2.2.7 Volt - Ampere Characteristics

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

indicates the junction current (I_J) related to the biased voltage (v). A positive value of (I_J) means that the current flows from P to N sides and the diode is in forward bias. Also it is known that the constant (η) in Eq.2.53

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

is equal 1 for germanium and equal 2 for silicon and (V_T) is the thermal voltage and is given by:

$$V_T = {}^{T}\!/_{11600} \qquad Eq.2.55$$

At room temperature V_T = 0.026 V. When V is positive and larger than V_T, Eq.2.47 will be:

$$I_j = I_o\, e^{V_F/\eta V_T} \qquad Eq.2.56$$

The junction current increased with voltage biased, and when the diode is reverse biased, Eq.2.47 will be:

$$I_j = I_O = IR = IS \qquad Eq.2.57$$

Understanding the Value of built – in voltage V_T

$$V_T = {}^{T}/_{11600} \qquad Eq. 2.55$$

At room temperature

V_T = 0.026 V.

0.026 = $^{T}/_{11600}$

T = 11600 x 0.026 = 301.6 °K

301.6 – 273 = 28.6 °C

$$V_T = {}^{T}/_{11600} \qquad Eq. 2.55$$

At room temperature (27 °C)

=

27 + 273 = 300 °K

$$V_T = {}^{300}/_{11600}$$

$$V_T = 0.02586$$

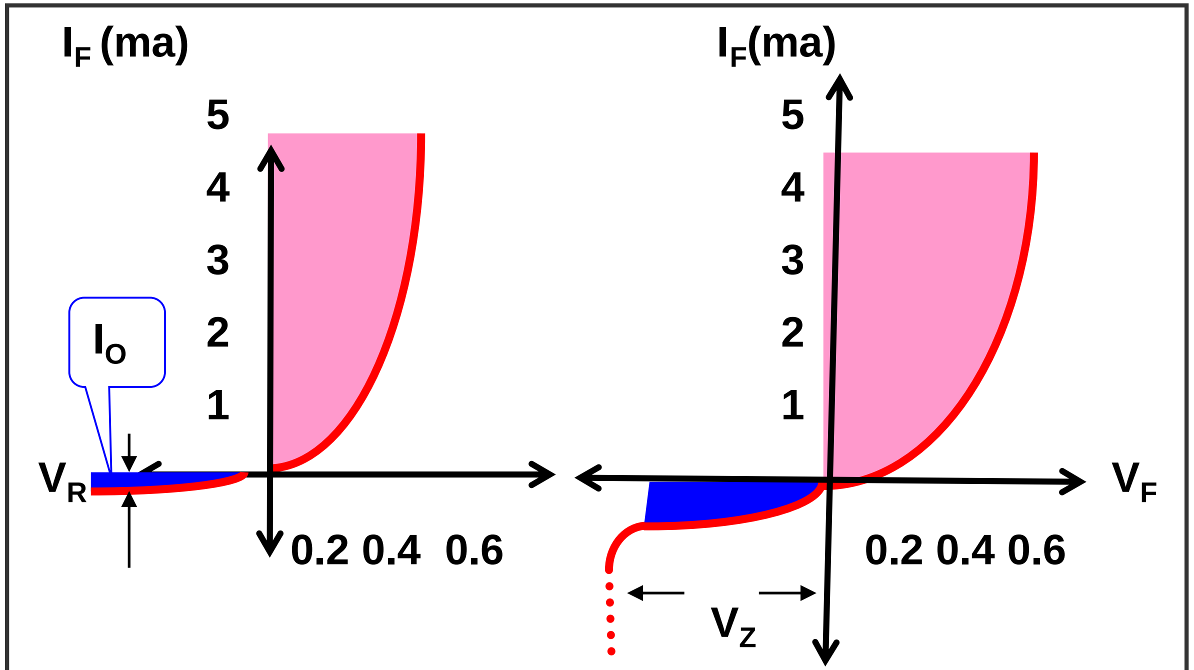


Fig. (2 – 19) I-V junction characteristics

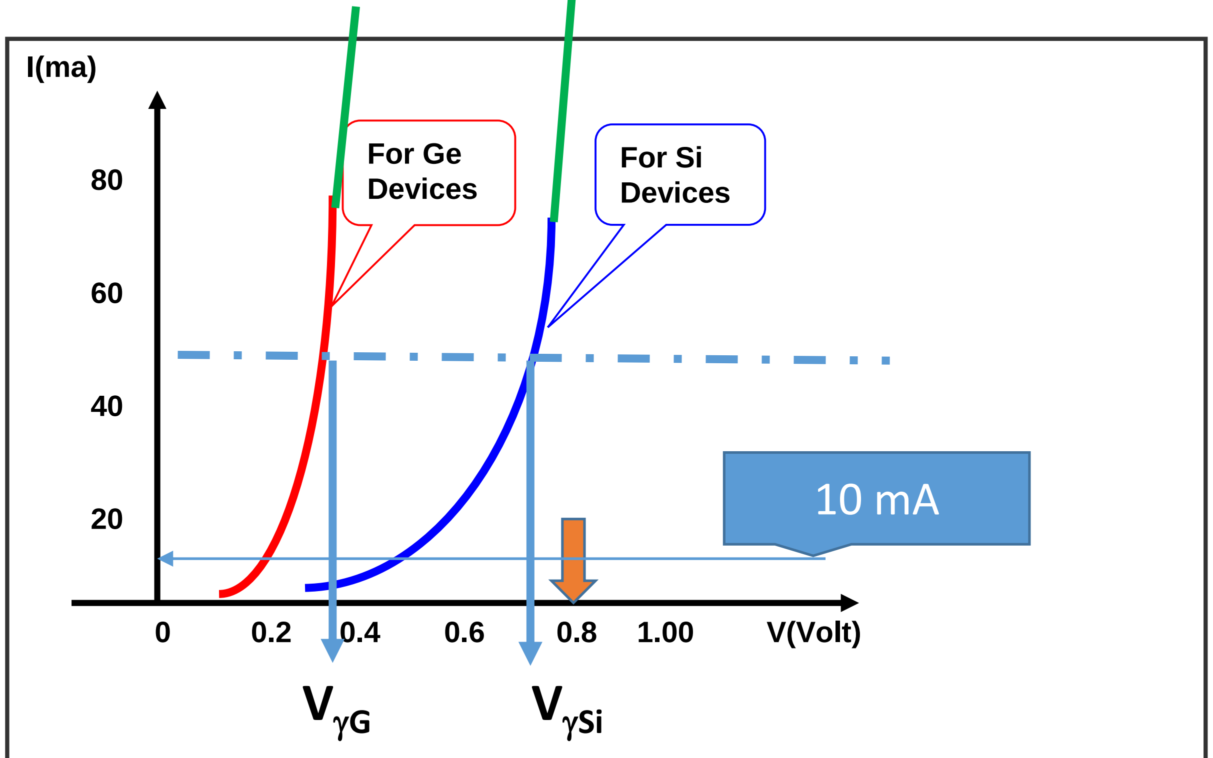


Figure 2.20 difference in V-I characteristics for Si, Ge

