CHAPTER 2

2.1 THEORY OF P-N JUNCTION

If two pieces of semiconductor materials with different conduction type are brought together in a contact, a junction is formed. It is the basic building block of almost active semiconductor devices. Before contact there is a large electron concentration in the n-side and a large hole concentration in the p-side. After the two sides are brought into contact, electrons are diffused from the n-side to the p-side and holes are diffused from the p-side to the n-side. However, each electron that diffuses into the p-side leaves a positively charged donor atom behind in the n-side, likewise the holes that diffuse into the n-side leaves a negatively charged acceptor atom behind in the p-side. An electric field is built-up between the ionized donors and acceptor atoms in such a direction as to oppose the further diffusion of electrons and holes and the system comes into equilibrium statement.

Figure (2-1,(2-2) shows such arrangement for symmetrical junctions has equal and opposite doping on two sides, to the left of junction, electron concentration is high and decreases sharply nearly zero at edge of the depletion region, to right of junction hole concentration increases sharply from zero to the equilibrium value at the other edge of the depletion region, the hole and electrons concentrations approach the normal equilibrium value.

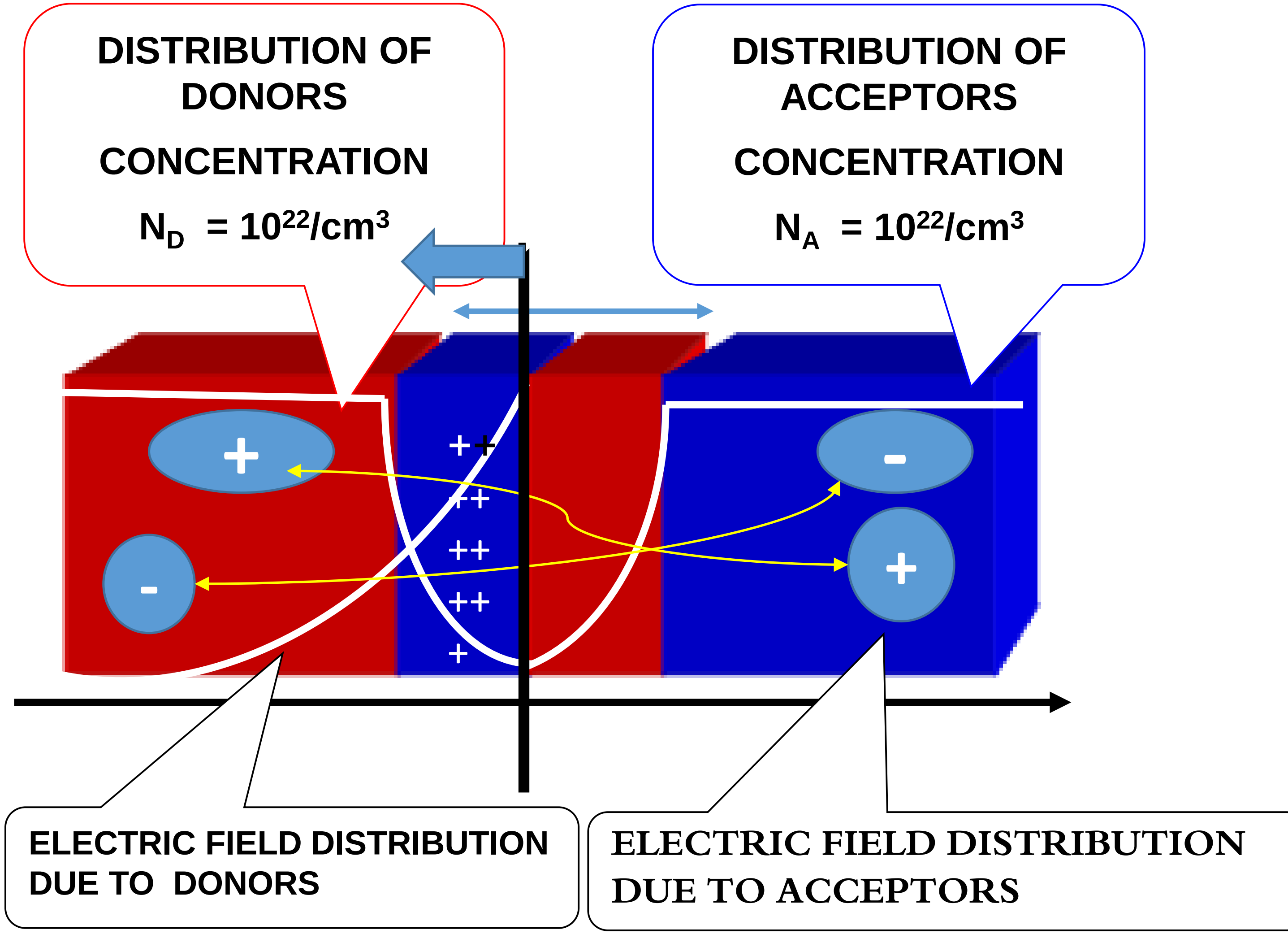


Fig. (2 - 1) Symmetrical PN Junction

Where $N_D = N_A$,$X_{m} = X_n + X_p$, and $X_n = X_p$

The electric field is the maximum at the junction and decreases linearly in receding from the junction within the depletion region of the junction (X_m), impurities are depleted of their holes or electrons. In some ways, the depletion region acts as insulating region, since it contains no mobile carriers. The built–in voltage V_T can be computed from the relation

$$V_T = \frac{K\,T}{q}\;ln\,\frac{N_D\,N_A}{n_i^2} \quad (2.1)$$

Commonly concentration of impurities on either side of the junction is not equal, corresponding picture of the depletion region is as shown in figure (2-3) for highly doped n – material (n^{+}- p). Most of depletion layer extends into the side has the lowest concentrations. It realized, that charge neutrality has to maintained as many positive charges as negative charges must presented in space charge of the depletion region.

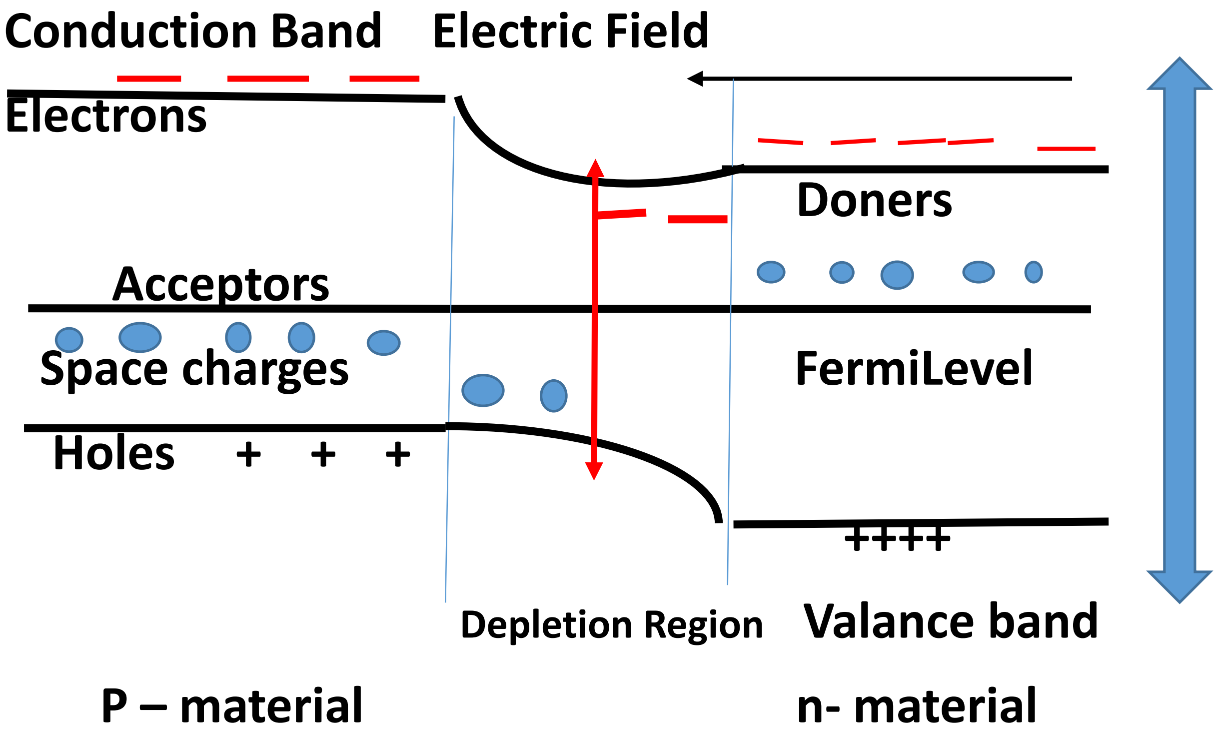


Fig. (2 – 2) p – n junction in Equilibrium case

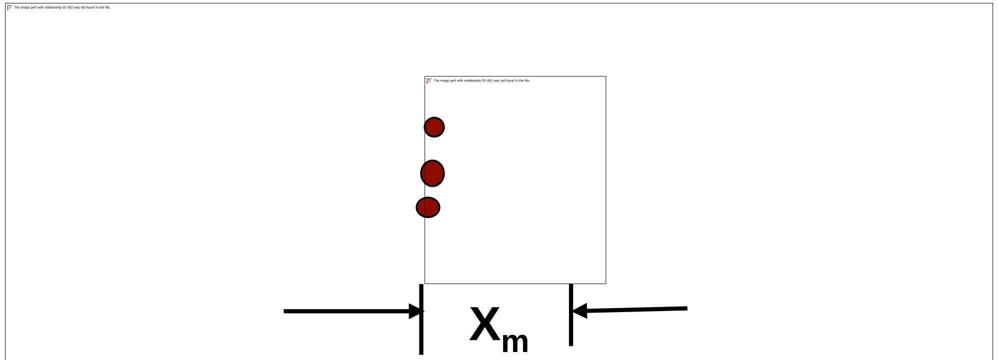


Fig. (2 – 3) Picture representation of N^{+} - p unsymmetrical Junction

Note, acceptor levels in the p-type side and the donor levels in the n-type side, most of them are ionized at room temperature. In addition, there is sufficient thermal energy at room temperature to ionize a few hole – electron pairs as evidenced by the electrons in conduction band of the p-type side and the holes in the valance band of the n-side. Since equilibrium is a condition that cannot support current flow in an external wire joining the p and n regions, the energy of electrons and holes must be equal in the two regions. The Fermi level must be a single level through the material. As a consequence of the constant Fermi level, there is an energy difference in both band edges at the junction. The energy difference equal to V_T expressed in eV can be thought as energy barrier that hinders diffusion of carriers from the high concentration side to the low concentration side.

Electrons tend to diffuse from the large concentration side in the n-region to the small concentration side in the p- region where recombination occurs. The balance of charge in the vicinity of the transition region will disturbed, the positively charges immobile donor atoms results a net positive charge on the n-side of the transition region. In the same manner, the diffusion of holes results a net negative charge immobile acceptor atoms on the p-side of the transition region. The negative charge must equal the positive charge. Also voltage difference due to the double layer of charge must at equilibrium be equal to the built-in voltage V_T which is the contact potential between the n and p material. The width of the depletion region is determined by the distribution of ionized impurities in the depletion region and by the potential of the energy barrier. The depletion region is very thin, usually in the order of 10^{-4}

The direction of the resulting field is such that a drift current of thermally generated electrons, is opposite in the direction to the diffusion current of electrons, and a drift current of thermally generated holes, is opposite in the direction to the diffusion current of holes, are established. At equilibrium, the contact potential assumes a value required to make the drift and the diffusion currents equal and opposite, so that there is no net current. the drift currents arise from minority carriers diffusing in the depletion region from regions and also from carriers of like sign thermally generated within depletion region, diffusion currents arise from majority carriers diffusing in the depletion region from regions and also from carriers of like sign thermally generated within the depletion region. When equilibrium is disturbed by applying a voltage V_o, there is little effect on the drift currents, but the effect on the diffusion currents is drastic exponentially in V_o.

