Carrier distribution equation (53A) \[ \delta p(x) = A e^{(x-x_n)/L_p} + B e^{(x-x_n)/L_p} \text{ for } \infty > x > x_n \]

Boundary conditions (BCs) are:

- \( p_n \) at \( x = x_n \) is \( p_c = p_n e^{qV_j/kT} \)
- \( p_n(x=l_n) = p_n \)

OR

\[ \text{(BC#1)} \; \delta p(x = x_n) = \Delta p = p_c - p_n = p_n e^{qV_j/kT} - 1 \], and \( \text{BC#2} \; \delta p(x = l_n) = 0 \).

Here, \( l_n \) is the length of n-region. The n-region is finite (not \( \infty \)).

Find A, B. using BC#1 gives \( A + B = p_n e^{qV_j/kT} - 1 \), and BC#2 gives \( A e^{(l_n-x_n)/L_p} + B e^{(l_n-x_n)/L_p} = 0 \).

**HW2-Q12 (a)** Write expression of junction capacitance \( C_J \) at:

- Equilibrium (\( W_0 \)) \( C_J \)
- Forward bias (\( W_1 \)) \( C_J \)
- Reverse bias \( W_2, C_J \)

(b) Write expressions for diffusion capacitance \( C_{\text{diff}} \) under forward bias.

**Method I**

\[ C_{\text{diff}} = \frac{dW_1}{dV_T} y \]

**Method II**

\[ C_{\text{diff}} = \frac{dW_2}{dV_T} y \]
HW3-Q.1 Fig. 1 shows a p-n junction under equilibrium. The device doping parameters are as shown in Fig. 1.

Other parameters are as follows:

Given $n_d$ in Si at room temperature ($T=300K$) = $1.5 \times 10^{10}$ cm$^{-3}$, the product of hole concentration $p$ and electron concentration $n$ outside the junction is constant $pn = (n_0)^2$. Assume all donors and acceptors are ionized at 300K.

n-side: Donor concentration $N_d = 10^{14}$ cm$^{-3}$, minority hole lifetime $\tau_p = 2 \times 10^{-6}$ sec.

Minority hole diffusion coefficient $D_p = 12.5$ cm$^2$/sec.

p-side: Acceptor concentration $N_a = 10^{16}$ cm$^{-3}$, $\tau_n = 10^{-5}$ sec. $D_n = 40$ cm$^2$/sec.

Effective mass: electrons $m_e = m_0 = 0.26m_0$, holes $m_h = m_p = 0.64m_0$.

Junction area $A = 10^3$ cm$^{-2}$, $n_o$ (300K) = $1.5 \times 10^{10}$ cm$^{-3}$. $e_f(Si)=11.8$, $e_o=8.85 \times 10^{-14}$ F/cm, $\varepsilon_f=\varepsilon_o$.

Assume all donors and acceptors are ionized at $T=300$ K. $E_g = 1.1eV$, $kT/q = 0.0259V$

(a) Find junction width $W_o$ and its components $x_n$ and $x_p$. HINT: Eqs. 33-35 page 103-104.

(b) Draw the junction boundaries for a forward biased p-n junction. For this you need to find the new junction width. Proportionally decrease the values and obtain new $x_n$ and $x_p$ values.

HINT: Use junction width $W = W_r$ under forward bias page 106 Eq. 41; $V=0.5V$. New Eq. $qA_No\eta_x = qA_Na \eta_p$

(c) Find hole concentration $p_e$ at the n-region boundary $x_n$ and electron concentration $n_e$ at $x_p$ under a forward bias of 0.7V. HINT: Use Eqs. 55 and 61 (pages 109-110). Electrons on p-side $n_e(x=\infty) = n_{pe}$ and $n_e = n_o(x_p)$.

(d) Write the boundary conditions for carrier concentration at the junction boundaries for holes and electrons and at infinite distance away from the junction. We are assuming both n and p regions are much larger than the diffusion lengths $L_n$ (for holes diffusing in n-region) and $L_p$ for electrons diffusing in the p-region.