Form of Eq.2.47; figure (2-19), the reverse current is constant independent of V_R, forward and reverse current is shown in figure (2.19b), the dashed portion of curve indicates, at reverse voltage (V_Z), at this voltage large reverse current flow and the diode to be in breakdown mode

Difference in V - I characteristics for Si, Ge is shown in figure (2-20), determine the cut-in, offset, break point or threshold voltage (V_γ) below which forward current is very small, less than 1% of its maximum value). The reverse saturation current in Ge is in the range of microamperes and the reverse saturation current in Si is in the range of nano amperes.

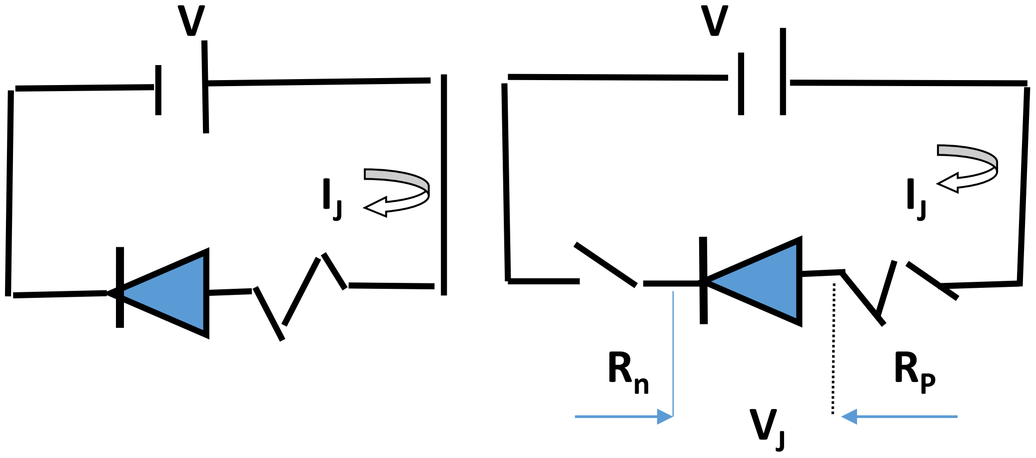


Fig. (2 - 21) Equivalent Circuit for a Diode

Since η = 2 for Si, the current increases as $e^{V/2VT}$ for the initial bias and then increased as $e^{V/VT}$. This initial dependence of current on voltage accounts for the delay in the rise of Si device characteristics.

2.2.8 Diode Resistance

Resistance R is defined as the ratio between voltage V and current I. At any point on the I-V characteristics of the diode, R is equal to the reciprocal of the slope of a line joining the operating point to the origin. In the specification sheet maximum V_F required to a given I_F and also V_R for a given I_R is indicated, for example,

V_F=0.8V at I_F = 10 ma gives R_F = 80 Ω

V_R=50 V at I_R = 0.1 μa gives R_R = 500 MΩ

In the non-ohm devices, the resistance drop depends upon the operating current, and in fact we have two possible resistances to consider.