When V_o positive on p-side, voltage is forward bias because the effect of voltage is to decrease energy barrier height and to increase the number of carriers that can diffuse across the depletion region as shown in figure (2 - 4), majority carriers from side will move into the depletion region and pass across the junction.

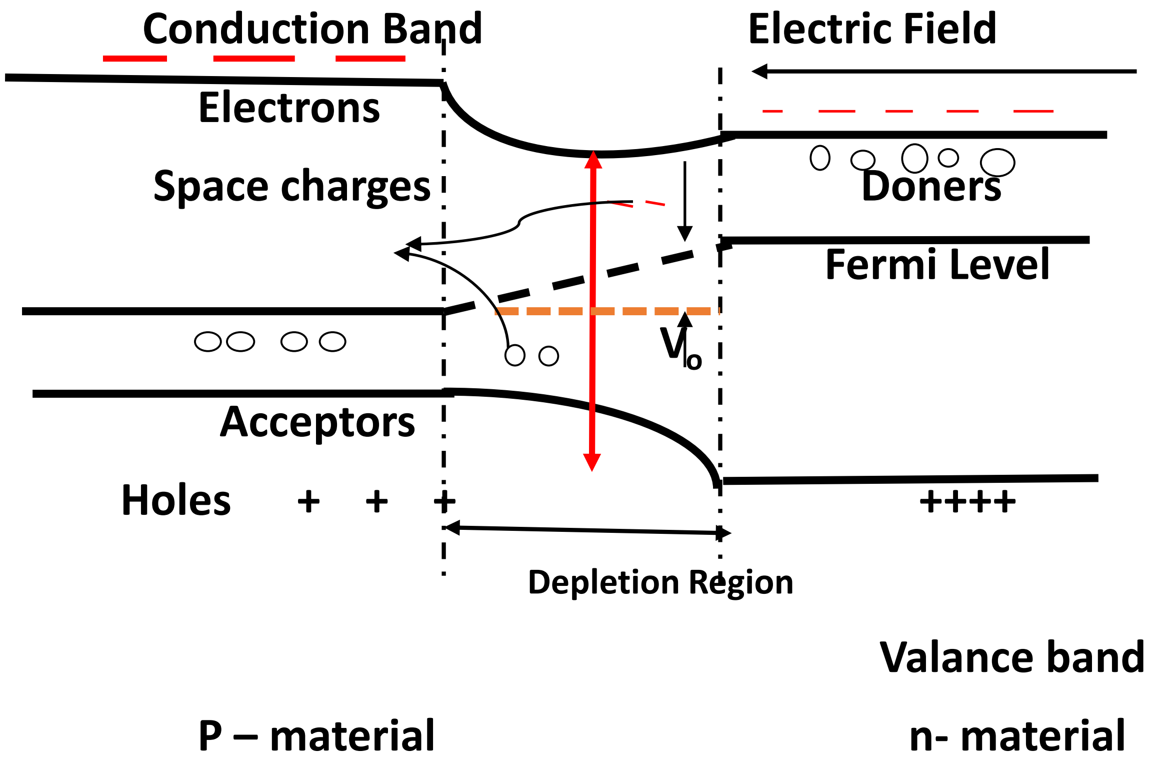


Fig. (2 – 4) p – n junction with forward bias

This low resistance direction and a current exist dependent on the carrier density, junction area, and applied potential, overall resistance can be representing as a high resistance, shunted by a capacitance due to the dielectric of the barrier layer. For small drift currents at moderate temperature and moderate impurity concentration, and for insignificant recombination of diffusion currents in the depletion region, we get good rectifying characteristics. Forward current increases exponentially with bias as diffusion current dominate. Reverse current is relatively voltage insensitive since the drift current dominates figure (2-5).

Figure (2-6) an arrangement for unsymmetrical junctions. As a result of such contact, diffusion of electrons and holes occurred until an electrical equilibrium will reached. Electric field will appear across the junction

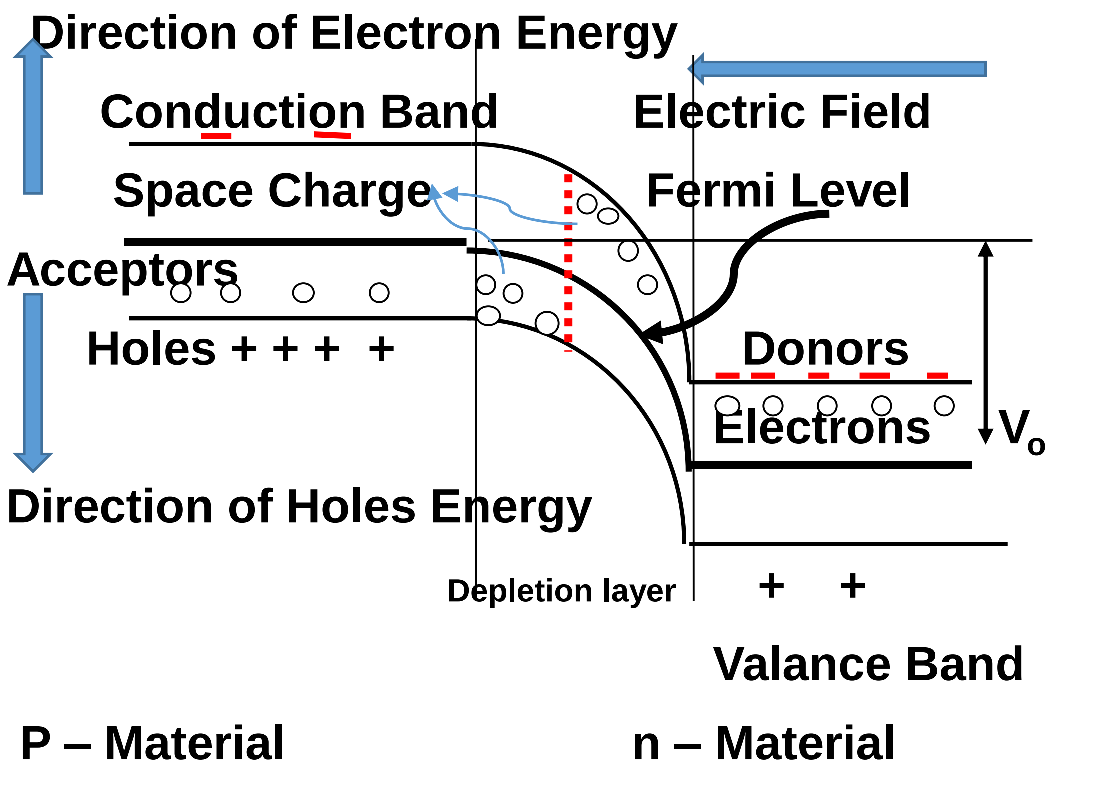


Fig. (2 – 5) p – n Junction with reverse Bias

Such electrical equilibrium will have established when the field becomes large to hinder more diffusion between the two sides and a depletion layer is existing and contain un-mobile charge carriers, this layer is also known as transition or space charge layer.

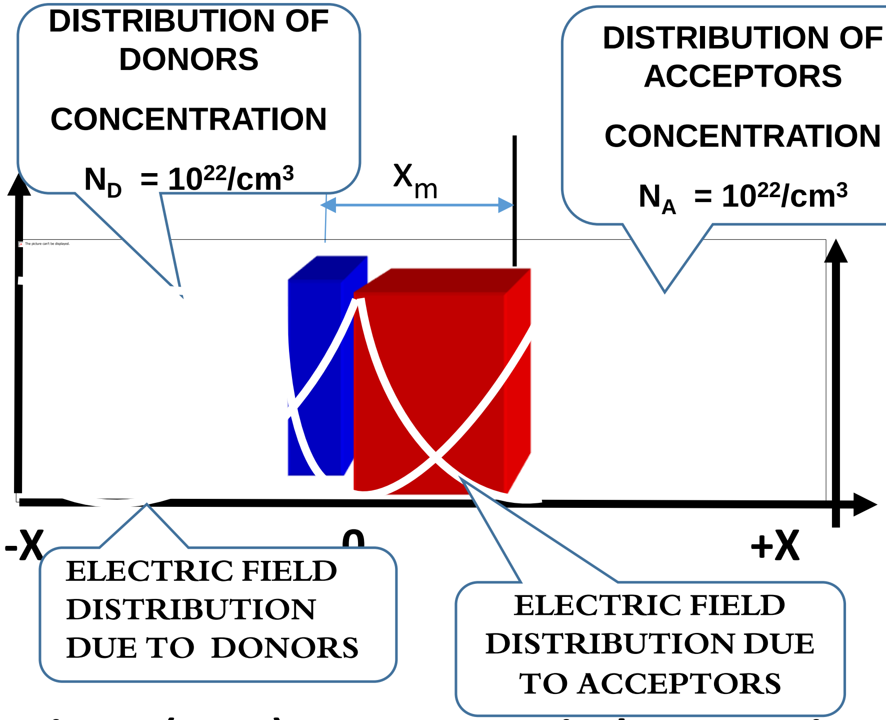


Figure (2 – 6) Un- Symmetrical PN Junction
Where N_D # N_A ,$X_m = X_n + X_p$, and X_n # X_p

