pn junction current

If we apply a potential difference between p and n regions, we will no longer be in equilibrium condition-the Fermi level energy will no longer constant through the system.

For Fig. 7.1 the potential barrier seen by electrons in the n region, holds back the large concentration of electrons in the n region and keeps them from flowing into p region. Similarly, the potential barrier seen by holes holds back the large concentration of holes in the p region and keeps them from flowing into the n region. The potential barrier, then, maintains the thermal equilibrium.

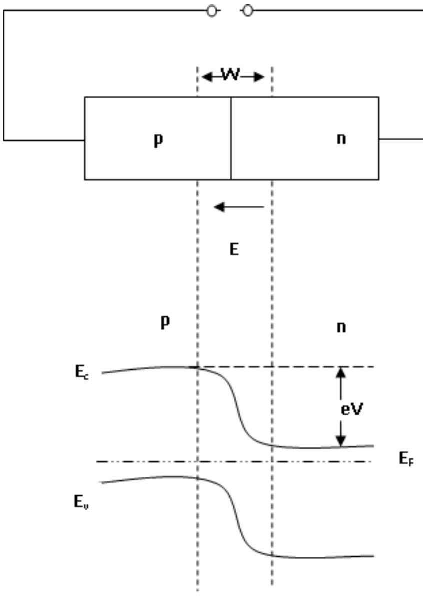
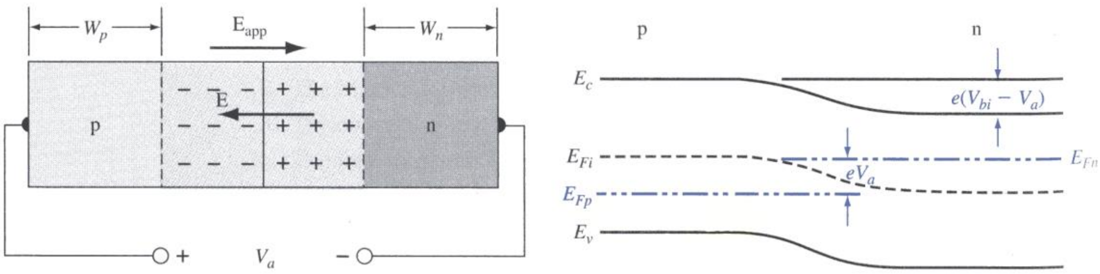


Fig. 7.1 A pn junction with zero-bias voltage showing the space charge electric field and Energy-band diagram of the thermal equilibrium pn junction.



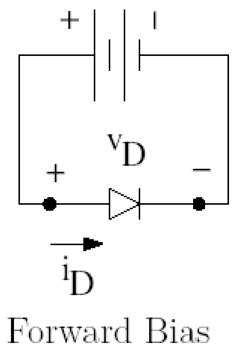


Fig. 7.2 A pn junction with an applied forward-bias voltage showing the directions of the electric field induced by V, and the space charge electric field. Energy-band diagram of the forward-biased pn junction. (b) pn junction diode symbol in forward-biased condition.

Fig. 7.2 shows the energy band diagram for the case when a positive voltage is applied to the p region with respect to n region. The total potential barrier now is reduced. The smaller potential barrier means that the electric field in the depletion region is also reduced. There will be a diffusion of holes and electrons across the space charge region. The flow of charge generates a current through the pn junction. The negative voltage applied to the n-type end pushes electrons towards the junction, while the positive voltage at the p-type end pushes holes towards the junction. This reduces the width of the depletion zone. This has the effect of shrinking the depletion region. As the applied voltage exceeds the internal electrical imbalance, current carriers of both types can cross the junction into the opposite ends of the crystal. Electrons flow through the circuit from the negative battery terminal to the positive terminal of the battery. The I-V characteristics of a junction diode is given by:

$$I = I_s\left(\exp\left(\frac{eV}{kT}\right) - 1\right)$$

Where I_s reverse saturation current.