One is the DC resistance; the other is the dynamic or small signal resistance (ac resistance). And useful equivalent circuit for the diode is shown in figure (2-21). The resistor R_P and R_n represent the bulk resistance of the structure, the junction voltage is given by:

$$V_J = V = I_J(R_n + R_p) (2.58)$$

The over all resistance of the junction is,

$$R_T = \frac{V}{I_J} = \frac{V_J}{I_J} + R_n + R_p (2.59)$$

$$R_T = \frac{V_J}{I_J} + R_n + R_p$$

Or $$R_T = R_{dc} + R_n + R_p (2.60)$$

The Dc resistance of the combination is $R_{dc} = R_T - (R_n + R_p)$

Dc resistance of ideal part of diode, (r_{dc}) determined graphically as shown in fig. (2.22) or it can be calculated from:

$$r_{dc} = \frac{V_J}{I_J} = \frac{V_J}{I_S\, exp\left[\frac{qV_J}{KT} - 1\right]} \quad (2.61)$$

Dynamic resistance (r_a) an important parameter and it is equal,

$$r_a = \frac{\partial V}{\partial I} \quad (2.62)$$

Dynamic resistance r_a is not constant depends upon the voltage and we find that the dynamic conductance for PN ideal diode is given by:

$$g = \frac{1}{R} = \frac{\partial I}{\partial V} = \frac{I_o e^{V/\eta V_T}}{\eta V_T} = \frac{I + I_o}{\eta V_T} \quad (2.63)$$

For reverse bias, where $V/\eta V_T \ll 1$, conductance g = 1/R will be very small and dynamic resistance r is very large.

For forward bias, where $V/\eta V_T \gg 1$, $I \gg I_o$ and dynamic resistance r is given by:

$$r_a = \frac{\eta V_T}{I} \quad (2.64)$$

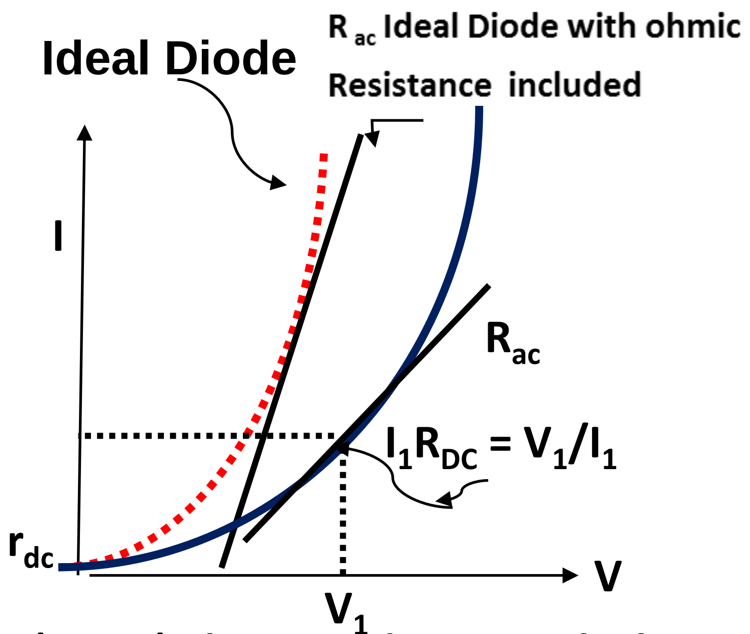


Fig. (2 - 22) Slopes and points which must be selected to obtain the four distinct resistances for ideal and real diode

Ac resistance r_{ac} of ideal diode determined from figure (2-22) as slope of C.C at the operating points or determined analytically as follows. It is convenient to calculate ac conductance (g_{ac}),