(e) Find and draw the carrier concentration profile $p_e(x)$ and $n_e(x)$ as a function of $x$ using the diffusion coefficient information...
Figure 2. Electron and hole concentration distribution in a forward biased diode. Extraterrestrial. What are the boundary conditions for a reverse biased junction with $V_r = -0.2V$.

Hole concentration $p_e = p(x_r) = p_{po}e^{(-V_r / kT)} = 2.25 \times 10^{12} * e^{(-0.2 \times 0.055)} = 99.66cm^{-3}$.

And, electron concentration $n_e = n_{po}e^{(-V_r / kT)} = 2.25 \times 10^{12} * e^{(-0.2 \times 0.055)} = 0.09966cm^{-3}$.

If $V_r$ is increased to -2V or so, the edge concentration will approach zero.

Q.1 (f) Draw the carrier concentration distribution after finding the junction width.

Reverse biased junction width $W_r$ at $V_r = -0.2V$ is given by $W_r = W_{eqb} \times [(V_r + V_t) / V_h t]^2$

$W_r = 0.9928(0.754 + 0.2) / 0.754 = 1.1167 \mu m$

Fig. 3. Carrier distribution in a slightly reverse biased diode $V_r = -0.2V$. 

\[ n_{po} = 1 \times 10^{15} \]
Q. 1(g) Hole Current

\[ I_p(x_n) = \frac{qAD_{p+} \rho_m}{L_p} \left( \frac{q^2 \tau_p}{e^{qV_L/T} - 1} \right) \approx \frac{1.6 \times 10^{-19} \times 10^{-3} \times 12.5 \times 2.25 \times 10^5}{5 \times 10^{-3}} \left( \frac{q^{1.5}}{e^{qV_L/T} - 1} \right) \]

\[ L_p = \sqrt{D_p \tau_p} = \sqrt{12.5 \times 2 \times 10^{-8}} = 5 \times 10^{-3} \text{ cm}, \quad \text{and} \quad e^{qV_L/T} - 1 = e^{0.0259} - 1 = 2.42 \times 10^8 - 1 \approx 2.42 \times 10^8 \]

\[ I_p = \frac{1.6 \times 10^{-19} \times 10^{-3} \times 12.5 \times 2.25 \times 10^5 \times 2.42 \times 10^8}{5 \times 10^{-3}} = 2.179 \times 10^{-5} \text{ Amp} \]

Electron current

\[ I_n(x_p) = \frac{qAD_n \mu_p}{L_n} \left( \frac{q^{1/2}}{e^{qV_L/T} - 1} \right) \approx \frac{1.6 \times 10^{-19} \times 10^{-3} \times 40 \times 2.25 \times 10^2}{2 \times 10^{-2}} \left( \frac{q^{1/2}}{e^{qV_L/T} - 1} \right) \]

\[ L_n = \sqrt{40 \times 10^{-5}} = 2 \times 10^{-2} \text{ cm}, \quad \text{and} \quad e^{qV_L/T} - 1 = e^{0.0259} - 1 = 2.42 \times 10^8 - 1 \approx 2.42 \times 10^8 \]

\[ I_n = \frac{1.6 \times 10^{-19} \times 10^{-3} \times 40 \times 2.25 \times 10^2 \times 2.42 \times 10^8}{2 \times 10^{-2}} = 1.74 \times 10^{-3} \text{ Amp} \]

Q1(h)

Equilibrium

Forward bias \( V = 0.2 \text{V} \)

Reverse bias \( V = -0.2 \text{V} \)

Q1(i)

\[ V_{\text{Breakdown}} = \frac{E_mW}{2} = \frac{E_\text{F} \epsilon_\text{F} \epsilon_\text{m}^2 (N_D)^{1}}{2q} = \frac{E_\text{F} \epsilon_\text{F} \epsilon_\text{m}^2}{2q} \frac{1}{N_D} \]

\[ L_n = \sqrt{D_n \tau_n} = \sqrt{100 \times 10^{-8}} = 10^{-3} \text{ cm} \quad \text{and} \quad N_B \equiv N_D = 10^{15} \text{ cm}^{-3} \]

