Chapter 6-2. Carrier injection under forward bias

Last class, we established the excess minority carrier concentration profile under biased conditions.

The excess minority carrier concentration at the edge of the depletion layer will increase under forward biased condition. The minimum carrier concentration decreases exponentially with distance from the depletion layer edge.

$$\Delta n_p(x'') = \Delta n_p(0)\, e^{-\frac{x''}{L_n}} \qquad \Delta p_n(x') = \Delta p_n(0)\, e^{-\frac{x'}{L_p}}$$

Carrier injection under forward bias

At equilibrium, # of holes *diffusing* **to** n-side equals # of holes *drifting* **from** n-side. When we apply external forward voltage, V_A, holes diffusing (injection) to n-side from p-side increases exponentially. This increases the hole concentration at the edge of the depletion layer on n-side.

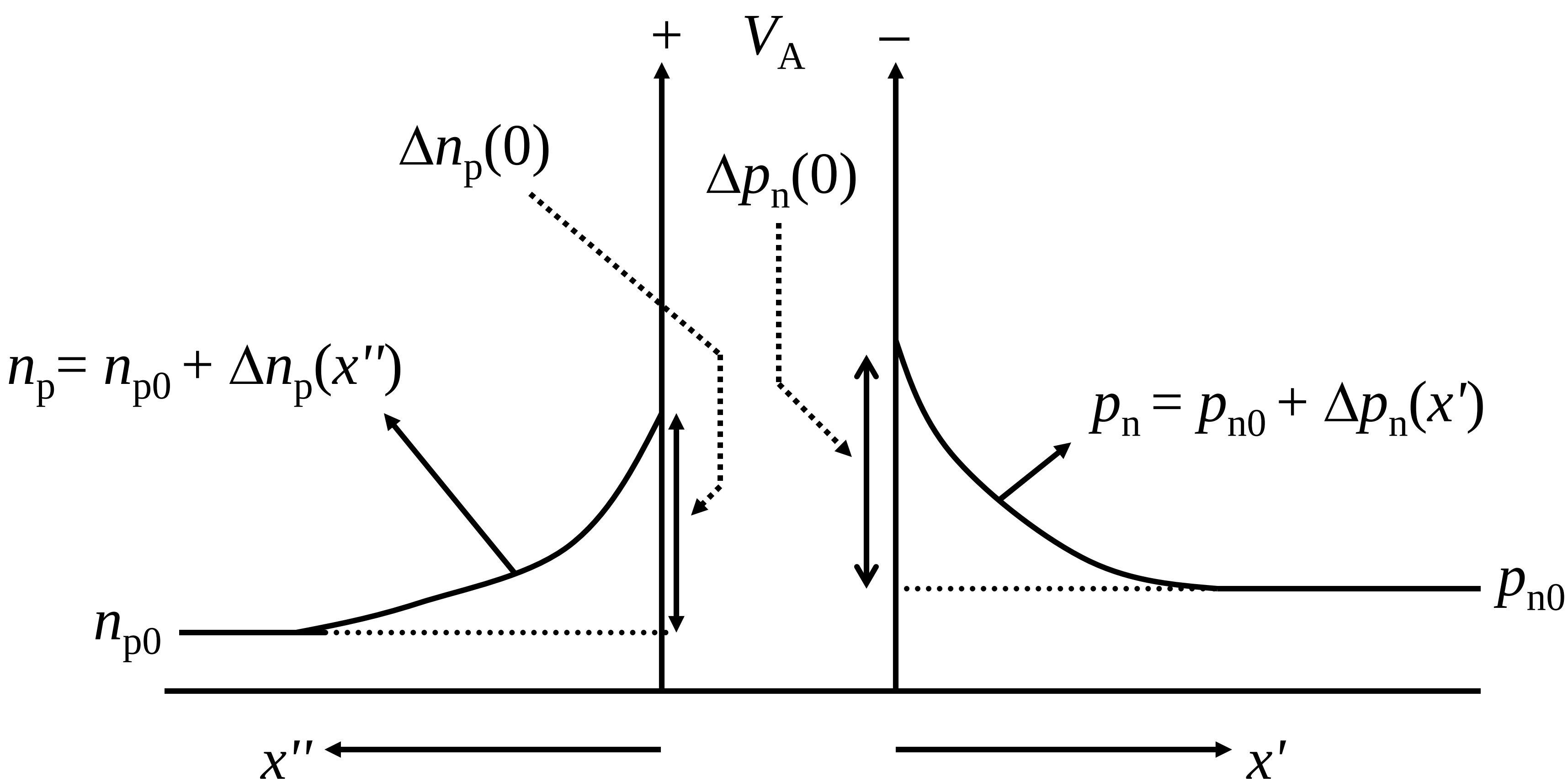
$$p_n(x_n) = p_{n0}\, e^{\frac{qV_A}{kT}}$$

$$\Delta p_n(x_n) = p_n(x_n) - p_{n0} = p_{n0}\,(e^{\frac{qV_A}{kT}} - 1)$$

Similarly,

$$\Delta n_p(-x_p) = n_{p0}\,(e^{\frac{qV_A}{kT}} - 1)$$

Minority carrier concentration profile under bias



$$\Delta n_p(x'') = \Delta n_p(0)\ e^{-\frac{x''}{L_n}} \qquad \Delta p_n(x') = \Delta p_n(0)\ e^{-\frac{x'}{L_p}}$$