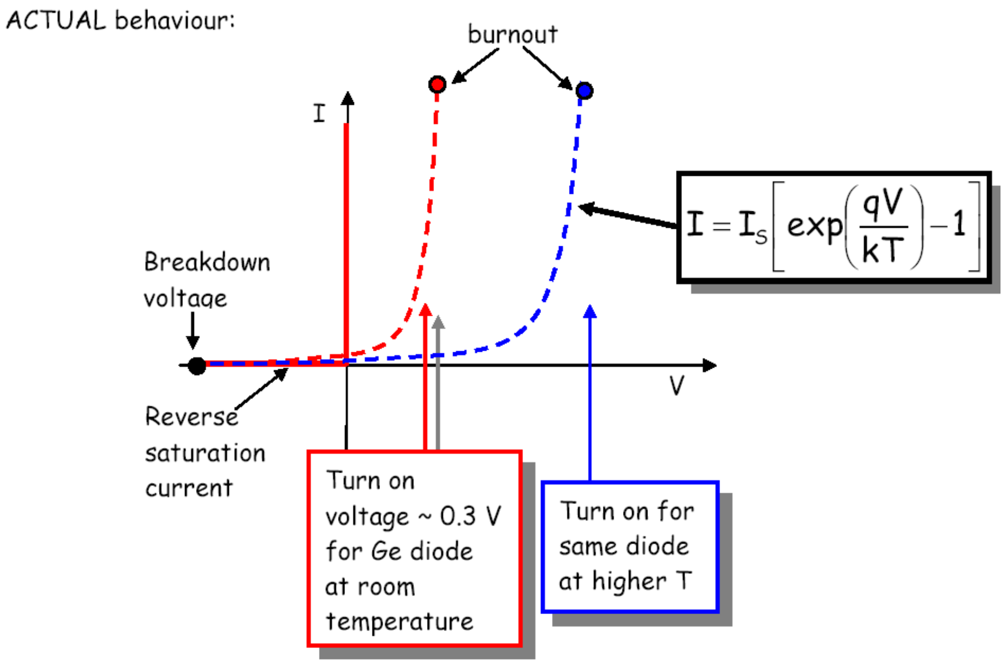


Fig. 7.3. The I-V characteristics of a junction diode.

The plot shows that when the diode is forward biased, the current increases exponentially with applied voltage.

Example

A Germanium diode draws 40mA with the forward bias 0.3V, T=300ºk, calculate the reverse saturation current $I_{s.}$