$$I_J = I_S exp\left[\frac{qV_J}{KT} - 1\right]$$

$$g_{ac} = \frac{dI_J}{dV_J} = I_S \frac{q}{KT} exp \frac{qV_J}{KT} (2.65)$$

$$g_{ac} = \frac{q}{KT}(I_J + I_s) = \frac{1}{r_{ac}} (2.66)$$

Ac resistance of real diode is then,

$$R_{ac} = r_{ac} + R_n + R_p (2.67)$$

$$R_{ac} = \frac{KT}{q}\left(\frac{1}{I_s + I_J}\right) + R_n + R_p (2.68)$$

At room temperature, value of R_{ac},

$$r_{ac} = \frac{25}{I_s + I_J} ohm (2.69)$$

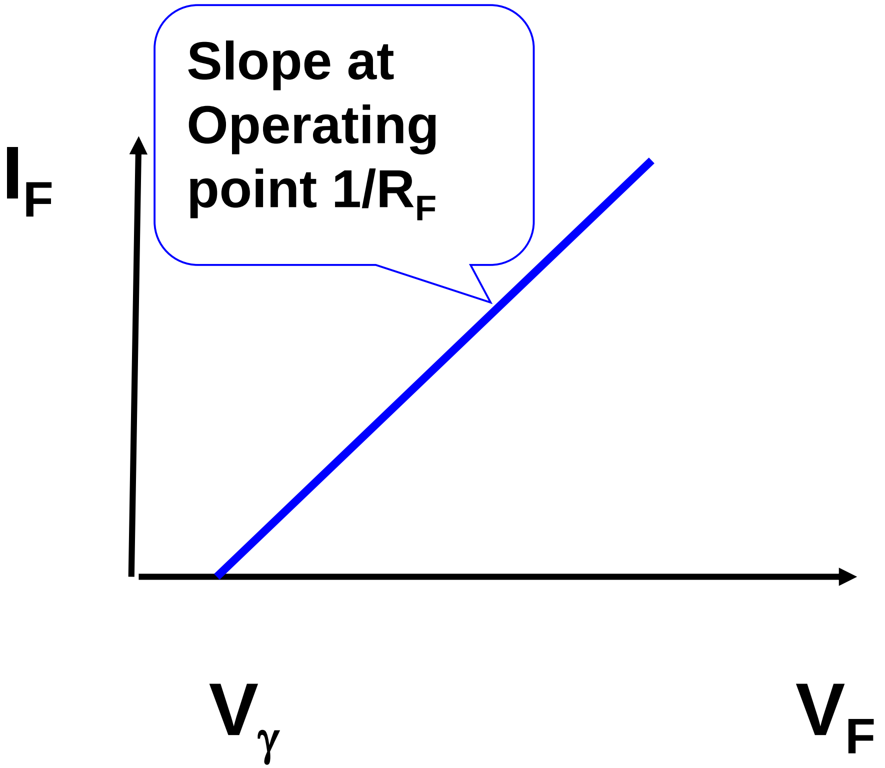


Fig. (2 – 24) Diode I–V Linear Approximation

Note that in some cases the ohmic series resistance will be important and in other is not. At very high current the forward ideal diode resistance becomes negligible compared with the series resistance. Since the series resistance in the real diode C.C becomes ohmic at high currents.

2.2.9 Calculation of hole and electron currents

current in the junction depend upon physical properties of the junction, properties of the crystal, density of impurities, impurity distribution, and many other factors.

When junction reverse biased, current of electrons from n-region to p-region is essentially zero. Also at the p-side of the transition region, the electron density must be almost zero, since electrons arriving at the point are swept down the potential hill.

There is a density of electrons in p-side of junction going from equilibrium value far from junction, to zero, at edge of transition region. A similar situation is for holes in the n-side of the junction. This is shown in figure (2 - 25). The forward direction is shown as well. It is observed that large number of electrons from the n-side enriches the majority carrier density on the p-side.

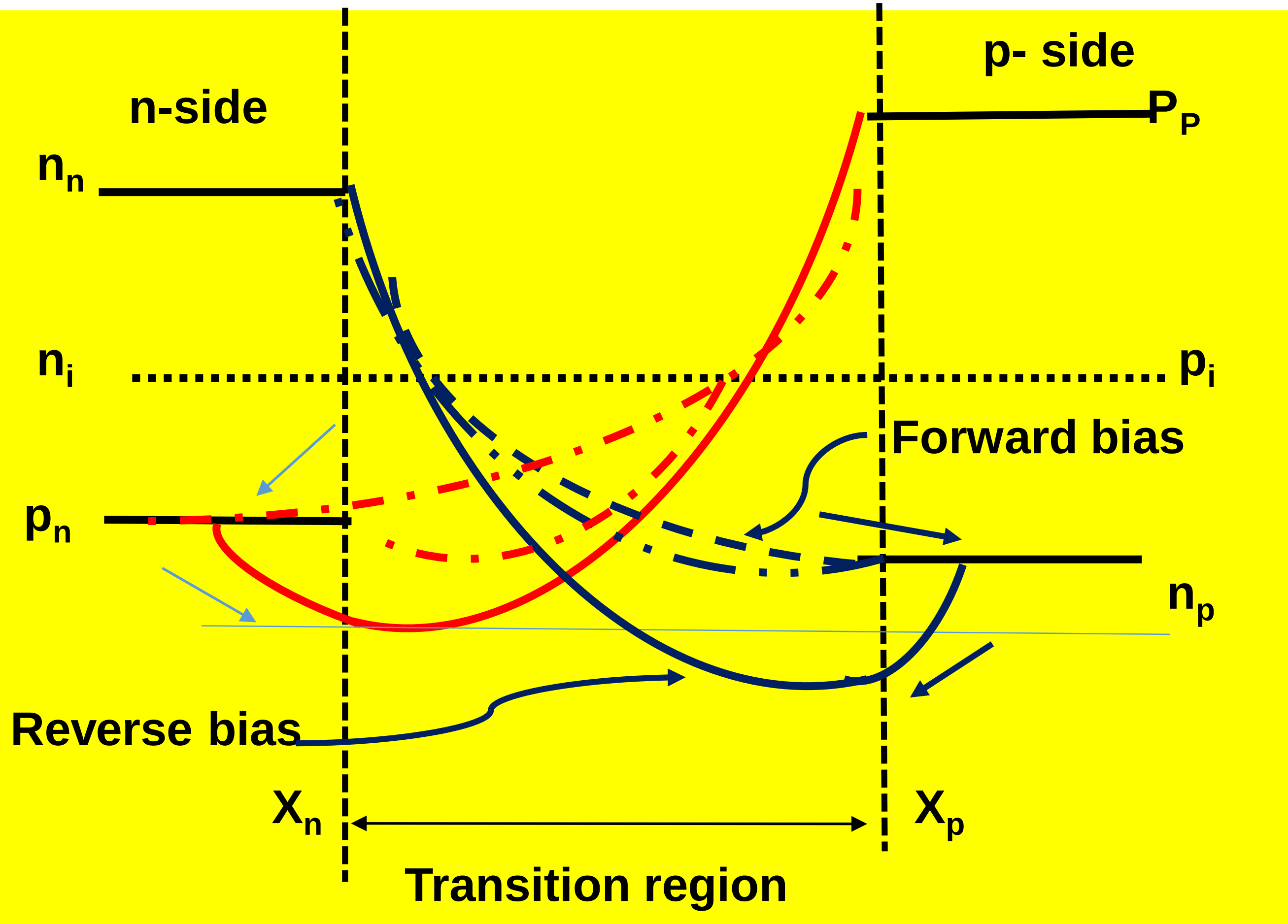


Fig. (2 - 25) Carriers densities on the two sides of the transition region, the p-side is more doped than n-side

