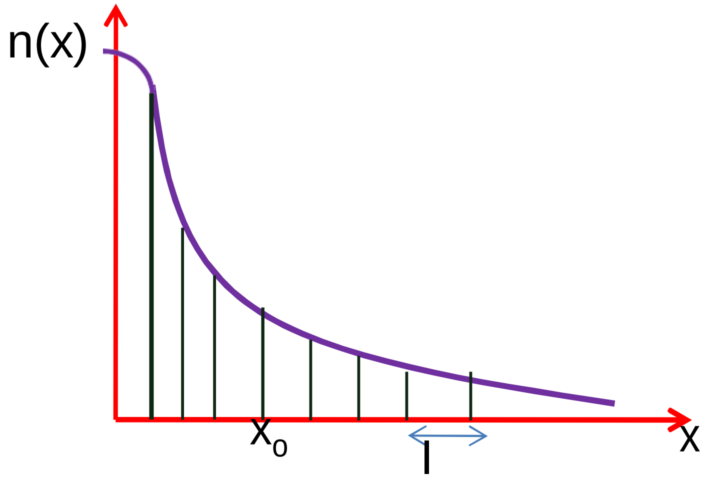


Fig.2

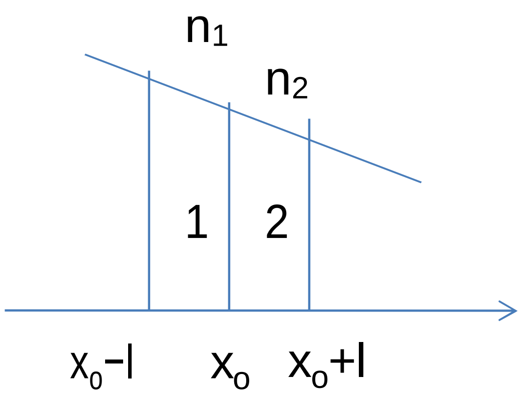


Fig.3

- Consider two segments (1) and (2) on either side of the position x_o, with carrier concentrations n_1 and n_2. the probability of electrons crossing from a given segment to both left and right sides are equal.
- The net number of electrons passing x_o from left to right in one mean free path time, t can be written as,

$$\frac{1}{2}(n_1Al - n_2Al) \qquad (1)$$

where A is the area of cross section of the sample. the electron flux density, $\varphi_n(x)$ which is the rate of electrons flow along +x direction per unit area is, $\varphi_n(x) = (l/2t)\,(n_1 - n_2)$ (2)

- $(n_1 - n_2)$ can be written as,

$$n_1 - n_2 = \frac{[n(x) - n(x+\Delta x)]l}{\Delta x} \qquad (3)$$

- Where x is taken as centre of each segment and $\Delta x = l$. In the limit of small Δx, eq.(3) can be written as,

$$n_1 - n_2 = Lt_{\Delta x \to 0} \frac{[n(x) - n(x+\Delta x)]l}{\Delta x} = -(\frac{dn(x)}{dx})l \qquad (4)$$

The minus sign is due to diffusion of electrons towards the decreasing concentration side,

$$\phi_n(x) = -\frac{l^2}{2t}\frac{dn(x)}{dx}$$

$$\phi_n(x) = -D_n \frac{dn(x)}{dx} \qquad (5)$$

Where $D_n = -\frac{l^2}{2t}$ is called the diffusion constant for electrons.

Similarly the flux density of holes can be written as,

$$\phi_p(x) = -D_p \frac{dp(x)}{dx} \qquad (6)$$

where D_p is the diffusion constant for holes.

The diffusion current density J(diff) can be written as the multiplication of charge carrier and its flux density,

$$J_n(x) = (-q)(-D_n)\frac{dn(x)}{dx} = qD_n \frac{dn(x)}{dx} \qquad (7)$$

$$J_p(x) = q(-D_p)\frac{dp(x)}{dx} = -qD_p \frac{dp(x)}{dx} \qquad (8)$$

It is important to note that both electrons and holes move together but their contribution to diffusion currents are in opposite direction.