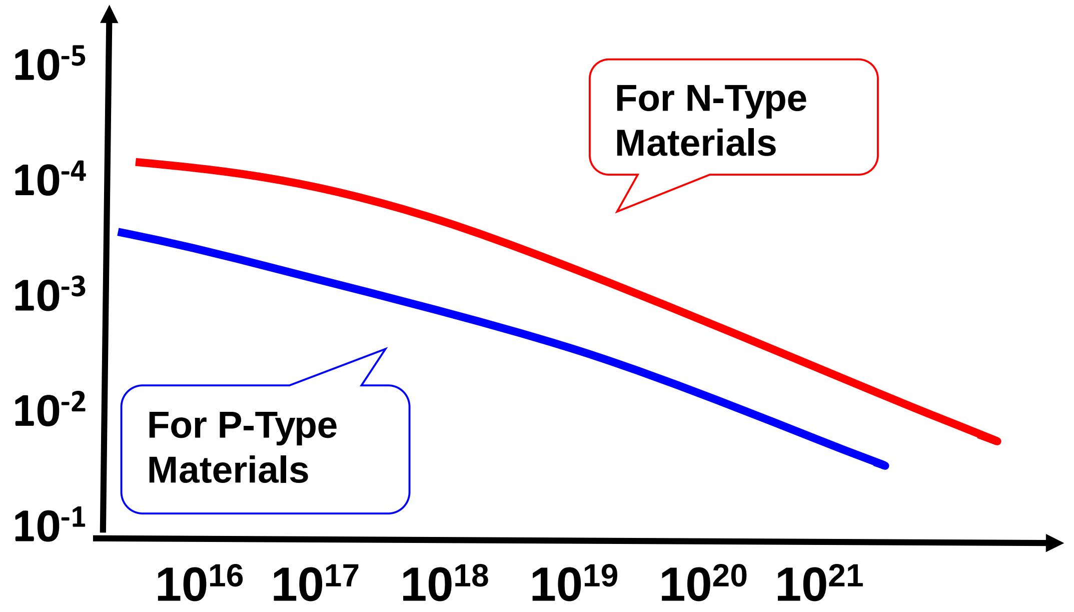
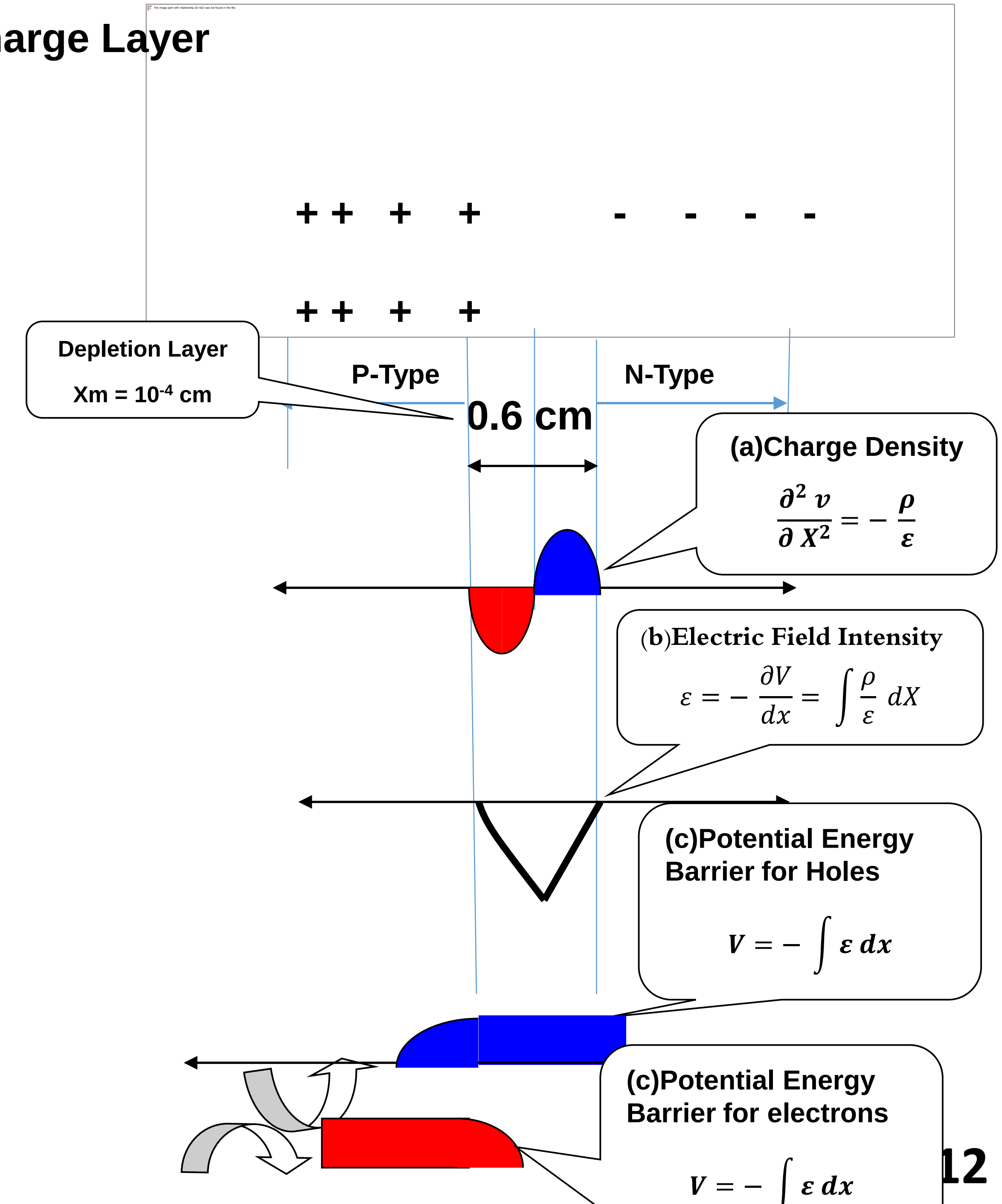


Fig. (2 – 7) Silicon Resistivity's as Function of Doping Concentration

The depletion layer is considered as the heart of the junction, where all the electrical phenomena are occurred. **Figure (2 – 7) shows the resistivity as function of doping concentration of N, P type for silicon . The electrical field intensity at the junction is shown in figure (2-8b).**

Figure (2 – 8) Electrical Phenomena inside the Space Charge Layer for PN Junction

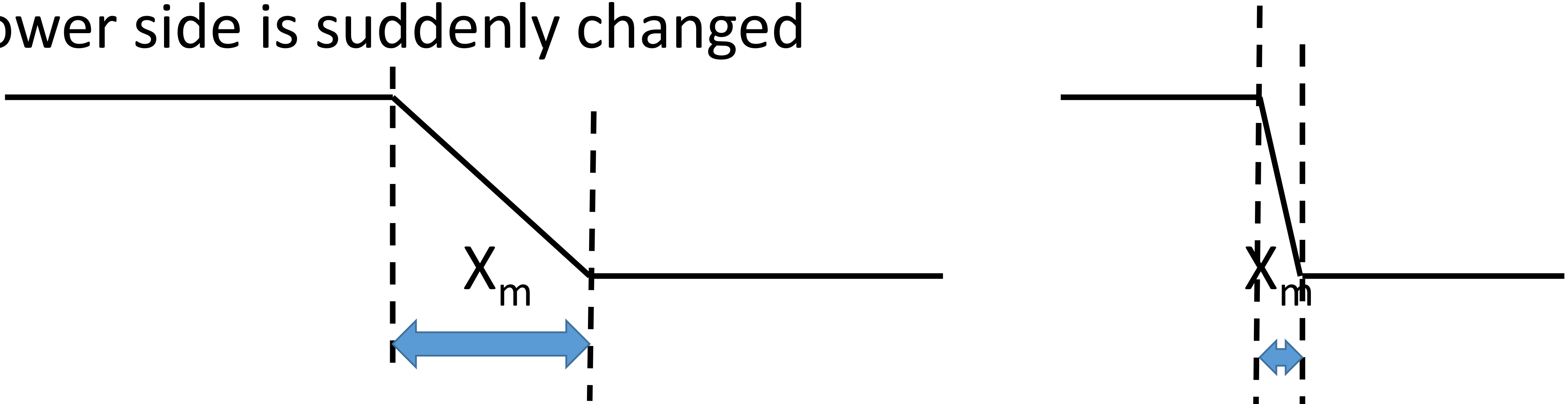


It is the integral of space charge intensity shown in figure (2-8a). Figure (2-8c) shows the electrostatic potential variation in the depletion region, which correspond to the potential energy barrier for the charge carriers. It is the negative integral of the electrical field intensity. Under open circuit condition , resultant current is zero, this allows us to calculate the height of the barrier voltage V_O which is in

There are two types of the junctions, mainly:

Graded Junction : where the diffusion from higher to lower side is gradually changed

Abrupt or step junction : where the diffusion from higher to lower side is suddenly changed



Over view for Graded and Abrupt or Step Junctions

$$X_{m(G)} >> X_{m(S)}$$

Example (50)

A silicon diode at temperature T = 300K has doping concentration $N_A = N_D = 1.2\times10^{16}$ cm $^{-3}$, $n_i = 1.5\times10^{10}$ cm $^{-3}$, D_n = 25 cm^2 s $^{-1}$, D_p = 10 cm^2 s $^{-1}$, K_S = 11.7, L_p = 2.2×10^{-3}cm and L_n = 3.5×10^{-3}cm, and cross section area = 1×10^{-2} cm^2 .

Solution:

The minority hole in n - region

$$\mathbf{p_{no} = \frac{n_i^2}{N_A} = \frac{2.25x10^{20}}{1.2x10^{16}} = 1.875x10^4\ cm^{-3}}$$

The minority electron in n_{po} p-region

$$\mathbf{n_{po} = \frac{n_i^2}{N_D} = \frac{2.25x10^{20}}{1.2x10^{16}} = 1.875x10^4\ cm^{-3}}$$

The reverse saturation current

$$I_s = A\left[\frac{q\,D_p p_{no}}{L_p} + \frac{q\,D_n n_{po}}{L_p}\right]$$

$$= 1.602\ x\ 10^{-19}\left[\frac{10\ x\ 1.0875\ x\ 10^4}{2.2\ x\ 10^{-3}} + \frac{25\ x\ 1.875\ x\ 10^4}{3.5\ x\ 10^{-3}}\right]$$

$$= 3.51\ x\ 10^{-13}\ A$$

Example (52)

Consider an abrupt p-n diode with N_a= 10^{18} cm^{-3} and N_d = 10^{16} cm^{-3}. Calculate the junction capacitance at zero bias. The diode area equals 10^{-4} cm^2. Repeat the problem while treating the diode as a one-sided diode and calculate the relative error.

Solution:

The built in potential of the diode equals:

The depletion layer width at zero bias equals:

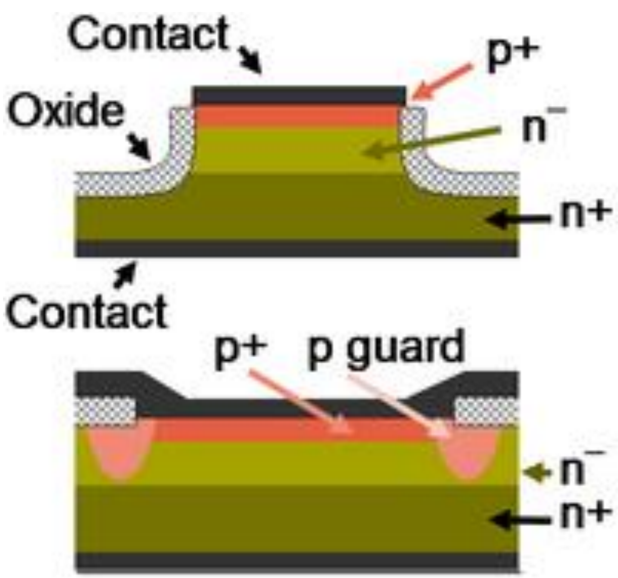
And the junction capacitance at zero bias equals:

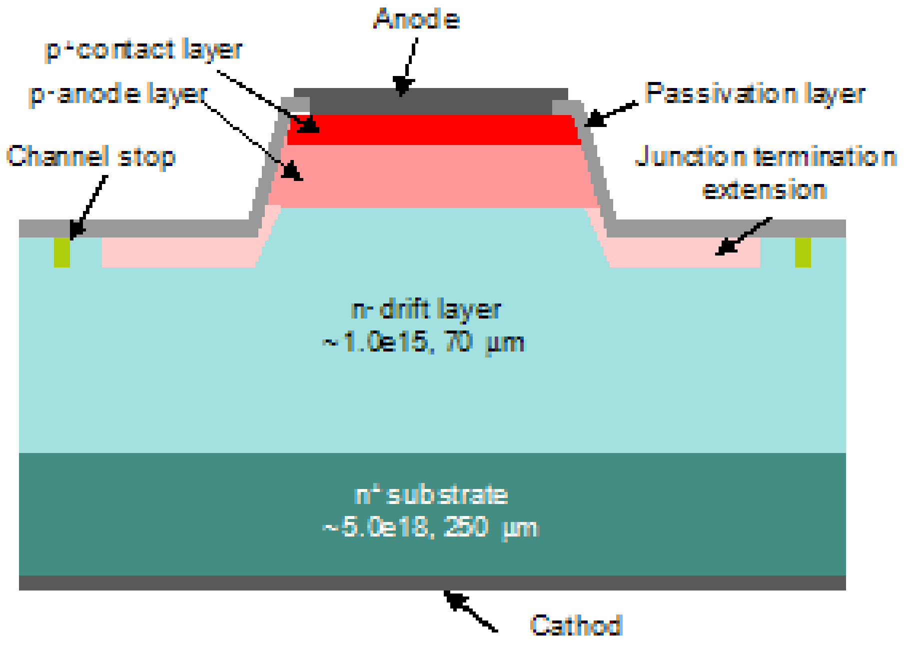
Repeating the analysis while treating the diode as a one-sided diode, one only has to consider the region with the lower doping density so that