Solution

$$I = I_s\left(\exp\left(\frac{eV}{kT}\right) - 1\right)$$

$$40\times10^{-3} = I_s(\exp(38.69\times0.3) - 1)$$

$$I_s = 0.36\mu A$$

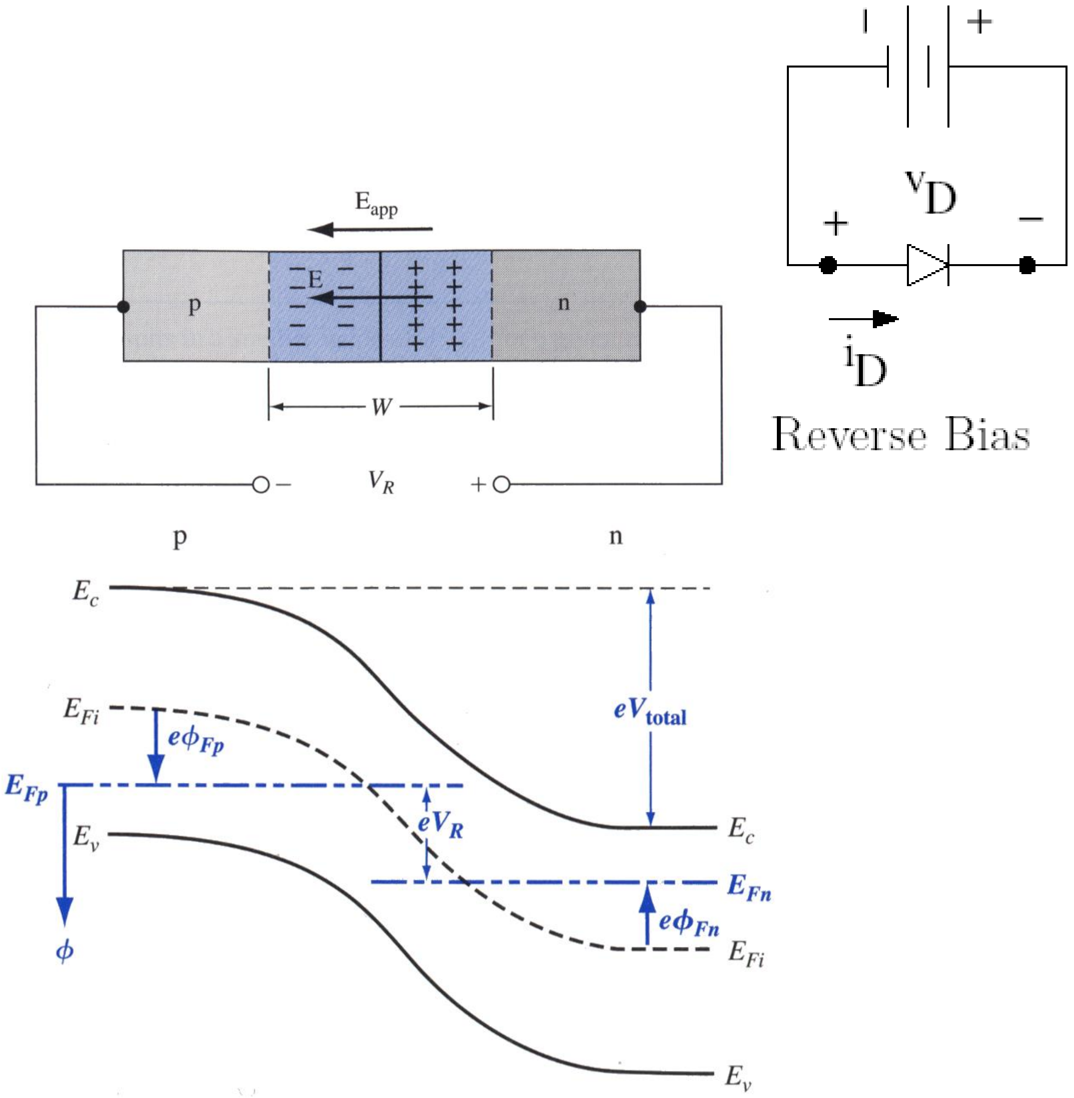


Fig. 7.4 A pn junction, with an applied reverse-bias voltage, showing the directions of the electric field induced by V, and the space charge electric field pn junction diode symbol in forward-biased condition. Energy-band diagram of pn junction under reverse bias.

Fig. 7.4 shows the energy band diagram of pn junction for the case when a positive voltage is applied to the n region with respect to p region. The connections are illustrated in the following diagram. Because the p-type material is now connected to the negative terminal of the power supply, the 'holes' in the p-type material are pulled away from the junction, causing the width of the depletion zone to increase. Similarly, because the n-type region is connected to the positive terminal, the electrons will also be pulled away from the junction. Therefore the depletion region widens, and does so increasingly with increasing reverse-bias voltage. The net effect therefore is widening of depletion layer will establish too great a barrier reducing the majority flow to zero. The minority carriers flow cause current called reverse saturation current I_s.

$$J_s = e\left[\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right]$$

where L_n and L_p are diffusion lengths of holes and electrons. The diffusion lengths are given by

$$L_n = \sqrt{D_n \tau_n} \qquad L_p = \sqrt{D_p \tau_p}$$

Where τ_n and τ_p are the carrier life time of electrons and holes.

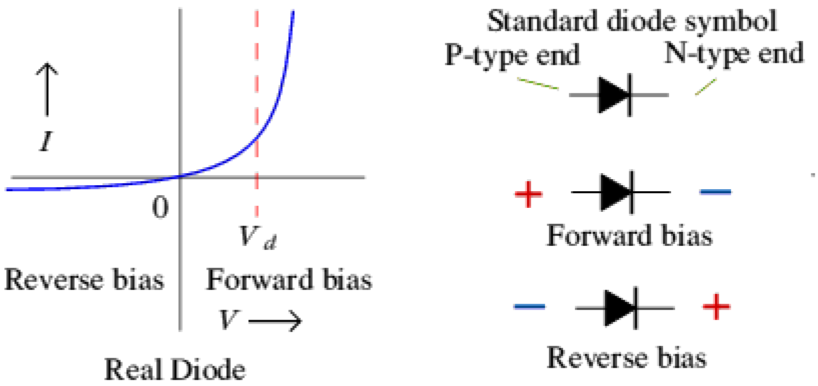


Fig.7.5. The I-V characteristics of a junction diode with standard diode symbol.