Diffusion and Drift Carriers Under Built in Field

- If an electric field is present in addition to the carrier gradient, the current density will have a drift component and a diffusion component.

$$J_n(x) = -n(x)q\mu_n E(x) + qD_n \frac{dn(x)}{dx} \tag{1}$$

$$J_p(x) \quad p(x)q \quad {}_p E(x) \quad qD_p \frac{dp(x)}{dx} \tag{2}$$

The total current density J(x) is the sum of the contributions due to electrons and holes, $J(x) = J_n(x) + J_p(x)$ (3)

At equilibrium, no net current flows in a semiconductor. Thus any fluctuation which would begin a diffusion current also sets up electric field which redistribute carriers by drift. At equilibrium, ex. 2 can be written as, $J_p(x) = 0$, or

$$p(x)q\mu_p E(x) = qD_p \frac{dp(x)}{dx} \tag{4}$$

- We know that,

$$p(x) = n_i e^{(E_i - E_F)/kT}$$

$$\frac{dp(x)}{dx} = n_i e^{(E_i - E_F)/kT} \left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right)/(kT) \qquad (5)$$

$$\frac{dp(x)}{dx} = \frac{p(x)}{kT}\left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right)$$

Eq. 4 can be written as,

$$\mu_p p(x)E(x) = \frac{D_p p(x)}{kT}\left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right) \qquad (6)$$

Equilibrium Fermi level does not vary with position, E_i is a measure of potential energy (-qV(x)). As the electrons are diffused along +x direction, they leave behind +ively ionized donor ions, which create an electric field thus opposing the diffusion. The above process changes the position of Fermi level, E_i ; so, E_i =-qV(x) or

$dE_i /dx = -q\, dV(x)/dx = =q\, E(x)$ (7)

By substituting eq.7 in eq.6, we get

$$\mu_p E(x) = \frac{D_p}{kT} qE(x)$$

eq.8 and is known as Einstein relation.

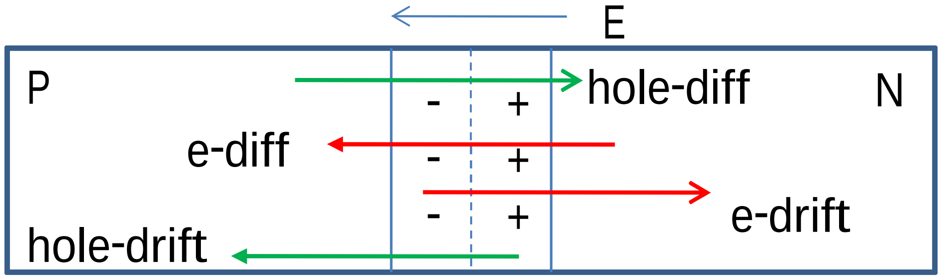
$$\frac{D_p}{\mu_p} = \frac{kT}{q} \qquad (8)$$

Contact Potential in a P−N junction

- The block diagram of a P−N junction before and after junction formation and their respective band structure diagram are shown in Fig.1. when the junctions are formed because of the gradient in the charge carriers, holes diffuse from p side to n side and electrons diffuse from n side to p side. Because of these diffusion uncompensated acceptor ions Na^{-} are left near the p side edge and uncompensated donor ions Nd^{+} are left near the n side edge. As a result these charged ions, electric field is set up at the transition region called depletion region.

- The electric field developed in the transition region leads to drifting of the charge carriers opposite to the direction of diffusion of charge carriers. In other words electrons drift towards n side and holes drift towards p side. The direction of the particle flow and their current direction is shown below.

	Particle Flow	*Current Direction*	
Hole diffusion	p → n	p → n	I_p (diff)
Hole drift	p ← n	p ← n	I_p (drift)
Electron diffusion	p ← n	p → n	I_n (diff)
Electron drift	p → n	p ← n	I_n (drift)



- At equilibrium, the net current flow across the junction is zero. In other words, the diffusion component of each charge carrier is equal and opposite to the corresponding drift component.