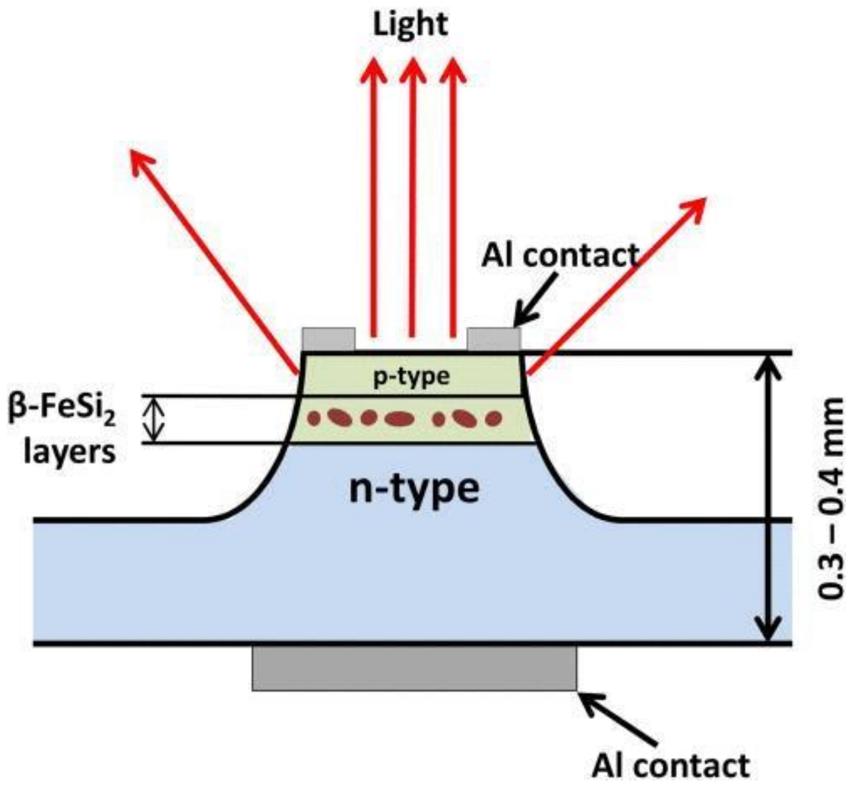
And the junction capacitance at zero bias equals

2.2 PHYSICAL DESCRIPTION OF THE DIODE

The key section of the planer diode involves the P^{+} - N junction, and acts as a rectifier. It allows the current to pass only in one direction but not the opposite direction. If we connect the junction with bias voltage as in figure (2-9), a large current flow is observed and its magnitude increases exponentially with the applied voltage. This is known as the forward bias. An ideal PN diode has zeroed ohm voltage drops, for such diode, the height of the potential barrier as shown in figure (2-8c) is decreased. For a forward bias, holes from P to N, and electrons from N to P cross the junction. They are the majority carriers and large current will flow.







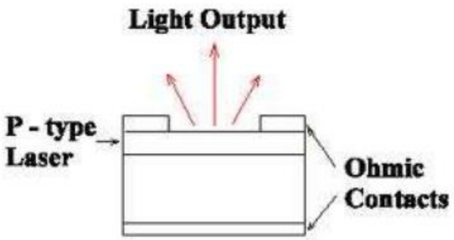
Mesa Diode Structure

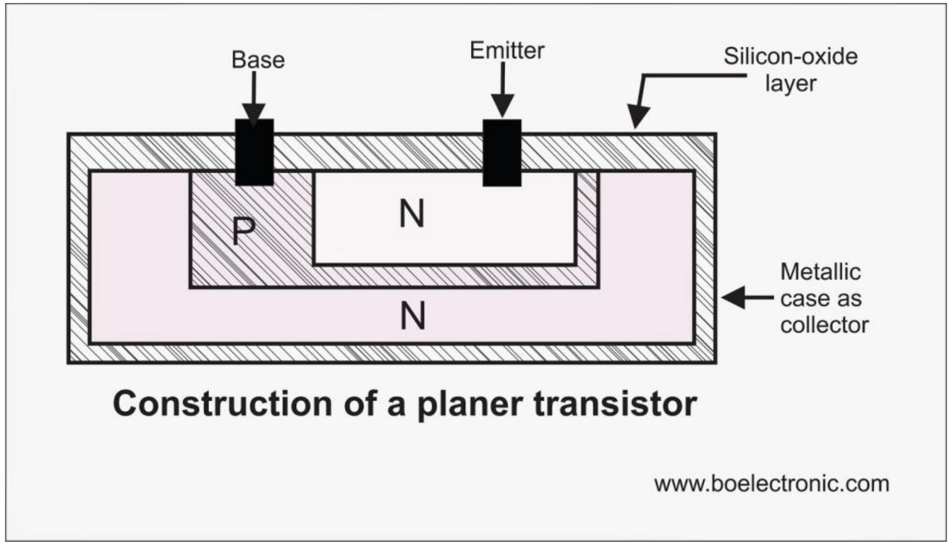
Structures of LED

There are five types of LED Structures

1. Planar LED
2. Dome LED
3. Surface Emitter LED(SLED)
4. Edge Emitting LED (ELED)
5. Super luminescent LED (SLD)

Planar LED





Construction of a planer transistor

If the two terminals of the battery interchange , current will disappear, this is known as reverse bias condition. The holes in the p - side, and electrons in the n - side are move away from the junction. Actually generated hole - electron pairs will appear due to the thermal energy. They constitute small current known as reverse saturation current I_R or I_o or I_s . Current will remain negligible until reverse voltage becomes very large, then at some critical voltage a large current surges through the diode under condition of junction breakdown. The mechanism of conduction in the reverse direction is described as, when no voltage is applied to PN diode, the potential barrier across the junction is shown in figure (2-8d).