<u>Example</u>

A pn junction with N_A=$10^{24}/m^3$, N_D=$10^{22}/m^3$, A=16mm^2, μ_n=0.4 $m^2/V.s$, μ_p=0.2 $m^2/V.s$. L_n=3×$10^{-4}m$, L_p=2×$10^{-4}m$, n_i=$10^{19}/m^3$, T=300°K Calculate p_p, n_p, n_n, p_n, σ_n, σ_p, D_n, D_p, I_s, V_{bi}, I if V= V_{bi}.

<u>Solution</u>

$$p_p = N_A = 10^{24} / m^3$$

$$n_p = \frac{n_i^2}{p_p} = \frac{\left(10^{19}\right)^2}{10^{24}} = 10^{14} / m^3$$

$$n_n = N_D = 10^{22} / m^3$$

$$p_n = \frac{n_i^2}{n_n} = \frac{\left(10^{19}\right)^2}{10^{22}} = 10^{11} / m^3$$

$$\sigma_n = N_D e\mu_n = 10^{22} \times 1.602 \times 10^{-19} \times 0.4 = 640 Sm^{-1}$$

$$\sigma_p = N_A e\mu_p = 10^{24} \times 1.602 \times 10^{-19} \times 0.2 = 3.2 \times 10^4 Sm^{-1}$$

$$D_n = \frac{\mu_n}{39} = 0.01 m^2 s^{-1} \qquad D_p = \frac{\mu_p}{39} = 0.005 m^2 s^{-1}$$

$$J_s = e\left[\frac{D_p P_n}{L_p} + \frac{D_n n_p}{L_n}\right]$$

$$I_s = Ae\left[\frac{D_p P_n}{L_p} + \frac{D_n n_p}{L_n}\right] = 0.64 \mu A$$

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_D N_A}{n_i^2}\right) = 0.34 V$$

$$I = I_s\left(\exp(\frac{eV}{kT}) - 1\right) = 70 mA$$

Depletion Width and Electric Field

Fig. 7.4 shows pn junction with an applied reverse-bias voltage V_R. The electric field originates on positive charge and terminates on negative charge. The width (W) of the space charge region increasing due to the increasing of the number of the positive charge and terminates on negative charge in the depletion region. The width (W) of the space charge region is given by replace the built in potential barrier by the total potential barrier as

$$W=\left\{\frac{2\varepsilon_s\left(V_{bi}+V_R\right)}{e}\left[\frac{N_a+N_d}{N_aN_d}\right]\right\}^{1/2}$$

Example

Calculate the space charge width in silicon pn junction when a reverse bias with 5V is applied at T=300K. Assume that $N_A=10^{22}/m^3$, $N_D=10^{21}/m^3$, $n_i=1.5\times10^{16}/m^3$.

solution

$$V_{bi}=\frac{kT}{e}\ln\left(\frac{N_DN_A}{n_i^2}\right)$$

$$V_{bi}=0.0259\ln\left(\frac{\left(10^{22}\right)\left(10^{21}\right)}{\left(1.5\times10^{16}\right)^2}\right)=0.635V$$

$$W=\left\{\frac{2\varepsilon_s\left(V_{bi}+V_R\right)}{e}\left[\frac{N_a+N_d}{N_aN_d}\right]\right\}^{1/2}$$

$$W=\left\{\frac{2(11.7)\left(8.85\times10^{-12}\right)(0.635+5)}{1.602\times10^{-19}}\left[\frac{10^{22}+10^{21}}{\left(10^{22}\right)\left(10^{21}\right)}\right]\right\}^{1/2}$$

$$W=2.83\mu m$$

Junction Capacitance

Since we have a separation of positive and negative charges in the depletion region, a capacitance is associated with pn junction. The junction capacitance is also referred to as the depletion layer capacitance and can be written as

$$C' = \left\{ \frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2} \quad (F/m^2)$$

Example

Calculate the junction capacitance for previous example if the cross-section area is 0.1µA.