Density gradient is now in the opposite direction, and electron flow to the right. Density gradient within crystal near the junction are very important because there is no electric field in the crystal body itself and current is almost by diffusion due to density gradient. Let us consider the minority electron current in the p-side. Differential equation describes the density gradient of electrons in the p-side in the steady state is (i.e., the continuity equation).

$$\frac{dn_p}{dt} = -\frac{n_p - n_{po}}{n} + \frac{1}{q}\frac{dI_{np}}{dx} \quad (2.70)$$

Where, (n_p) is electron density as function of (x) as shown in figure (2-26).

Since field strength ε is negligible, we have only to consider diffusion current,

$$I_{np} = qD_n \frac{dn_p}{dx} (2.71)$$

In steady state flow of current, we have $dn_p / dt = 0$, then from equation (2.70) and (2.71), we find,

$$-\frac{n_p - n_{po}}{n} + D_n \frac{d^2 n_p}{dx^2} = 0 (2.72)$$

From eq. (2.72)

$$n_p(x) = n_{po} + D_n \tau_n \frac{d^2 n_p}{dx^2} = n_{po} L_n^2 \frac{d^2 n_p}{dx^2}$$

Where, $L_n = \sqrt{D_n \tau_n}$ and since n_{po} is constant, then,

$$n_p(x) - n_{po} = L_n^2 \frac{d^2 (n_p - n_{po})}{dx^2}$$

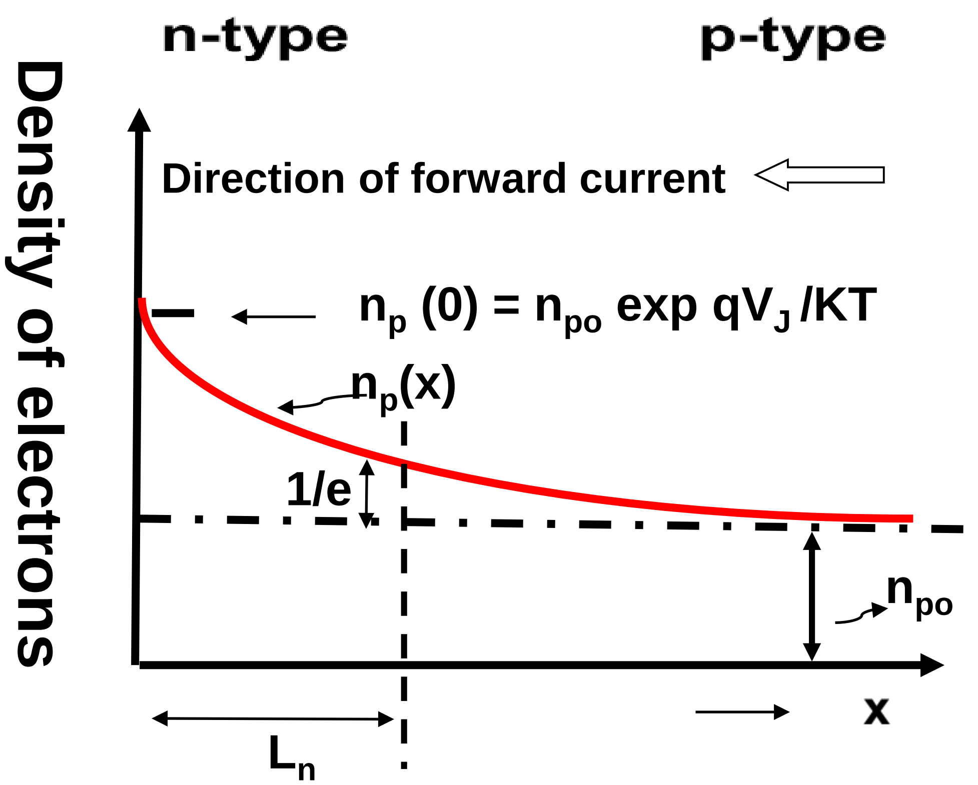


Fig. (2 - 26) Electron concentration in the p-side decreases with increasing distance

General solution of equation is,

$$n_p(x) - n_{po} = Aexp\left(-\frac{x}{L_n}\right) + Bexp\left(-\frac{x}{L_n}\right) (2.73)$$

Where, A, and B are two constants which determined from the boundary conditions, $n_p(x) = n_{po}$ at x = infinity, consequently B = 0 because n_p would go to infinity for x → infinity $n_p(0) = n_{po}$ exp qV_J/KT at x = 0 , which gives

$$A = n_{po}exp\frac{qV_j}{KT} - n_{po} = n_{po}\left(exp\frac{qV_j}{KT} - 1\right)$$

Then the solution to this equation is,

$$n_p(x) = n_{po}\left(exp\frac{qV_j}{KT} - 1\right)exp\frac{-x}{L_n} + n_{po}(2.74)$$

The carriers diffuse down, decreasing density gradient, and on the average they move a distance (L_n) before recombining.