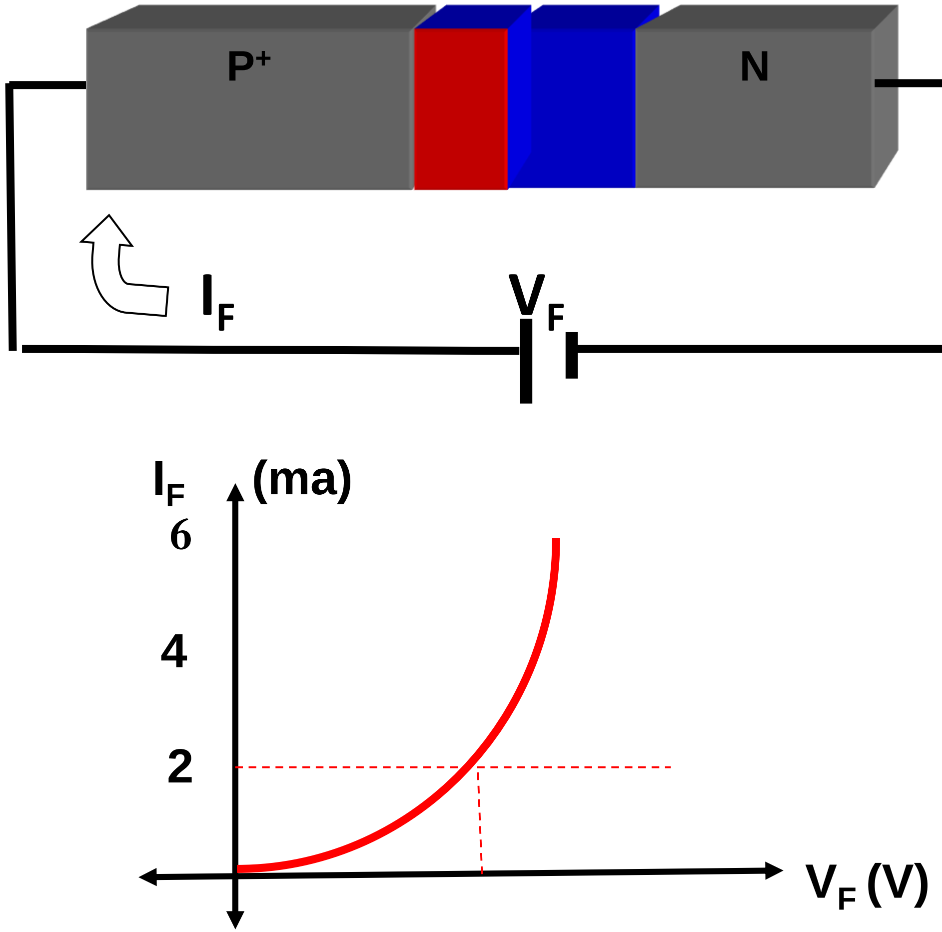


Fig. (2 – 9) PN Junction in Forward Bias

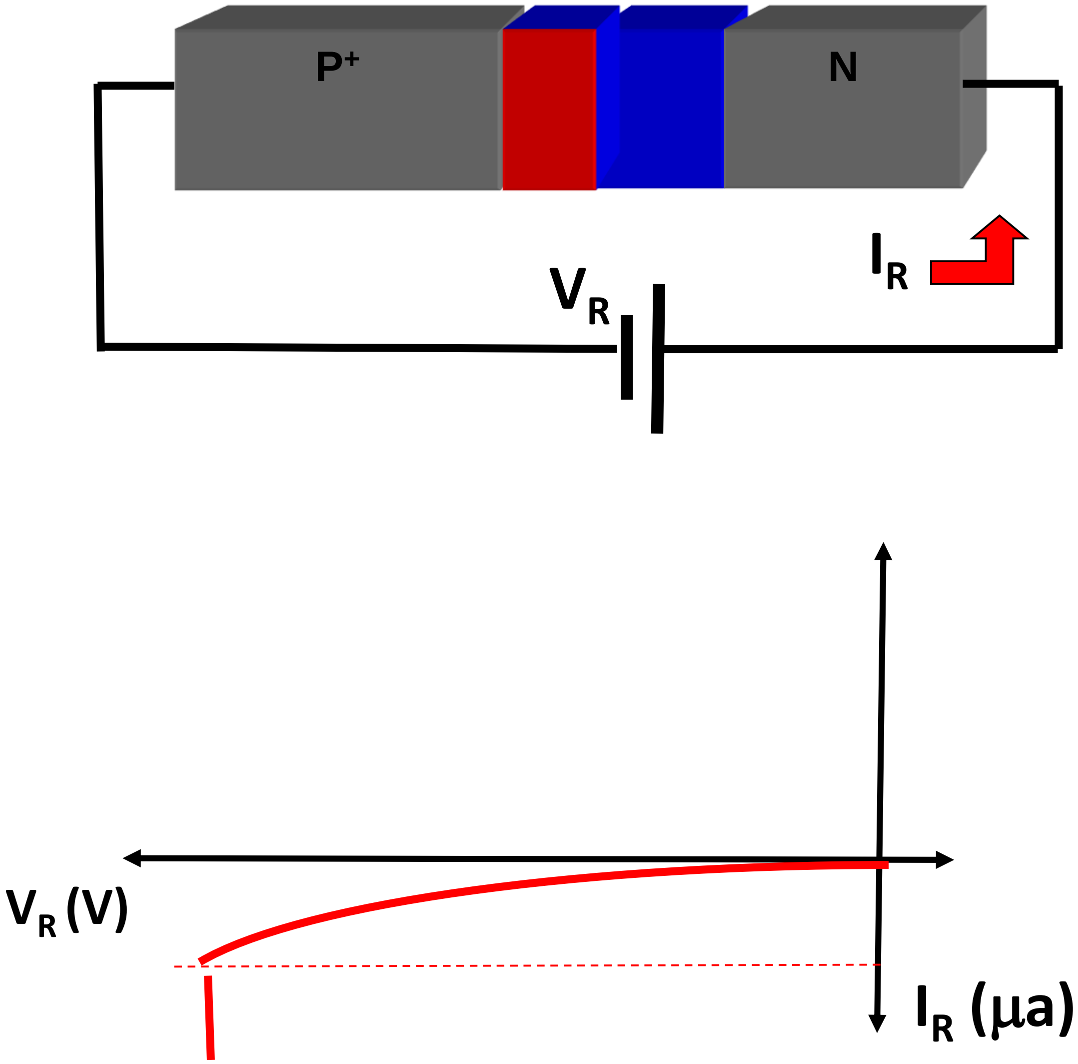
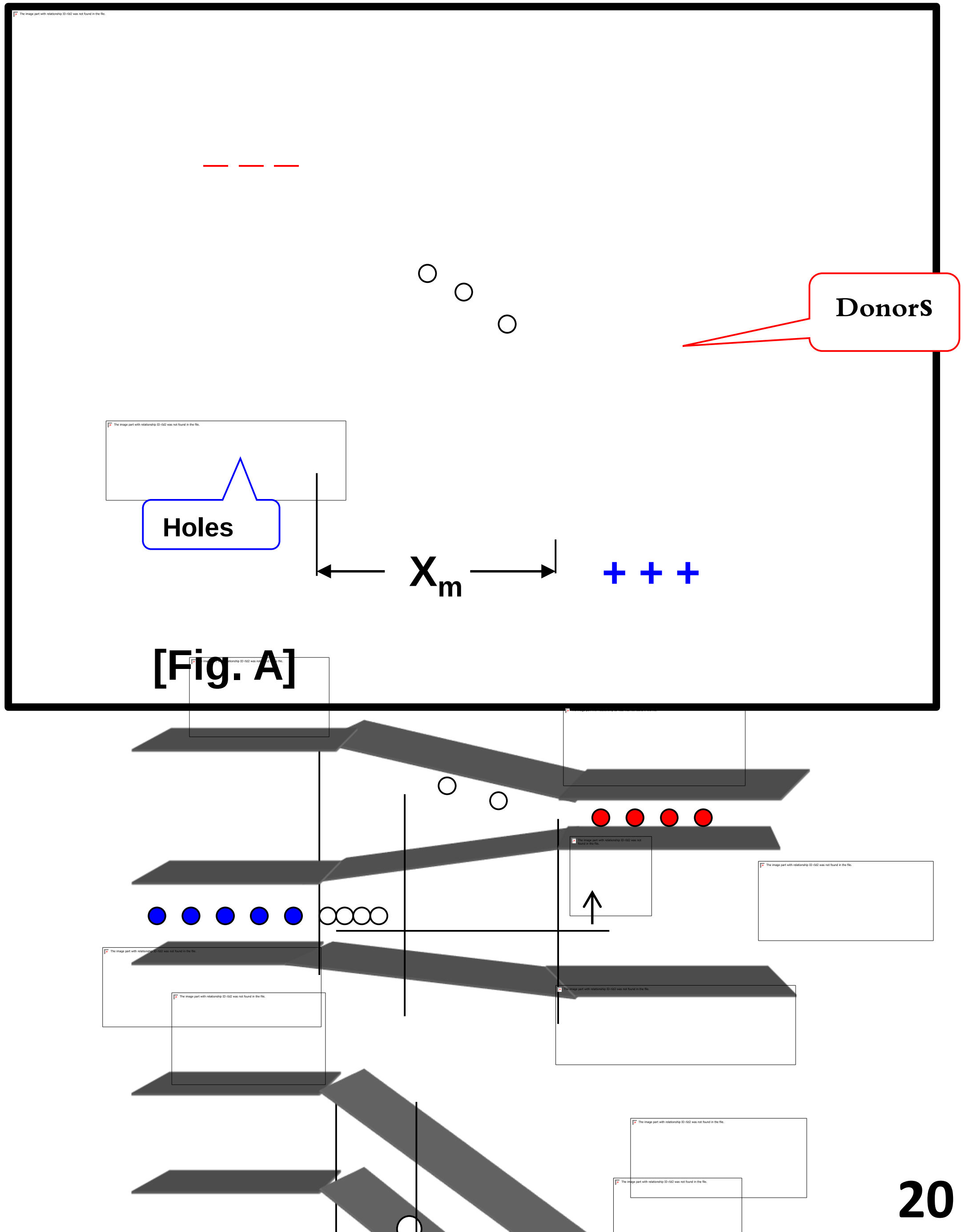


Fig. (2 – 10) PN Junction in Reverse Bias

When reverse voltage applied, height of potential barrier increased, reduces flow of majority carrier's (p_P), and (n_n), also reduce flow of minority carriers (p_n), and (n_p). Note that, current increased by increasing temperature. Reverse bias condition is shown in figure (2-10). P-N junction can be used as a switch, rectifier, light detector, solar cell, microwave diode, or in compound semiconductors as a light emitter or laser diode. Figure (2-11), shows energy band representation for PN Junction. Equation 2.1 of the potential barrier derived from the following consideration. When no voltage is applied to the p-n junction, no current passes through external circuit even when the n–region, is shorted as shown in figure (2-12).

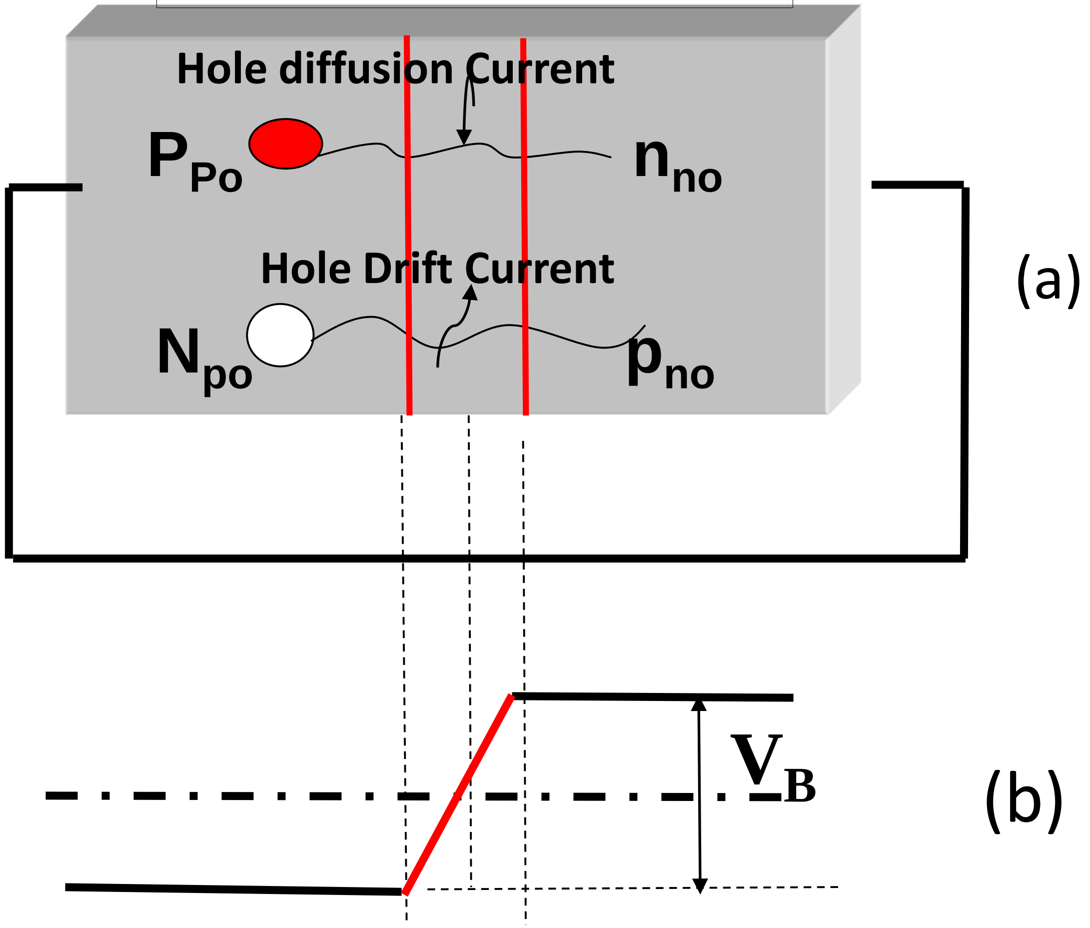
Thus, net current through the junction must be zero separately both for free electrons and holes. Considering free electron current only at the junction figure (2-12a), one finds that there are two components of current density flowing across the junction. J_{1n} is the component of the current density that flows down the potential barrier with the electron flowing from p-region to n-region and it is the drift current density due to the free electrons under the influence of the field on account of the potential barrier and J_{1n} may be written as:

$$J_{1n} = qn\mu_n\varepsilon \qquad (2.2)$$



[Fig. A]

Where ε is electric field intensity caused due to potential barrier voltage V_B, and (n) is density of free electrons. Current density component J_{2n} flow of electrons from n-region where free electrons are majority carriers to p-region where they become minority current flows due to diffusion, thus, $J_{2n} = qD_n \frac{dn}{dx}$ (2.3)



D_n is diffusion constant for electrons and dn/dx is the gradient of electron density. When applied voltage is zero, sum of the two components is equal to zero, hence:

$$J_{1n} + J_{2n} = qn\mu_n\varepsilon + qD_n\frac{dn}{dx} = 0 \quad (2.4)$$

Rearranging and integrating the equation across the depletion layer (a-b) near the junction,

$$-\int_a^b \epsilon dx = \frac{D_n}{\mu_n}\int_{n_p}^{n_n}\frac{dn}{n}(2-5)$$

Where n_n and n_p are the densities of free electrons in the n-region and the p-region respectively

$$V_b - V_a = V_T = \frac{D_n}{\mu_n}\ln\frac{n_n}{n_p}(2.6)$$

Where V_a and V_b potential at (a),(b) (figure 2.12b), Using Einstein relation,

$$D_n/\mu_n = KT/q \,,$$

We get the barrier potential $V = \frac{KT}{q}\ln\frac{n_n}{n_p}\,(2.7)$

Or,

$$n_n = n_p \exp\frac{qV_B}{KT}\,(2.8)$$

Considering hole current and using the relationship $p_n = n_i^2/n_n$, We get

$$V_T = \frac{KT}{q}\ln\frac{p_p}{p_n} = \frac{KT}{q}\ln\frac{p_p\, n_n}{n_i^2} \quad (2.9)$$

Or $$p_p = p_n \exp\left(\frac{qV_B}{KT}\right)(2.10)$$

For a typical germanium p-n junction doped to 10^{16} impurity atoms per cm^3, the barrier potential at room temperature is about 0.3V. This barrier potential cannot be measured because the net current is zero and the crystal is electrically neutral to the outside.

Example (53)

Calculate the built-in potential barrier of a pn junction. Consider a silicon pn junction at T = 300 K, doped at $N_a = 10^{16}$ cm^{-3} in the p-region and $N_d = 10^{17} cm^{-3}$ in the n-region.

Solution:

We have $n_i = 1.5 \times 10^{10} cm^{-3}$ for silicon at room temperature. We then find

$$V_{bi} = V_T \ln\left(\frac{N_d N_A}{n_i^2}\right)$$

$$= 0.026 \ln\left[\frac{10^{16} \text{x}\, 10^{17}}{(1.5 \text{ x } 10^{10})^2}\right] = 0.757 \text{ V}$$

Comment: Because of the log function, the magnitude of V_{bi} is not a strong function of the doping concentrations. Therefore, the value of V_{bi} for silicon pn junctions is usually within 0.1 to 0.2 V of this calculated value.

Example (54)

An abrupt silicon p-n junction (Na = 10^{16} cm^{-3} and N_d = 4 x 10^{16} cm^{-3}) is biased with V_a = 0.6 V. Calculate the ideal diode current assuming that the n-type region is much smaller than the diffusion length with w_n' = 1 mm and assuming a "long" p-type region. Use μ_n = 1000 cm2/V-s and μ_p = 300 cm2/V-s. The minority carrier lifetime is 10 ms and the diode area is 100 mm by 100 mm.