  J_p(diff)+ J_p(drift) = 0 (1) and J_n(diff)+ J_n(drift) = 0 (2)

Eq. (1) can be written as,

$$-qD_p \frac{dp(x)}{dx} + q\mu_p p(x)E(x) = 0$$

$$\frac{\mu_p}{D_p} E(x) = \frac{1}{p(x)} \frac{dp(x)}{dx}$$

$$\frac{q}{kT}\left(-\frac{dv(x)}{dx}\right) = \frac{1}{p(x)} \frac{dp(x)}{dx}$$

$$-\frac{q}{kT} dv(x) = \frac{dp(x)}{p(x)}$$

$$-\frac{q}{kT}\int_{vp}^{vn} dv(x) = \int_{p_p}^{p_n} \frac{dp(x)}{p(x)} \qquad (3)$$

where v_p and v_n are the electric potential at p side and n side respectively. p_p and p_n are the majority hole concentration at p side and minority hole concentration at n side respectively. Eq. 3 can be written as,

$$-\frac{q}{kT}(v_n - v_p) = \ln\left(\frac{p_n}{p_p}\right)$$

$$(v_n - v_p) = \frac{kT}{q} \ln\left(\frac{p_p}{p_n}\right)$$

or

$$V_o = \frac{kT}{q} \ln\left(\frac{p_p}{p_n}\right)$$

(4); where V_o is the contact potential.

Eq. (4) can also be written as, $V_o = \frac{kT}{q} \ln(N_a N_d / n_i^2)$ (5)

Where $p_p = N_a$ and $p_n = n_i^2/p_p = n_i^2/N_a$ have been substituted.

Eq. 4 can be written in a different form,

$$p_p = p_n \, e^{qV_o / kT} \qquad (6)$$

Similarly we can write the equation in terms of electron concentration,

$$n_n = n_p \, e^{qV_o / kT} \qquad (7)$$

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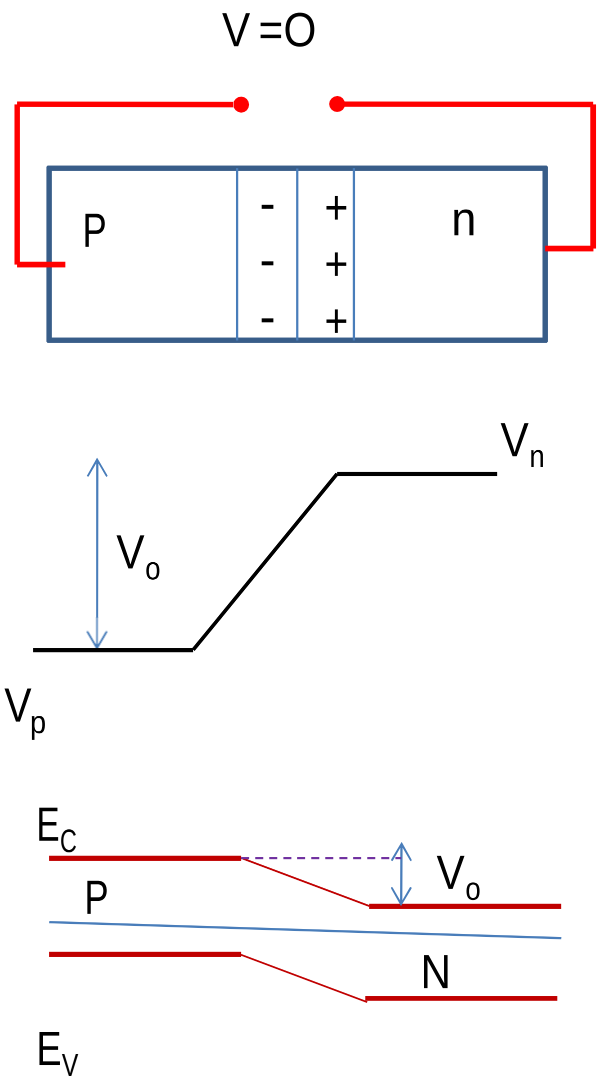
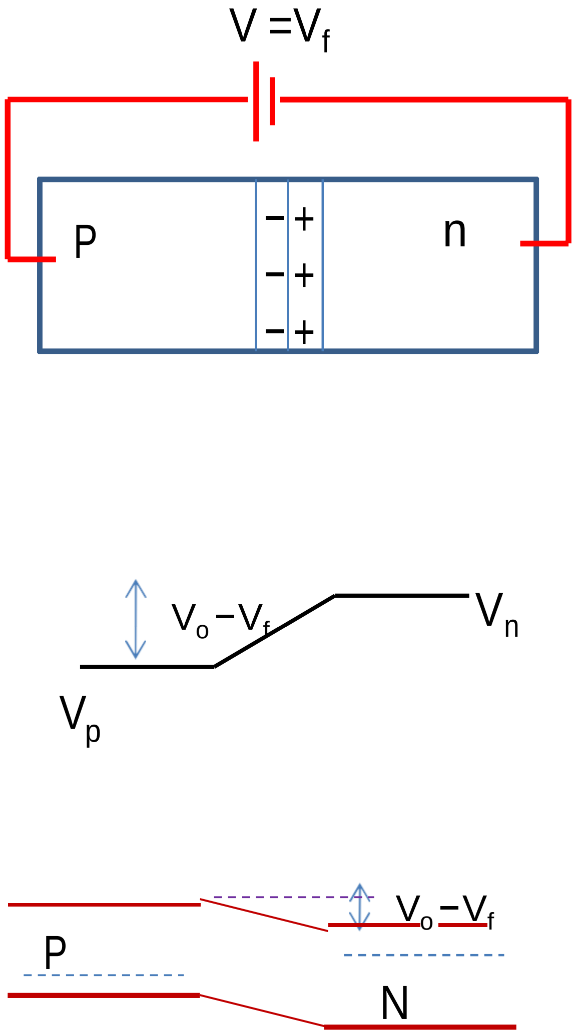
Qualitative Description of Current Flow at a Junction