From Eq. (2.73) we see that the density of electrons in the p-type material depend upon the number being injected across the junction. This number is controlled by the bias voltage (V_J). As we move away from the junction the density of electrons becomes that of the steady state equilibrium density in the p-material (n_{po}). From Eq. (2.71) and (2.74), we have,

$$I_{np}(x) = -\frac{qD_n n_{po}}{L_n}\left(exp\frac{qV_j}{KT} - 1\right) exp\frac{-x}{L_n} (2.75)$$

Then at x = 0

$$I_{np}(0) = \frac{qD_n n_{po}}{L_n}\left(exp\frac{qV_j}{KT} - 1\right) (2.76)$$

The negative sign is due to the negative sign of the concentration gradient dn/dx.

If we treated the holes in the n-side in a similar manner, we obtain,

$$I_{pn}(0) = \frac{qD_p p_{no}}{L_p}\left(exp\frac{qV_j}{KT} - 1\right) (2.77)$$

The junction current I_J is given by,

$$I_J = I_{np}(0) + I_{pn}(0) (2.78)$$

$$I_J = \left[\frac{qD_n n_{po}}{L_n} + \frac{qD_p p_{no}}{L_p}\right]\left(exp\frac{qV_j}{KT} - 1\right) (2.79)$$

We now have an expression for the junction current in terms of the physical properties of the bulk material which makes up the device.

$$I_{pn}(0) = \frac{qD_p p_{no}}{L_p} (2.80)$$

$$I_{np}(0) = \frac{qD_n n_{po}}{L_n} (2.81)$$

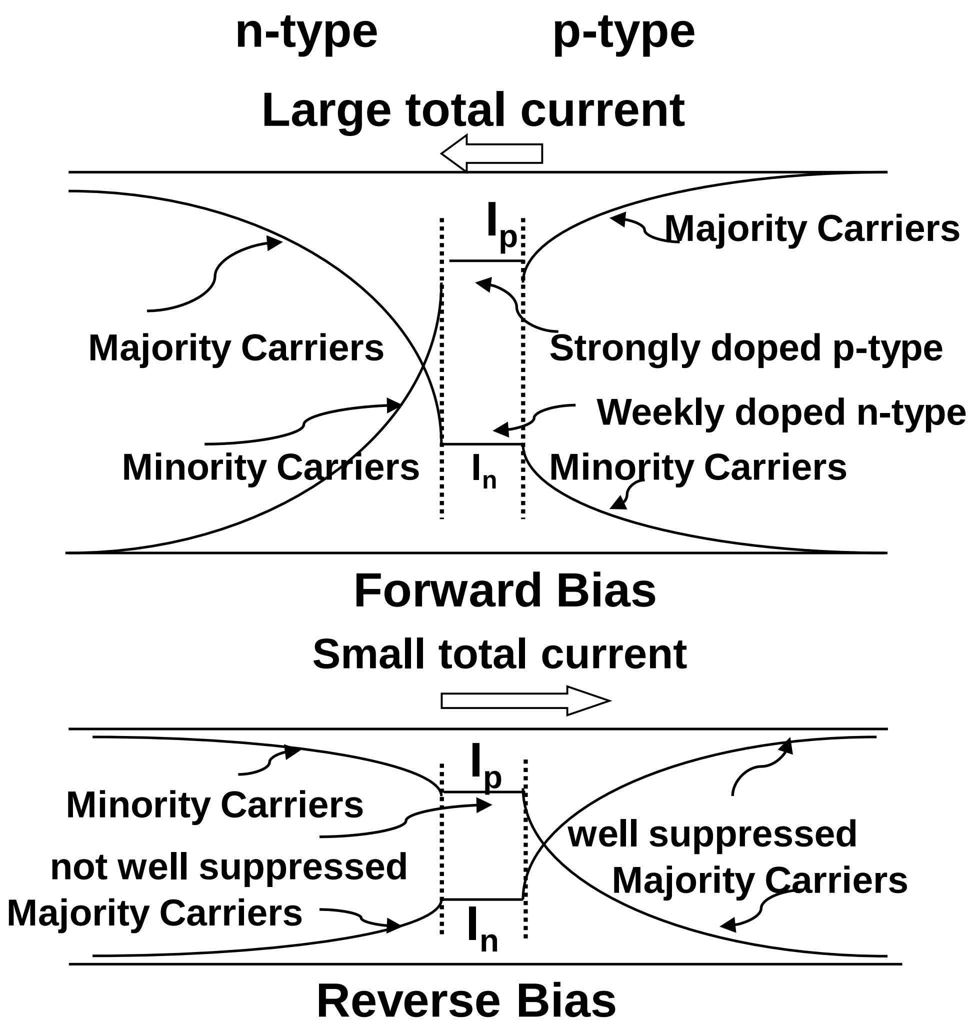


Fig. (2 - 27), relative magnitude of the current near the junction. Notice that only excess currents are shown, thus in forward direction it is majority carriers which carry current, and in reverse direction it is minority carriers which carry current, level of current in transition region is controlled by amount of doping and suppression of the two carriers type.

