8.16 Consider an ideal silicon pn junction diode with the geometry shown in Figure P8.16. The doping concentrations are $N_a = 5 \times 10^{16}$ cm^{-3} and $N_d = 1.5 \times 10^{16}$ cm^{-3}, and the minority carrier lifetimes are $\tau_{n0} = 2 \times 10^{-7}$ s and $\tau_{p0} = 8 \times 10^{-8}$ s. The cross-sectional area is $A = 5 \times 10^{-4}$ cm^2. Calculate (*a*) the ideal reverse-saturation current due to holes, (*b*) the ideal reverse-saturation current due to electrons, (*c*) the hole concentration at $x = x_n$ for $V_a = 0.8V_{bi}$, (*d*) the electron current at $x = x_n$ for $V_a = 0.8\,V_{bi}$, and (*e*) the electron current at $x = x_n + (1/2)L_p$ for $V_a = 0.8\,V_{bi}$.

- Change doping concentrations to $N_a = 4 \times 10^{16}$ cm^{-3} and $N_d = 10^{16}$ cm^{-3}. First, calculate the minority thermal equilibrium carrier concentrations and diffusion lengths for the n & p regions. [Hint: e) find total current & hole current at $x = x_n + L_p/2$, subtract to get electron current.]

From Table B.4, $n_i = 1.5 \times 10^{10}$ cm^{-3} for silicon at 300 K.

From page 323 'Note', $D_n = 25$ cm^2/s and $D_p = 10$ cm^2/s. Use given τ_{n0} & τ_{p0}.

n region Since $N_d >> n_i \Rightarrow n_{n0} \cong N_d = 10^{16}$ cm^{-3}.

Per (4.43), $p_{n0} = n_i^2 / n_{n0} = (1.5\times10^{10})^2 / 10^{16}$ $\Rightarrow$ **$p_{n0} = 2.25 \times 10^4$ cm^{-3}**.

From p. 283, $L_p = \sqrt{D_p\,\tau_{p0}} = \sqrt{10\,(8\times10^{-8})}$ $\Rightarrow$ **$L_p = 8.944272 \times 10^{-4}$ cm**.

p region Since $N_a >> n_i \Rightarrow p_{p0} \cong N_a = 4 \times 10^{16}$ cm^{-3}.

Per (4.43), $n_{p0} = n_i^2 / p_{p0} = (1.5\times10^{10})^2 / 4\times10^{16}$ $\Rightarrow$ **$n_{p0} = 5625$ cm^{-3}**.

From p. 283, $L_n = \sqrt{D_n\,\tau_{n0}} = \sqrt{25\,(2\times10^{-7})}$ $\Rightarrow$ **$L_n = 2.236068 \times 10^{-3}$ cm**.

a) Per (8.26), $J_s = \dfrac{eD_p\,p_{n0}}{L_p} + \dfrac{eD_n\,n_{p0}}{L_n} = J_{s,p} + J_{s,n}$.

For holes, the ideal reverse saturation current density is

$$J_{s,p} = \frac{eD_p\,p_{n0}}{L_p} = \frac{1.602176634\times10^{-19}(10)\,2.25\times10^4}{8.944272\times10^{-4}} = 4.0303978 \times 10^{-11} \text{ A/cm}^2,$$

and current is $I_{s,p} = J_{s,p} A = 4.0303978 \times 10^{-11}\,(5 \times 10^{-4})$ $\Rightarrow$ **$I_{s,p} = 2.0152 \times 10^{-14}$ A**.

b) For electrons, the ideal reverse saturation current density is

$$J_{s,n} = \frac{eD_n\,n_{p0}}{L_n} = \frac{1.602176634\times10^{-19}(25)\,5625}{2.236068\times10^{-3}} = 1.0076 \times 10^{-11} \text{ A/cm}^2,$$

and current is $I_{s,n} = J_{s,n} A = 1.0076 \times 10^{-11}\,(5 \times 10^{-4})$ $\Rightarrow$ **$I_{s,n} = 5.0380 \times 10^{-15}$ A**.

Per (7.10), $V_t = \dfrac{k_B T}{e} = \dfrac{8.617333\times10^{-5}\,\text{eV/K}\,(300\,\text{K})}{e}$ = 0.025852 V, and

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.025852 \ln\left(\frac{4\times10^{16}\,(10^{16})}{(1.5\times10^{10})^2}\right) = 0.729191 \text{ V.}$$

c) Per (8.11a),

$$p_n(x_n) = p_{n0}\, e^{V_a/V_t} = 2.25\times10^4\, e^{0.8(0.729191)/0.025852} \Rightarrow \underline{\mathbf{p_n(x_n) = 1.4193\times10^{14}\ cm^{-3}}}.$$

d) Per (8.24), $J_n(-x_p) = \dfrac{eD_n n_{p0}}{L_n}\left(e^{V_a/V_t} - 1\right) = J_n(x_n)$ since the electron current density is constant across the depletion layer.

$$J_n(x_n) = \frac{1.602176634\times10^{-19}(25)\,5625}{2.236068\times10^{-3}}\left(e^{0.8(0.729191)/0.025852} - 1\right) = 0.06356088 \text{ A/cm}^2.$$

$$I_n(x_n) = J_n(x_n)\, A = 0.06356088\ (5\times10^{-4}) \qquad \Rightarrow \underline{\mathbf{I_n(x_n) = 31.7804\ \mu A}}.$$

e) Per KCL, the total current through the diode is constant. We can find it by computing the current through the depletion layer using (8.26) and (8.27).

Per (8.26), $J_s = \dfrac{eD_p p_{n0}}{L_p} + \dfrac{eD_n n_{p0}}{L_n} = J_{s,p} + J_{s,n} = 4.0303978\times10^{-11} + 1.0076\times10^{-11}$

$$\Rightarrow J_s = 5.038\times10^{-11} \text{ A/cm}^2.$$

Per (8.27), $J = J_s\left(e^{V_a/V_t} - 1\right) = 5.038\times10^{-11}\left(e^{0.8(0.729191)/0.025852} - 1\right) \Rightarrow J = 0.3178 \text{ A/cm}^2$.

Total diode current is $I = JA = 0.3178\ (5\times10^{-4})$ $\Rightarrow \underline{I = 0.1589 \text{ mA} = 158.9\ \mu\text{A}}$.

Per (8.28), $J_p(x) = \dfrac{eD_p p_{n0}}{L_p}\left(e^{V_a/V_t} - 1\right)e^{(x_n - x)/L_p}$. So, at $x = x_n + L_p/2$, we get

$$J_p(x = x_n + L_p/2) = 4.0304\times10^{-11}\left(e^{0.8(0.729191)/0.025852} - 1\right)e^{-0.5} \Rightarrow J_p(x) = 0.1542 \text{ A/cm}^2,$$

and a hole current of $I_p(x) = J_p(x)\,A = 0.1542\,(5\times10^{-4}) = 7.71032\times10^{-5}$ A.

By KCL, the majority electron current at $x = x_n + L_p/2$ is then

$I_n(x) = I - I_p(x) = 1.589\times10^{-4} - 7.71032\times10^{-5} \Rightarrow \underline{\mathbf{I_n(x = x_n + L_p/2) = 8.180\times10^{-5}\ A = 81.8\ \mu A}}$.