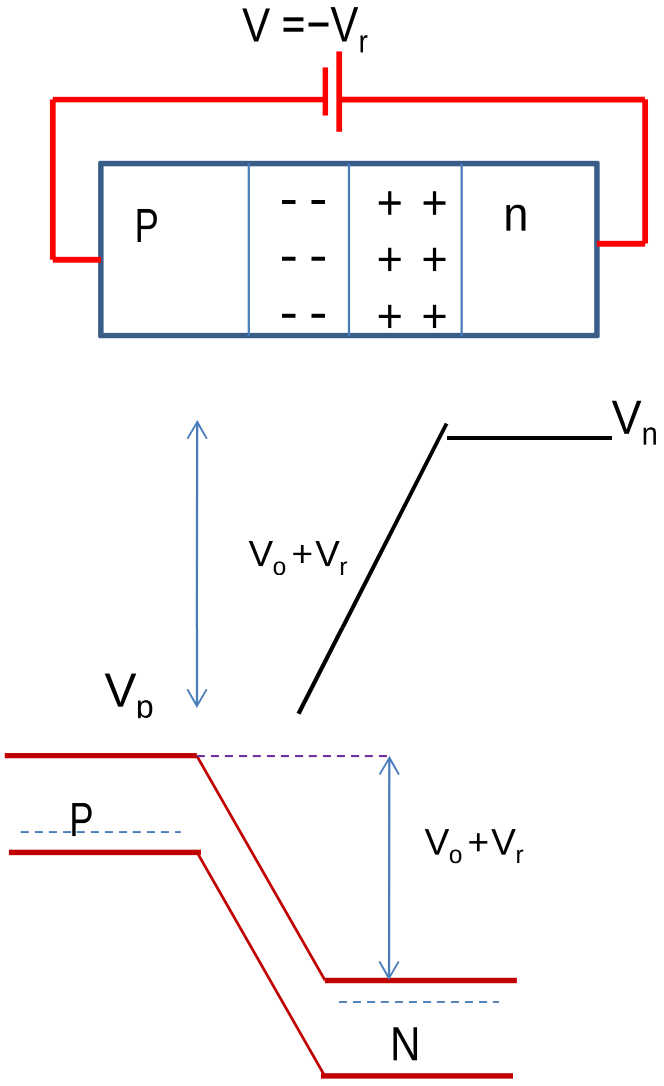
- We assume that an applied bias V appears across the junction rather than in the neutral p or n side. The above assumption may be justified because the length of each region is small compared to the area of cross section and the doping is generally moderate to heavy. Thus the resistance is small in each neutron region.
- Since the applied voltage changes the electrostatic potential barrier and the electric field within the transition region, we would expect changes in the junction current, energy levels, and depletion width etc. let us discuss qualitatively the effect of biasing across the junction.
- Under forward bias, the potential of p side is increased with respect to the n-side , so the potential barrier is reduced to $(V_o - V_f)$. Under reverse bias, the potential of p-side is reduced further with respect to n-side. So, the contact potential is increased from its equilibrium value V_o to $(V_o + V_r)$. They are shown in fig. 1



Unbiased P−N Jn.