Thus, we have the desired currents in terms of measurable properties. It is usually more convent to have these currents in form of life time.

Using $L_n = \sqrt{D_n \tau_n}$, $L_p = \sqrt{D_p \tau_p}$, we obtain,

$$I_J = q\left[\frac{p_{no}}{\tau_p} L_p + \frac{n_{po}}{\tau_n} L_n\right] (2.82)$$

The reverse saturation current increases directly with the minority carrier density. The minority carrier density increases with temperature exponentially. Hence the connection between the reverse bias saturation current is explained. Equation (2.80) may be rewritten in term of more useful parameters as follows. If the donor and acceptors are completely ionized, we have,

$$p_{no} n_{no} = n_i^2 \quad , \; p_{po} n_{po} = n_i^2 (2.83)$$

$$p_{po} = N_A and n_{no} = N_D (2.84)$$

Then, $$p_{no} = \frac{n_i^2}{N_D} and n_{po} = \frac{n_i^2}{N_A}$$

And $$I_o = q n_i^2 \left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right] (2.85)$$

The x- dependent current equations tell us that current is carried by holes at some points in junction and by electrons at other points. This variation is shown in figure (2-27). The last equation (2.85) may be used to calculate reverse bias saturation current if doping or resistivity of each side of junction is known It is important for the transistor later, to say something about the ratio of electrons and holes currents. From eq. (2.75) and (2.76) , it follows that,

$$\frac{I_n}{I_p} = \frac{D_n L_p n_{po}}{D_p L_n p_{no}} \quad (2.86)$$

Since, we have that $D_n/D_p = \mu_n/\mu_p$ (Einstein Equation)

$$\frac{I_n}{I_p} = \frac{\mu_n L_p n_{po}}{\mu_p L_n p_{no}} = \frac{\sigma_n L_p}{\sigma_p L_n} \quad (2.87)$$

Apart from the ratio L_p/L_n which is of the order of unity, the ration of electron current to hole current is determined by the conductivity (σ_n) of the n-region over the conductivity (σ_p) of the p-region. Thus, if the conductivity (σ_n) of the n-region is 100 times as large as that of the p-region, the current across the junction is carried for 99% by electrons and for 1% by holes. Typical values for (L_n) and (L_p) are of the order of 10^{-3} mm.

2.2.10 Temperature Dependence of PN Junction

We deduce that, $\partial I/\partial t = 0.08\%\ /^{o}C$ for Si, $0.11\%/^{o}C$ for Ge, also we have found that the reverse saturation current increases by $7\%/^{o}C$ for Ge, Si. We conclude that the reverse saturation current double it self-every $10^{o}C$ rise in temperature. The much larger value of the reverse saturation current for Ge than for Si, and since the temperature dependence is the same for both materials, then the elevated temperature in Ge devices will develop an excessive large reverse saturation current, where for Si, reverse saturation current will be quite modest. For more clarification, an increase in temperature from room temperature to $90\,^{o}C$ increases the reverse saturation current for Ge to hundreds of microamperes, in Si it rises to tenth of microamperes

2.2.11. Space Charge or Transition Capacitance

In reverse bias, the majority carrier's moves away from the junction, and the thickness of depletion layer is increased, such phenomena has capacitance effect.

$$C_T = \left|\frac{\partial Q}{\partial V}\right| \qquad Eq.2.39$$

∂ Q is the increase in charge caused by ∂V in a time ∂t, results current,

$$i = C_T \frac{\partial Q}{\partial V} \qquad Eq.2.40$$

C_T is an important parameter must be considered where an analysis of electrical circuit is required, especially if the diode has an abrupt junction. Figure (2-28) shows the charge density as function of distance for abrupt junction. Since the net charge must be zero at no bias, then:

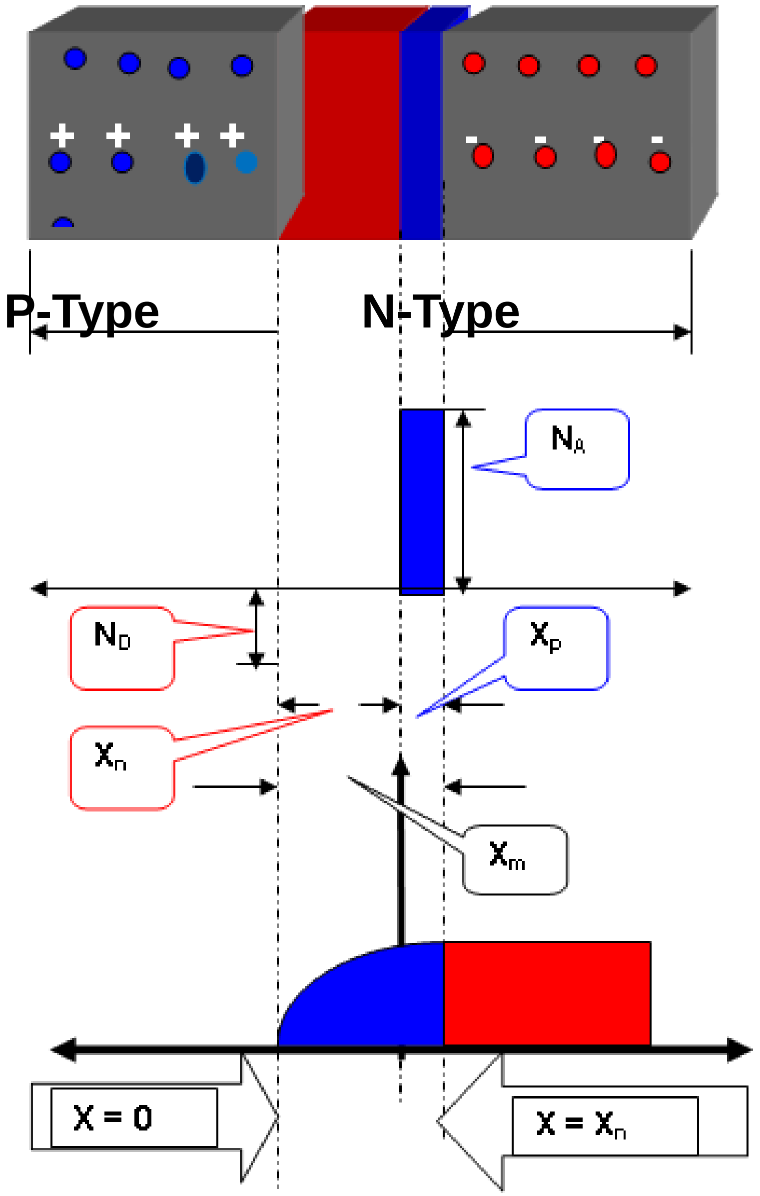


Fig. (2 – 28) Charge density as function of distance

$$C_T = \frac{\partial Q}{\partial V} = q\, A\, N_A \left|\frac{\partial x}{\partial V}\right| \qquad Eq. 2.45$$

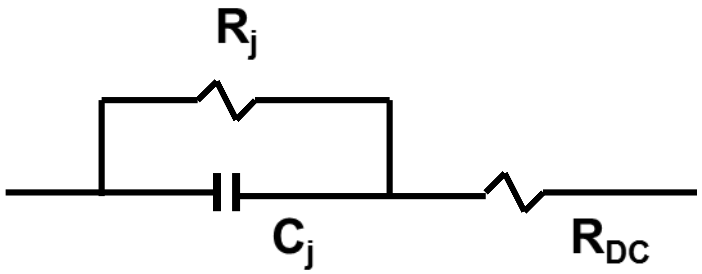


Fig. (2 – 29) Diode Equivalent Circuit

From Eq.2.43,

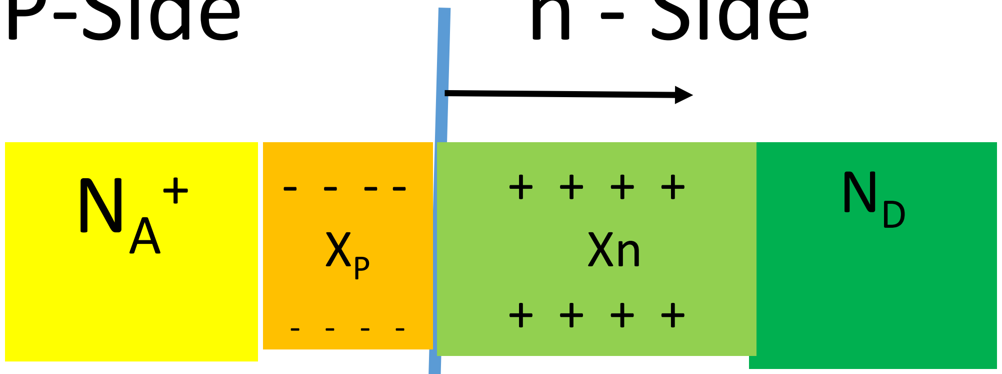
$$\frac{\partial Q}{\partial V} = \frac{\epsilon}{q\, x\, N_A} \qquad Eq. 2.46$$

$$and \qquad C_T\, \frac{\epsilon\, A}{x} \qquad Eq. 2.47$$

Figure (2-29) equivalent circuit for P-N diode resistance. Depletion layer of the pn junction exhibits the behavior of a capacitance having the same geometry and dielectric constant, as can be shown in figure (2-30) .

Clarification for depletion layer extension in the too sides of p-n junction

P-Side n - Side



Force one x its Arm one = Force two x its Arm two

$$N_A^+ X_p = N_D X_n$$

$q\,N_A$ $q\,N_D$

If N_A<< N_D, then X_p>>X_n, for simplicity, we neglect X_n, and the relationship between potential and charge density is given by Poisson's equation.

$$\frac{\partial^2 V}{\partial x^2} = \frac{q\,N_A}{\epsilon} \quad where\ \epsilon = \epsilon_r\,\epsilon_o$$

At ε = -∂V/∂X= 0 at X=0, so V=0 at X=0, by integration Poisson's Equation above, we get:

$$V = \frac{qN_A x^2}{2\,\epsilon} \qquad Eq.2.42$$

At X = $X_p \cong X_m$ and V = V_B, so:

$$V_B = \frac{q x_m^2 N_A}{2\,\epsilon} \qquad Eq.2.43$$

And if A is the area of the junction,

$$Q = q\,N_A x_A \qquad Eq.2.44$$