Solution

$$C' = \left\{ \frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2}$$

$$C' = \left\{ \frac{(1.602\times10^{-19})(11.7\times8.85\times10^{-12})(10^{22})(10^{21})}{2(0.635+5)(10^{22}+10^{21})} \right\}^{1/2}$$

$$C' = 3.66\times10^{-5} F/m^2$$

$$C = C'A = 3.66\times10^{-5}\times0.1\times10^{-6} = 3.66pF$$

Comparing the equation of for the total depletion width (W) and the junction capacitance (C') we can write

$$C' = \frac{\varepsilon_s}{W}$$

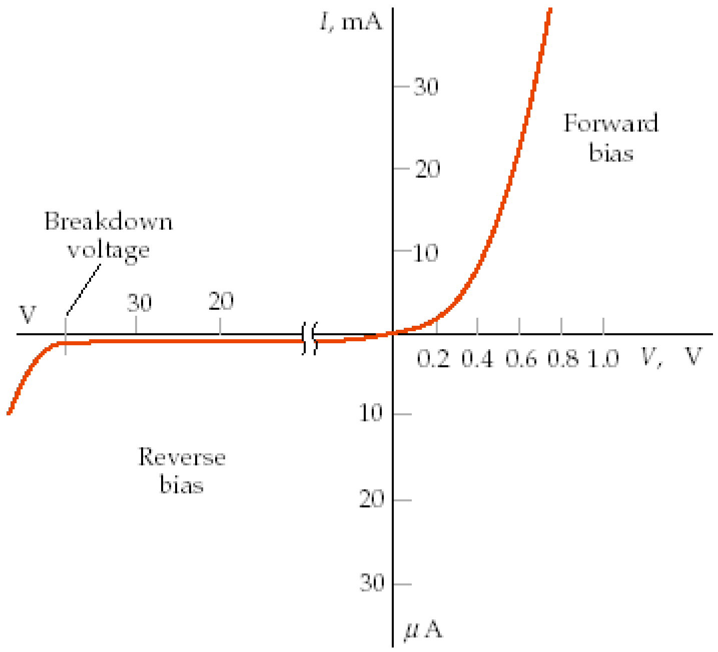


Fig.7.6. The I-V characteristics of a junction diode shows breakdown voltage.

The strength of the depletion zone electric field increases as the reverse-bias voltage increases. Once the electric field intensity increases beyond a critical level, the p-n junction depletion zone breaks-down and current begins to flow, usually by either the Zener or avalanche breakdown processes. Both of these breakdown processes are non-destructive and are reversible, so long as the amount of current flowing does not reach levels that cause the semiconductor material to overheat and cause thermal damage.

The maximum reverse bias potential that can be applied before entering the zener region is called peak inverse voltage PIV.

Silicon versus Germanium

Silicon diodes have higher PIV, current rating and wider temperature range than Germanium diodes.

PIV$_{(Si)}$=1000V, **PIV**$_{(Ge)}$=400V. Temperature may rise 200^{o}C for Si, whereas 100^{o}C for Ge. The disadvantage of Si is $V_{T(si)}$=0.7V while $V_{T(Ge)}$=0.3V.

Problems

Q1: A pn junction with $N_A=10^{22}/m^3$, $N_D=10^{21}/m^3$, $A=10^{-6}m^2$, T=300°K, $L_n=7.1\times10^{-4}m$, $L_p=3.5\times10^{-4}m$, $n_i=1.6\times10^{16}/m^3$. Calculate barrier potential and the reverse saturation current.

(Ans: 0.63V, 1.6×10^{-13}A)

Q2: Calculate forward current in Ge diode at 20^{o}C when the forward bias 0.3V, compare this value with that after a temperature rise of 50^{o}C. Assume that reverse saturation current doubles for every 10^{o}C rise in temperature, I_s=1µA.

(Ans: 0.143A, 0.811A)

Q3: Calculate the space charge width in silicon pn junction and junction capacitance when a reverse bias with 8V is applied at T=300K. Assume that $N_A=5\times10^{22}/m^3$, $N_D=5\times10^{21}/m^3$, $n_i=1.5\times10^{16}/m^3$.

(Ans: 1.57µm)