Solution:

The current is calculated from:

With

$$D_n = \mu_n V_t = 1000 \text{ x } 0.0258 = 25.8 \text{ cm}^2/\text{V-s}$$

$$D_p = \mu_p V_t = 300 \text{ x } 0.0258 = 7.75 \text{ cm}^2/\text{V-s}$$

$$n_{p0} = n_i^2/N_a = 10^{20}/10^{16} = 10^4 \text{ cm}^{-3}$$

$$p_{n0} = n_i^2/N_d = 10^{20}/4 \text{ x } 10^{16} = 2.5 \text{ x } 10^3 \text{ cm}^{-3}$$

- **Yielding I = 40.7 mA**

2.2.1 DC voltage – current analysis in p-n junction

Derivation for direct current in p-n be considered. Fig. (2-13) shows holes & electron current components versus distance in n^+- p junction with forward bias. It assumed current flow in one dimensional, so no recombination takes place in depletion layer and drift current within depletion layer are small.

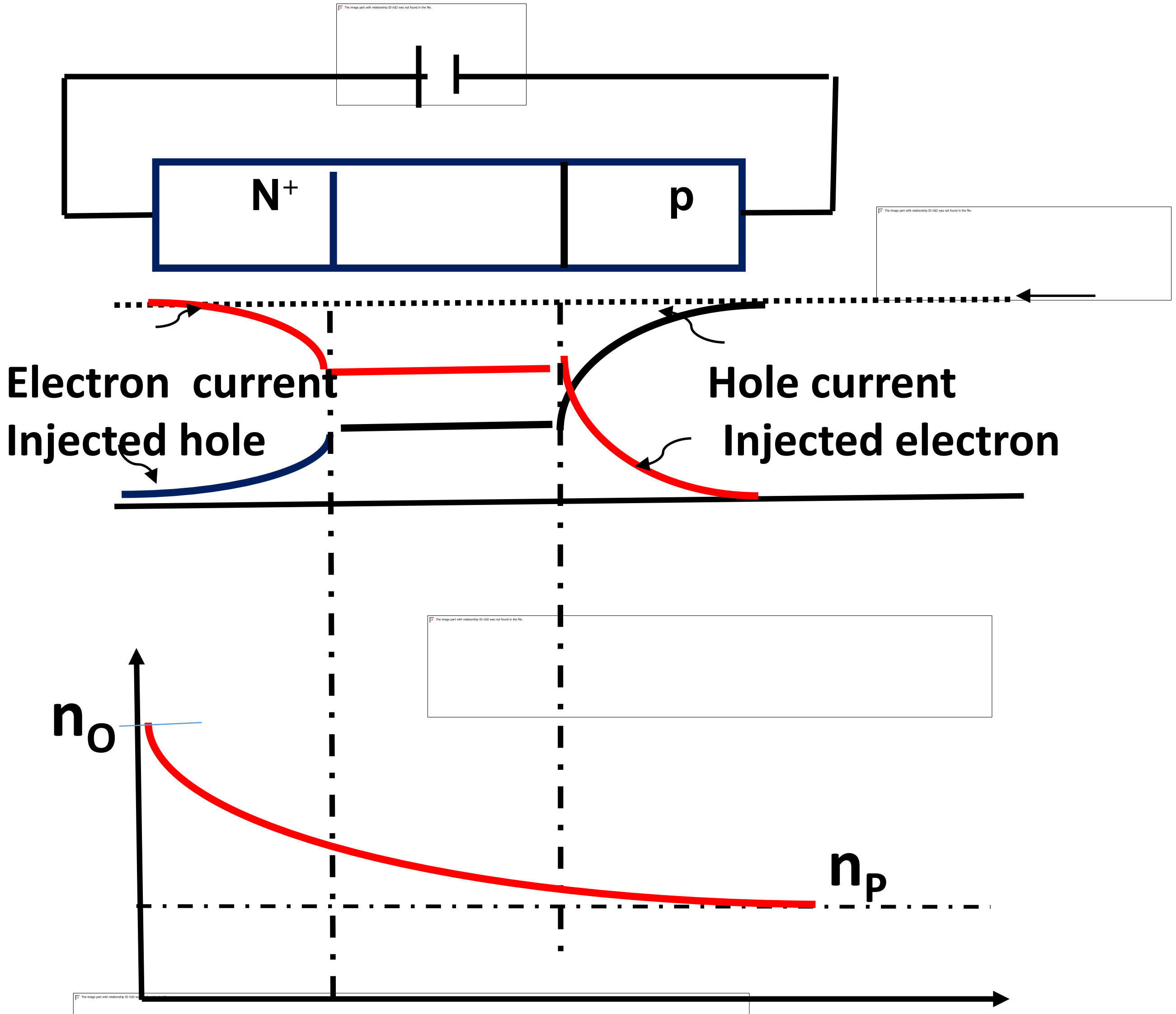


Fig. (2 - 13) Hole and electron current components versus distance in pn junction

In n-material, total current is equal to electron current, in which some recombine with holes that are injected into n^+ material from p-region. Thus, it decreases toward junction in such a way that sum of electrons current and injected hole current equals total current. Remains current of I_n at the junction diffuses into the p-material. Injected electrons then recombine, and the electron concentration in p-material decreases with distance from junction until the equilibrium concentration of electrons in p-material, n_p, is reached. The same be made with respect to injected hole current in n-material. The total current flowing will be nearly equal to sum of electron and hole diffusion currents at junction.

An expression for the electron current following under these conditions can be obtained in elemental volume extending from x to x + dx , net flux of carriers into the volume plus the rate of recombination of carriers within volume must under steady state conditions equal zero.

The flux of electrons entering the left face is,

$$F(x) = D_n \frac{\partial n}{\partial x} \qquad (2.11)$$

, and the flux of electrons leaving x + dx is,

$$F(x + dx) = F(x) + \frac{\partial F}{\partial x} dx \qquad (2.12)$$

Thus the net flux entering the volume is,

$$F(x) - F(x + dx) = D_n \frac{\partial^2 n}{\partial x^2} dx \qquad (2.13)$$

Since excess carriers recombine exponentially, the rate of recombination is proportional to the carrier excess and rate of carriers removal from the elemental volume by the recombination is equal to,

$$+\frac{(n-n_p)}{\tau_n}(2.14)$$

Where τ_n is electron carrier life time in p-region semiconductor, from continuity we have,

$$D_n\frac{\partial^n n}{\partial x^2}-\frac{(n-n_p)}{\tau_n} = 0(2.15)$$

Solution of equation (2.15) subject to the boundary conditions ($n = n_o$ at $x = 0$, $n=n_p$ at $x= \infty$) gives,

$$n - n_p = (n_o - n_p)\frac{e^{-x}}{\sqrt{D_n \tau_n}} (2.16)$$

Rate of diffusion of electrons which leads to an electron diffusion current density is directly proportional to the electron concentration gradient. In one-dimensional case,

$$J_n = qD_n \frac{dn}{dx} + qn\mu_n \varepsilon (2.17)$$

Where J_n is total electron current density, D_n is electron diffusion constant in m^2/s, and dn/dx is the concentration gradient of electrons. Both electron diffusion current density qD_n (dn/dx) and electron drift current density $qn\mu_n\varepsilon$ are included because in practical case, such motion of electrons in the base region of a transistor.

From eq. (2.17),

$$I_n = qAD_n \frac{\partial n}{\partial x}\mathrm{I}_{x=0} = \frac{qAD_n(n_o - n_p)}{\sqrt{D_n \tau_n}} \quad (2.18)$$

Concentration of electrons at right edge of depletion region is related to applied voltage V_o. From Fermi level considerations, it can shown that injected level of electron is,

$$n_o = n_p e^{qV_o/KT} \quad (2.19)$$

Thus,

$$I_n = \frac{qAD_n n_p}{L_n}\left(e^{qV_o/KT} - 1\right) \quad (2.20)$$

Where, A is cross sectional area of junction, V_o is applied junction volt, τ_n is electron life time in p-material, n_p is electron density in p-side, D_n is the electron diffusion constant, $L_n = \sqrt{D_n \tau_n}$ is electron diffusion length in the p-side.

Similar expression established for the hole current, giving a total current flow of,

$$I = I_s\left(e^{qV_o/KT} - 1\right)(2.21)$$

Where, $I_s = qA\left[\left(\frac{n_p}{\tau_n}\right)L_n + \left(\frac{p_n}{\tau_p}\right)L_p\right]$

, τ_p is hole life time in n-material, p_n is hole density in n-side, D_p is hole diffusion constant, $L_p = \sqrt{D_p \tau_p}$ is hole diffusion length in the n-side. Eq. (2.21) is known as the ideal rectifier equation, this equation derived for a forward bias junction,