Carrier injection under forward bias (continued)

Change of axes to x' and x'' (see graph)

x'' axis

$$\Delta n_{\mathrm{p}}(0) = n_{\mathrm{p0}}\left(e^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right)$$

$$\Delta n_{\mathrm{p}}(x'') = \Delta n_{\mathrm{p}}(0)\, \mathrm{e}^{-\frac{x''}{L_{\mathrm{n}}}}$$

$$= n_{\mathrm{p0}}\left(\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right) \mathrm{e}^{-\frac{x''}{L_{\mathrm{n}}}}$$

x' axis

$$\Delta p_{\mathrm{n}}(0) = p_{\mathrm{n0}}\left(\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right)$$

$$\Delta p_{\mathrm{n}}(x') = \Delta p_{\mathrm{n}}(0)\, \mathrm{e}^{-\frac{x'}{L_{\mathrm{p}}}}$$

$$= p_{\mathrm{no}}\left(\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right) \mathrm{e}^{-\frac{x'}{L_{\mathrm{p}}}}$$

General current and minority carrier diffusion equations

Simplified equations

$$J_{\mathrm{p}}(x) = qp\mu_{\mathrm{p}}\mathcal{E} - qD_{\mathrm{p}}\frac{\mathrm{d}p}{\mathrm{d}x}$$

$$J_{\mathrm{p}}(x) = -qD_{\mathrm{p}}\frac{\mathrm{d}p}{\mathrm{d}x}$$

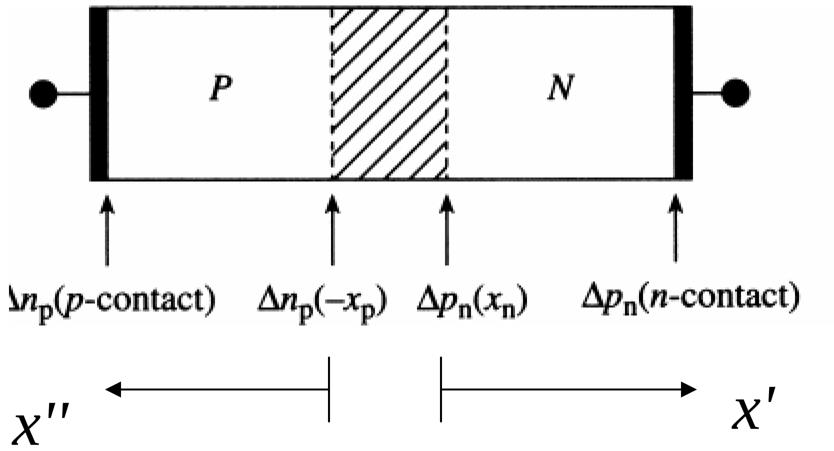
$$J_{\mathrm{n}}(x) = qn\mu_{\mathrm{n}}\mathcal{E} + qD_{\mathrm{n}}\frac{\mathrm{d}n}{\mathrm{d}x}$$

$$\frac{\partial \Delta p}{\partial t} = D_{\mathrm{p}}\frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_{\mathrm{p}}} + G_{\mathrm{L}}$$

$$0 = D_{\mathrm{p}}\frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_{\mathrm{p}}}$$

$$\frac{\partial \Delta n}{\partial t} = D_{\mathrm{n}}\frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_{\mathrm{n}}} + G_{\mathrm{L}}$$

Current equations applied to a diode



$$J_n(x'') = qD_n \frac{d\Delta n}{dx''} \qquad J_p(x') = -qD_p \frac{d\Delta p}{dx'}$$

Find J_n and J_p at the edge of the depletion layer and add them to get the total current.

Assumption: No generation or recombination inside the depletion layer.