Fig. 26 (Ref. S. M. Sze text shows \( V_{br} = 300 \text{V} \)) shows the breakdown voltages for various doping levels.
HW2-Q11. Draw the carrier distribution plots under (a) forward bias $V_F = 0.7V$. First do HW3-Q1.

\[
\frac{KT}{q} = 8.62 \times 10^{-5} \times 300K = 0.0159\text{eV}
\]

\[
\frac{KT}{q} = \frac{0.0159\text{eV}}{0.0159\text{eV}} = 0.159\text{eV}
\]

(b) Reverse bias of 2V for the p-n junction given below in Fig. 5. First do HW3-Q1

\[
\begin{align*}
\frac{\phi_c - \phi_n}{kT} &= 2.71 \times 10^3 \times 0.0159\text{eV} \\
n_e &= n_p = e^{\frac{-0.7}{0.0159\text{eV}}} \\
 &= 2.25 \times 10^{12} \text{cm}^{-3}
\end{align*}
\]

Fig. 5 p-n junction.

HW2-Q12. (a) Draw the energy band diagram under forward bias of 0.7V for the device of Fig. 5. 

**HINT:** Draw the Fermi level as a horizontal line under equilibrium; draw two vertical lines representing the junction with width $W_j$; draw a new Fermi level for p-side which represents forward bias that is p-side level is $qV_F$ below the n-side Fermi level; draw the p-Si conduction and valence bands with respect to the new Fermi level; draw the n-Si CB and VB with respect to old Fermi level.
Q2(b) Draw the energy band diagram for the device of Fig. 2 under reverse-bias of 2.0 V.

HINT: Draw a new Fermi level for p-side which represents reverse bias that is p-side level is $qV_r$ above the n-side Fermi level.

Energy band diagram for a forward biased diode

Energy band diagram for a reverse biased diode

Q3 Figure 3 shows an n$^+$-p Si diode.

Fig. 3 An abrupt n-p Si diode under forward bias.

n$^+$-side: Donor concentration $N_D = 10^{20}$ cm$^{-3}$, minority hole lifetime $\tau_p = 2 \times 10^6$ sec.

Minority hole diffusion coefficient $D_p = 12.5$ cm$^2$/sec.

p-side: Acceptor concentration $N_A = 10^{16}$ cm$^{-3}$, $\tau_n = 10^{-5}$ sec. $D_n = 40$ cm$^2$/sec.

Effective mass: electrons $m_e = m_0 = 0.26 m_0$, holes $m_i = m_p = 0.57 m_0$, $m_n = 9.1 \times 10^{-31}$ kg

Junction area $A = 10^2$ cm$^2$, $n_i (300K) = 1.5 \times 10^{10}$ cm$^3$. $\varepsilon_Si = 11.8$, $\varepsilon_n = 8.85 \times 10^{-14}$ F/cm, $\varepsilon_p = \varepsilon_n$

Assume all donors and acceptors are ionized at $T = 300$ K. $E_g = 1.1$ eV,

Boltzmann Constant $k = 8.65 \times 10^{-5}$ eV/K.

(a) Draw the energy band diagram under equilibrium, forward biasing $V_F = 0.7$ V, and reverse biasing of $V_R = 2$ V.

(b) Find the reverse situation current $I_S$.

(c) Plot current and carrier distribution in the entire diode at $V_F = 0.7$ V. For $x$ axis, plot carrier and current values at $x = 0$ (that is at junction boundary) and $x/L_n$, $x/2L_n$, and $x/3L_n$ on p-side and $x = -x/L_p$ and $x/2L_p$ and $x/3L_p$ on the n-side.

(d) What happens to the energy when electrons recombine in the p-region?

BONUS: Q4(a) Level of doping in a diode that determines avalanche or Zener breakdown. How do you calculate the breakdown voltage (see page 152)?

(b) Draw the energy band diagram for a Zener diode. HINT: Zener diode has junction width is about 100Å or smaller.

Q4(b) Electric field just internal to the junction if you were to put a 3 V bias across the junction.