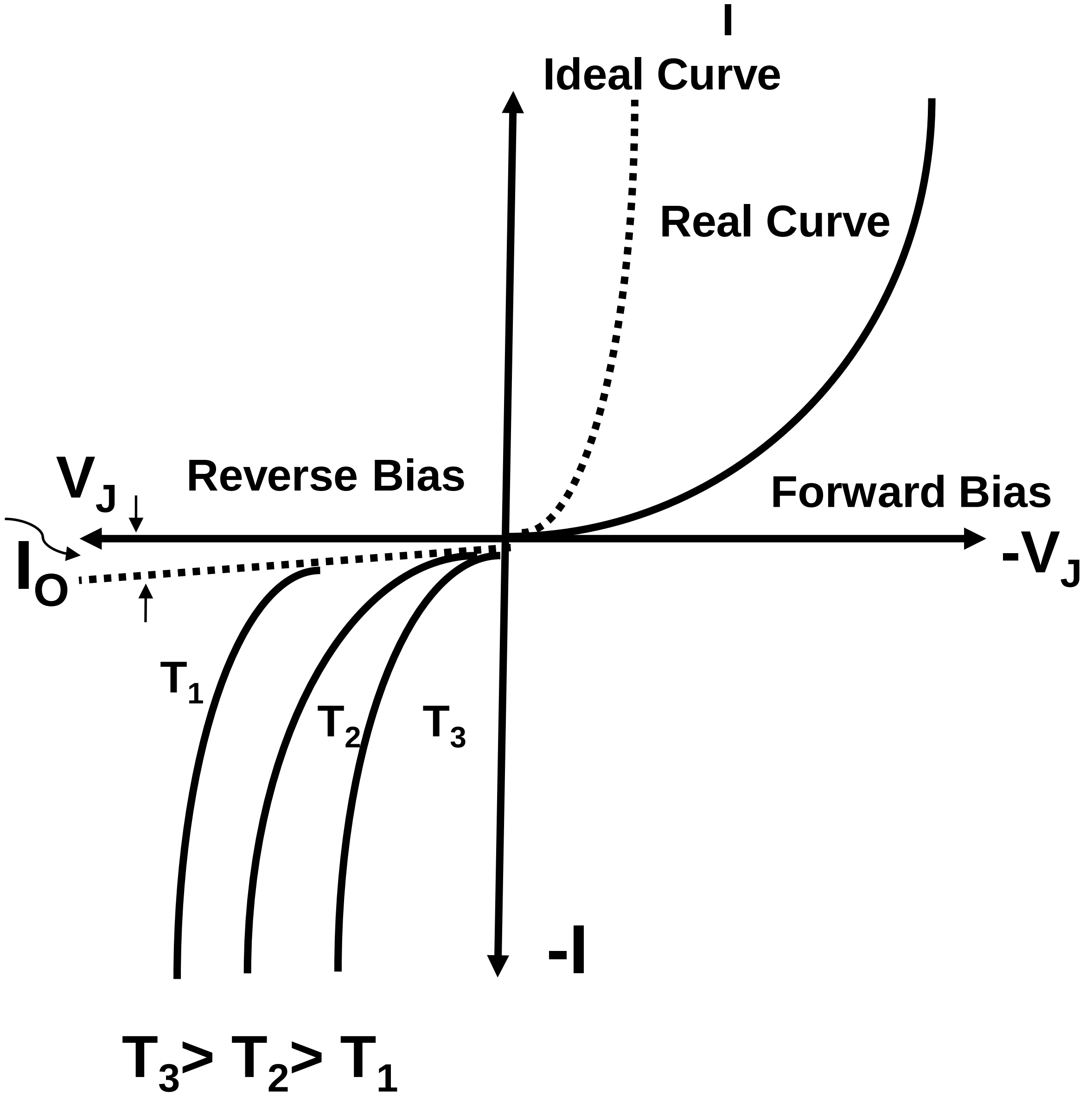


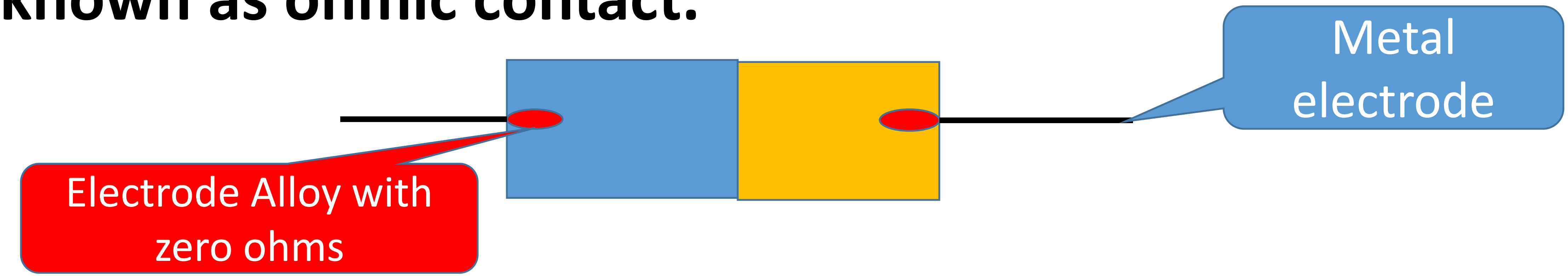
Fig. (2 - 14) Ideal and Real V-A Characteristics of p-n Junction it shown that it is equally valid for reverse bias. Experimentally it found many diodes follow ideal rectifier equation over a current range of six orders of magnitude, or even more. The quantity I_s is called a saturation current. The ideal rectifier characteristics also hold to about same accuracy for Schottky barrier diodes having a high barrier (ϕ) at the interface between the metal and semiconductor materials, provided that saturation current I_s given the value,

$$I_s = AT^2 e^{-q\emptyset/_{KT}} \quad (2.22)$$

The diode equation is plotted in figure (2.14) for ideal and real voltage - current characteristics of a p-n junction at different temperature.

2.2.2 Ohmic Contact

Two metal electrodes be alloyed to p-n junction to allow flow of current in external circuit. Such electrode has a contact potential developed across it. We assume, such contact has been manufactured with zero resistance in a way that, they are non-rectifying element. In other words, the contact potential across these electrodes is independent of the direction and magnitude of current, such contact is known as ohmic contact.



2.2.3 Short and Open Circuit junction

At no bias voltage, and junction is in a short circuit mode, current should be zero, and barrier voltage V_o or V_t or V_B remains unchanged. If I # 0 at V=0, the metal will be heated, such energy is supplied by the junction itself, so such junction needs to cooling. Since under short circuit condition, the sum of voltages will be zero, and the barrier voltage V_o will be compensated by metal -semiconductor contact potential at the ohmic contact.

2.2.4 Band Structure of Open Circuit Junction

For reaching electrical equilibrium in a PN junction, Fermi level must be constant along the junction, Fermi level is closer to conduction band in n-type side and closer to valance band in p-type side. Figure (2-15) shows energy band diagram in a p-n junction and shift of energy level is appeared . From figure (2-15), we can see:

$$E_o = E_{CP} - E_{Cn} = E_{vp} - e_{vn} = E_1 + E_2 \quad Eq.2.23$$

Where E_o is the barrier voltage at the junction, and:

$$1/_2\, E_g - E_1 = E_F - E_{vp} \quad Eq.2.24$$

$$1/_2\, E_g - E_2 = E_{cn} - E_F \quad Eq.2.25$$

By adding Eq. 2.24, and Eq. 2.25, we get:

$$E_1 + E_2 = E_g - (E_{Cn} - E_F) - (E_F - E_{vn}) = Eq.2.26$$

From Eq.2.23, and Eq. 2.26, then:

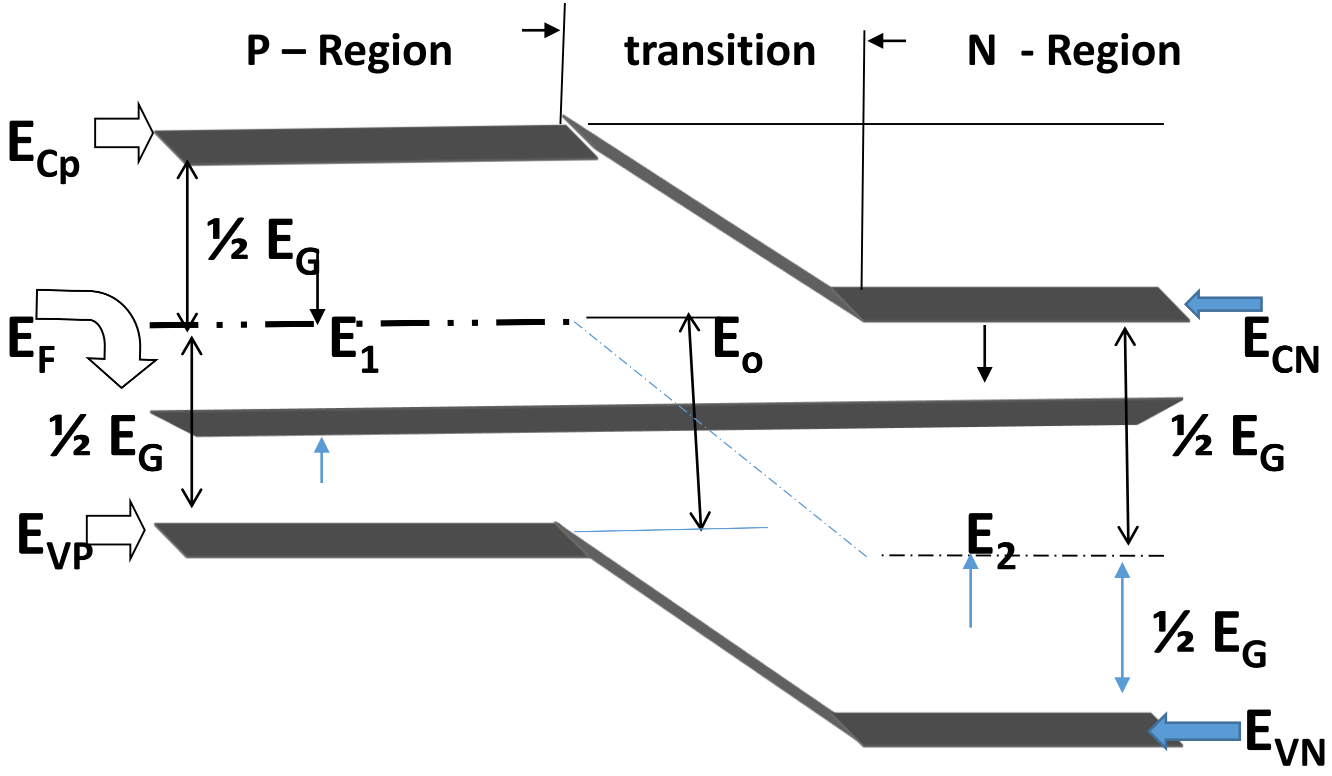


Fig. (2 – 15) Energies Representation in PN Junction

$$E_o = E_1 + E_2 \quad = E_g - (E_{Cn} - E_F) - (E_F - E_{vn}) = \; Eq.2.27$$

And we have before:

$$n_i^2 = n\,p = \; N_c\,N_v\,e^{-(E_g/KT)}$$

From which, $$E_g = KT\,ln\,\frac{N_c\,N_v}{n_i^2} \qquad Eq.2.28$$

And also we have before,

$E_F = E_c = KT \, ln \, {}^{N_c}/_{N_D}$ From which:

$$E_{Cn} - E_F = KT \, ln \, {}^{N_c}/_{N_D} \qquad Eq.2.29$$

And also we have before,

$$E_F = E_v + KT \, ln \, {}^{N_v}/_{N_A}$$

From which: $E_F - E_{vn} = KT \, ln \, {}^{N_v}/_{N_A} \qquad Eq.2.30$

By substituting Eqs.2.28, 2.29, and 2.30 in Eq.2.27, we have:

$$E_o = KT \, ln \, \frac{N_c \, N_v}{n_i^2} = V_o \qquad Eq.2.31$$

When a forward bias is applied to a PN junction, injected minority carriers decreased exponentially with distance from the junction as shown in the next equation:

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

And also the diffusion current is given before as: $J_p = -q\, D_p \frac{\partial p}{\partial x}$

In figure (2-16), there are four current components (I_{pp} ,I_{nn}, I_{pn} , I_{np}), the total current due to minorities at x=0 is,

$$I = I_{pn(o)} + I_{np(o)} \qquad Eq. 2.32$$

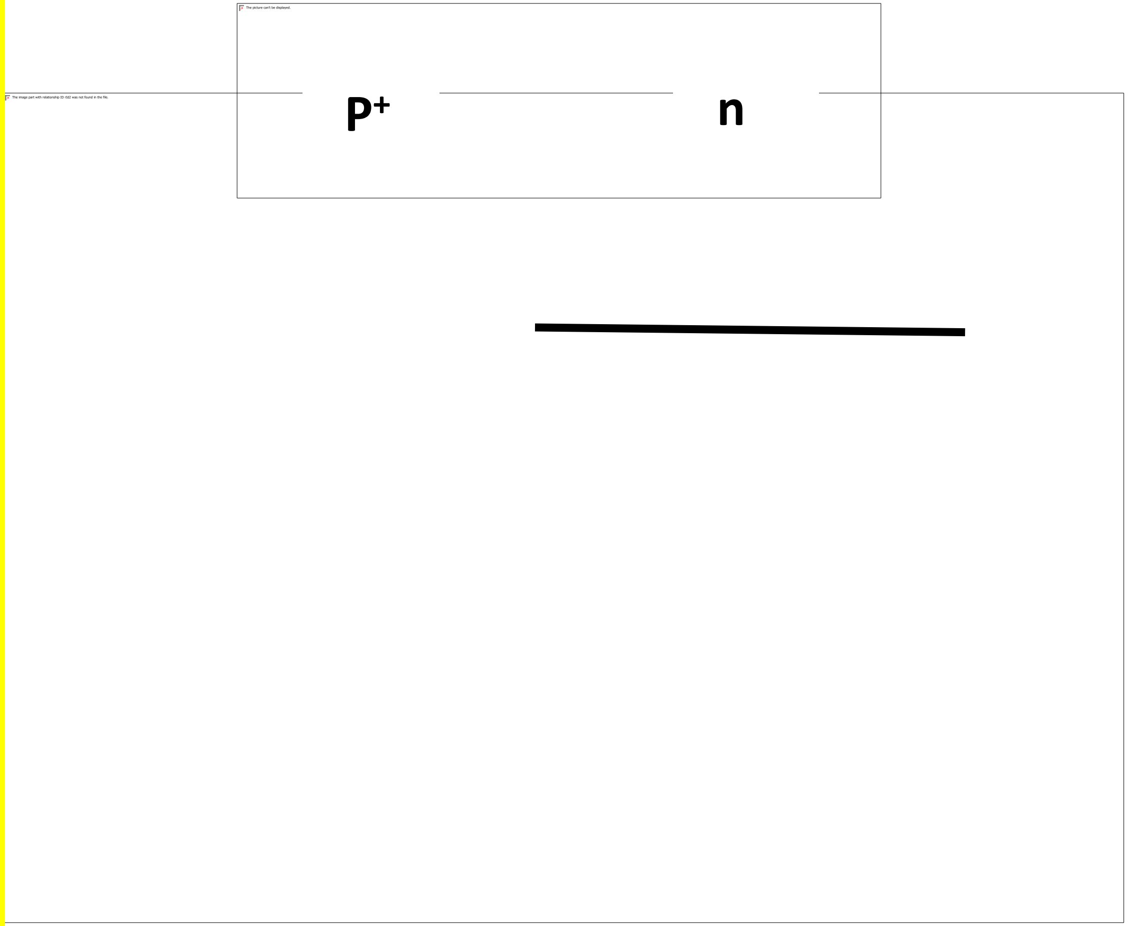


Figure 2-16 Current component in pn junction

In the p-side, It is clear that, the total current (I) is equal to I_{pp} added to I_{np} ,

$$I_{pp(x)} = I + I_{np(x)} \qquad Eq. 2.33$$

In N-side, It is clear that, the total current (I) is equal to I_{nn} added to I_{pn} , The total current in diode at junction equal to zero, $I_{nn(x)} = I + I_{pn(x)} \qquad Eq. 2.34$