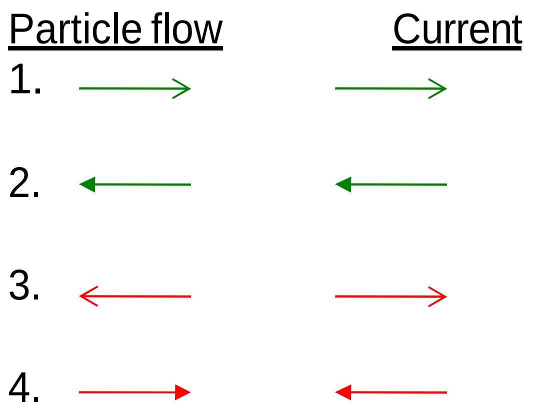


Forward biased P−N Jn.



Reverse biased P−N Jn.

Un biased P−N Jn.



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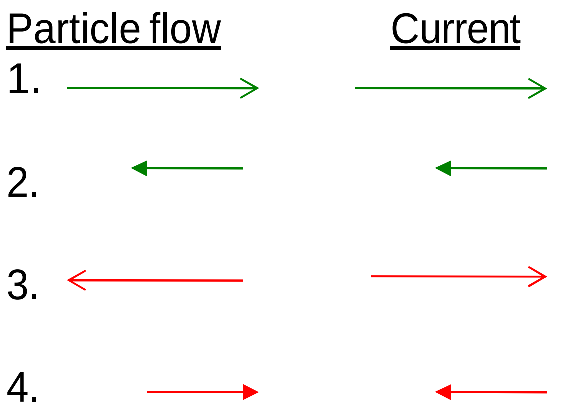
1. Hole diffusion
2. Hole drift
3. Electron diffusion
4. Electron drift

Forward biased P−N Jn.



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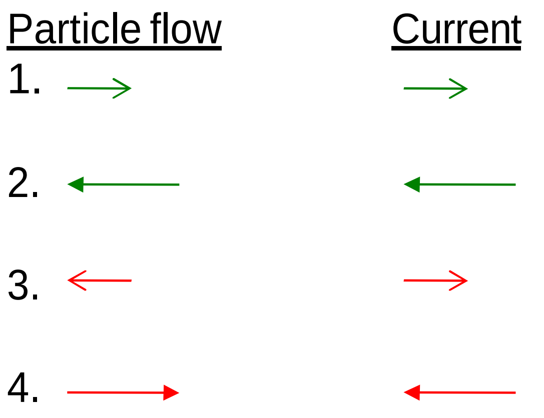
1. Hole diffusion
2. Hole drift
3. Electron diffusion
4. Electron drift

Reverse biased P−N Jn.



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1. Hole diffusion
2. Hole drift
3. Electron diffusion
4. Electron drift

- The electric field within the transition region can be determined from the potential barrier. The field decreases with forward bias because the applied field is opposite to the built in field. Under reverse bias the field at the junction is increased.
- The change in electric field at the junction causes the change in transition region. Since the electric field at the junction is low during the forward bias, the space charge across the junction is also low. The low space charge results in low transition width. Due to increase in electric field during the reverse bias, the transition region is increased.
- The separation of energy band is low $q(v_o - v_f)$ during the forward bias and high $q(v_{-+} V_r)$ during the reverse bias.
- The diffusion current is composed of the diffusion of majority electrons from n−side to p−side and majority holes from p−side to n−side. Under forward bias, since the potential barrier is reduced across the junction more and more majority carriers are easily diffused through the junction, thereby increasing the diffusion current
- We can assume that drift current is almost independent of field or potential barrier. Because it not only depends on how fast the minority carriers are drifted but also how often. Since the minority carrier concentrations near the transition region are almost independent of biasing and its concentration is small.

- The total current crossing the junction is the sum of the diffusion and drift currents. At equilibrium without any biasing the net current is zero. That is the diffusion current is equal to the drift current,

$$\left|I\right|_{diff} = \left|I\right|_{drift} = I_o$$

- Total current $I = I_{diff} - I_{drift} = 0$ (1)

- Under forward bias $V = V_f$, the probability of majority carrier diffusion increases by a factor $\exp(qv_f / kT)$. Thus the diffusion current density under forward bias is $I_o \exp(-qv_f / kT)$ and the total current, which is the sum of

$$I = I_o(e^{-(qv_f/kT)} - 1) \qquad \text{--(2)}$$