Current equations applied to a diode

$$J_{\mathrm{p}} = -qD_{\mathrm{p}} \frac{\mathrm{d}}{\mathrm{d}x'} p_{\mathrm{n}}$$

$$= -qD_{\mathrm{p}} \frac{\mathrm{d}}{\mathrm{d}x'} \left[p_{\mathrm{n0}} + \Delta p_{\mathrm{n}}(0)\, \mathrm{e}^{-x'/L_{\mathrm{p}}} \right]$$

$$= +q \left(\frac{D_{\mathrm{p}}}{L_{\mathrm{p}}} \right) \Delta p_{\mathrm{n}}(0)\, \mathrm{e}^{-x'/L_{\mathrm{p}}}$$

Therefore,

$$J_{\mathrm{p}}(x'=0) = \left(\frac{qD_{\mathrm{p}}}{L_{\mathrm{p}}} \right) \Delta p_{\mathrm{n}}(0) = \left(\frac{qD_{\mathrm{p}}}{L_{\mathrm{p}}} \right) p_{\mathrm{n0}} \left(\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right)$$

Diode current equations

Similarly, $$J_n(x''=0) = -\left(\frac{qD_n}{L_n}\right) n_{p0} \left(e^{\frac{qV_A}{kT}} - 1\right)$$

Current due to electrons will be along positive x' direction.

And total current equals,

$$J = \left(\frac{qD_p}{L_p} p_{n0} + \frac{qD_n}{L_n} n_{p0}\right) \left(\mathrm{e}^{\frac{qV_A}{kT}} - 1\right)$$ Shockley equation

$$J = J_0 \left(e^{\frac{qV_A}{kT}} - 1\right)$$

Forward and reverse bias characteristics

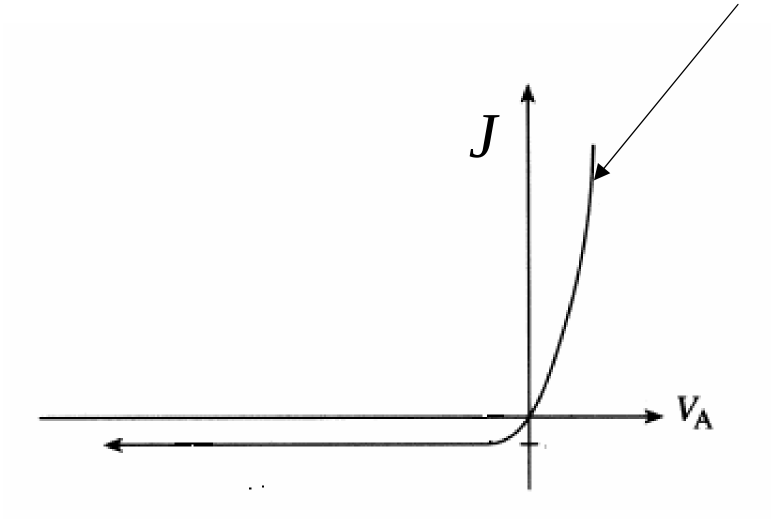
Large forward bias ($V_A >> kT/q$):

$$J = J_0 \, e^{\frac{qV_A}{kT}}$$

Large reverse bias ($V_A << -kT/q$):

$$J = -J_0$$

$$J = J_0 \left(e^{\frac{qV_A}{kT}} - 1\right)$$



Example 1

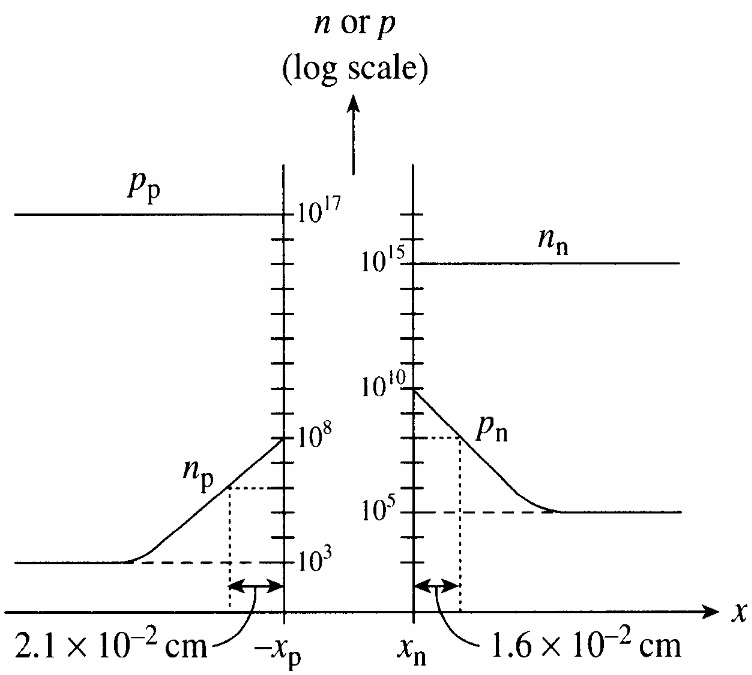


Figure E6.3

Figure 6.3 is a dimensioned plot of the steady state carrier concentration inside a pn junction diode maintained at room temperature.

a. Is the diode forward or reverse biased? Explain

b. Do low-level injection conditions prevail in the quasi-neutral region of the diode? Explain

c. Determine the applied voltage, V_A

d. Determine the hole diffusion length, L_p