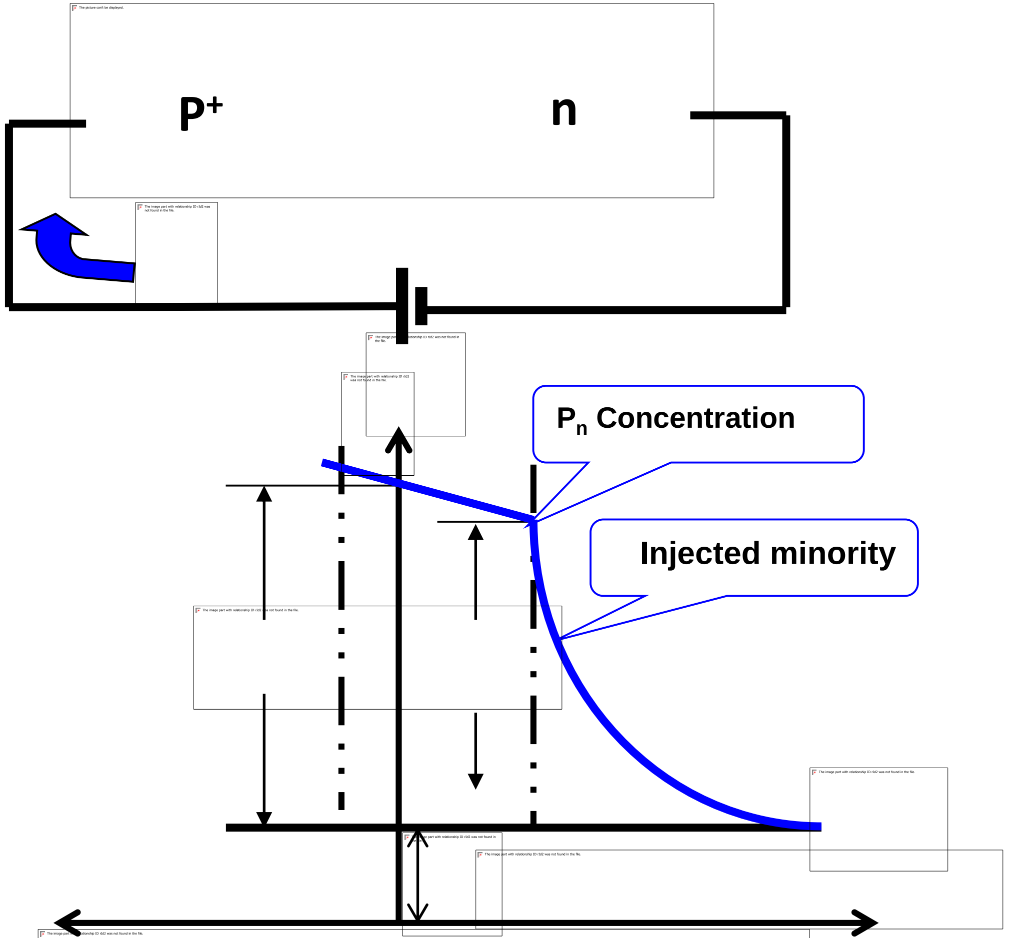
$$I_{T=} I_{pp} + I_{np} - I_{nn} - I_{pn} = 0 \qquad Eq. 2.35$$

Note that in un- symmetrical junction,

$$I_{nn} \neq I_{pp} \quad \& \quad I_{np} \neq I_{pn}$$

2.2.5 The Quantitative Theory of PN Currents

If a forward bias is applied to junction, holes are injected from P-into N-side; and also electrons are injected from N into P-side. Let us analyze one component only, for example injected holes in N-side (injected electrons in P-side has same analysis).The concentration of holes in n-side is increased above its thermal equilibrium value (p_n), which is given by:



$$p_{n(x)} = p_{n(1)}\, e^{-\left(x/L_p\right)} + p_n \qquad Eq.2.36$$

Injected or excess concentration at x = 0 is,

$$p_{n1} = p_{n(0)} - p_n \qquad Eq.2.37$$

From before, the diffusion component is given by:

$$J_p = -q\, D_p\, \partial p/\partial x$$

From which, the diffusion hole current in the n-side is given by:

$$I_{pn} = -q\, A\, D_p\, {}^{\partial pn}\!/_{dx} \qquad Eq.2.38$$

Derivative of Eq.2.36 and substitute in Eq.2.38, we obtain:

$$I_{pn(x)} = \frac{q\, A\, D_p\, p_{n1}}{L_p}\, e^{-\left(x/L_p\right)} \qquad Eq.2.39$$

Equation 2.39 verifies hole current decreases exponentially with distance. injected carriers are a function of voltage.

2.2.6 General Current Law of the Junction

If hole concentration at edges of depletion layer are (p_p) and (p_n) in p and n material. If the barrier voltage across depletion is (V_B), then majority concentration defined as:

$$p_p = p_n \, e^{(V_B/V_T)} \qquad Eq. 2.40$$

If we apply Eq.2.40 to the case of open circuit junction, then:

$$p_p = p_{p(o)} \ \& \ p_n = p_{n(o)} \ \& \ V_B = V_o$$

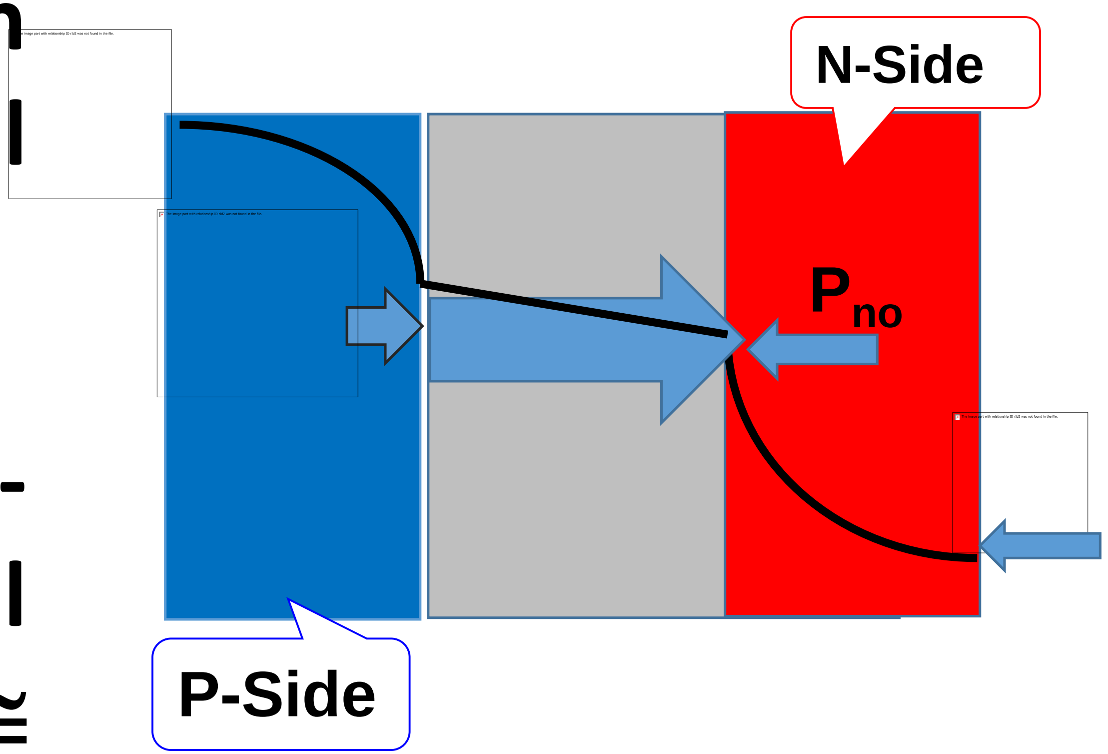
By substitute these values in Eq.2.40, we get V_o (contact Potential).

If forward bias is applied V, then V_B is decreased from its initial value by the amount V, or:

$$V_B = V_o - V \quad (2.41)$$

Hole concentration throughout p-side is nearly constant and equal thermal equilibrium value or $p_p \cong p_{po}$, and it is varying with distance into n-side as indicated in figure (2-18). At the edge of the depletion layer where:

$$X = 0 \quad \& \; p_n = p_{n(o)}$$



Equation 2.18 becomes:

$$p_{p(o)} = p_{n(o)}\, e^{(V_o - V)/V_T} \qquad Eq.2.42$$

$$p_{n(o)} = p_n\, e^{V_B/V_T} \qquad Eq.2.43$$

This boundary condition is called law of the injection. For forward bias V > 0, and the hole concentration (p_{no}) at junction is greater than the thermal value (P_n) (similar law is valid for electrons). The hole concentration (p_{n1}) injected into n-side at the junction is obtained by substituting Eq.2.43 in 2.37 gives:

$$p_{n(o)} = p_n \left[e^{V/V_T} - 1\right] \qquad Eq.2.44$$

The hole current $I_{pn(0)}$ crosses junction into n-side. With x = 0 , using Eq.2.44 ,we have:

$$I_{pn(o)} = \frac{q\, A\, D_p\, p_n}{L_p} \left[e^{V/V_T} - 1\right] \qquad Eq.2.45$$

And the electron current $I_{np(0)}$ crossing the junction into p-side is given by :

$$I_{np(o)} = \frac{q\,A\,D_n\,n_p}{L_n}\left[e^{V/V_T} - 1\right] \qquad Eq.2.46$$

Finally total current is sum of $I_{pn(0)}$ and $I_{np(0)}$,

$$I = I_o\left[e^{V/V_T} - 1\right] \qquad Eq.2.47$$

$$I_o = \left[\frac{q\,A\,D_p\,p_n}{L_p} + \frac{q\,A\,D_n\,n_p}{L_n}\right] \quad Eq.2,48$$

For reverse bias $-V>V_T$, Eq.2.47 becomes:

$$I = I_o \qquad Eq.2.49$$

I_o is the reverse saturation current, Eq.2.48 can be written in the following form:

$$I_o = q\,A\left[\frac{D_p}{L_p\,N_D} + \frac{D_n}{L_n\,N_A}\right]n_i^2 \qquad Eq.2.50$$

And since,

$$n_i^2 = A_o T^3 e^{-E_{go}/KT} = A_o T^3 e^{-V_{go}/V_T} \qquad Eq. 2.51$$

V_{go} is voltage numerically equal to energy gap E_{go} in electron volt. The temperature dependence of the reverse saturation current is:

$$I_o = K_1 T^2 e^{V_{go}/V_T} \qquad Eq. 2.52$$

Where, K_1 is constant independent of temperature. Eq.2.47 is also depending on the material of the device, so it can be rewritten as:

$$I = I_o \left[e^{V/\eta V_T} - 1\right] \qquad Eq. 2.53$$

Where η can be more than 1 for some materials and the reverse saturation current is:

$$I_o = K_2 T^{3/2} e^{-V_{go}/2 V_T} \qquad Eq. 2.54$$

Where, (K_2) is constant independent on temperature