Solid State Diodes
Figure 3.1 - Basic p-n junction diode

Metallurgical Junction

\[ p_p = N_A \]
\[ n_p = \frac{n_i^2}{N_A} \]
\[ n_n = N_D \]
\[ p_n = \frac{n_i^2}{N_D} \]
Figure 3.4 - Space charge region formation near the metallurgical junction
Figure 3.5 - (a) Charge density (C/cm³), (b) electric field (V/cm) and (c) electrostatic potential (V) in the space charge region of p-n junction
Figure 3.6 - Diode with external applied voltage $v_D$
Figure 3.10 - Diode with applied voltage $v_D$
Figure 3.11 - Diode i-v characteristic on semilog scale

\[
\begin{align*}
Slope & = 1 \text{ decade/60 mV} \\
I_S & = 10^{-15} \text{ A} \\
V_T & = 0.025 \text{ V}
\end{align*}
\]
Diode Temperature Coefficient

- From the current equation
  \[ i_D = I_S \exp \left( \frac{v_D}{V_I} - 1 \right) \]

- we get for the diode in the forward bias
  \[ v_D = V_T \ln \left( \frac{I_F}{I_S} \right) + 1 = \frac{kT}{q} \ln \left( \frac{I_F}{I_S} \right) + 1 \approx \frac{kT}{q} \ln \left( \frac{I_F}{I_S} \right) \]

- so the temperature coefficient is
  \[ \frac{dv_D}{dT} = \frac{k}{q} \ln \left( \frac{I_F}{I_S} \right) + \frac{kT}{q} \frac{1}{I_S} \frac{dI_S}{dT} = \frac{v_D - V_{G0} - 3V_T}{T} \]
Diode Temperature Coefficient

where

\[ i_D \gg I_S \approx n_i^2 \]
and

\[ V_{G0} = \frac{E_G}{q} \]
represents silicon bandgap energy at 0K

for silicon diode with \( V_D = 0.65V \), \( E_G = 1.12eV \),
and \( V_T = 0.025V \)

\[ \frac{dv_D}{dT} = \frac{(0.65 - 1.12 - 0.075)V}{300K} = -1.82 \text{ mV / K} \]
pn Junction under Reverse Bias

First, we must understand the *complete* structure of the pn junction-- starting in thermal equilibrium:

![Diagram of pn junction under reverse bias]

How can \( V_D = 0 \) and the built-in potential barrier be \( \phi_B \approx 1 \text{ V} \) (approx.)?

Answer: look at the complete circuit ... including the potential barriers at the p-type silicon-to-metal (\( \phi_{pm} \)) and the metal-to-n-type silicon (\( \phi_{mn} \)) junctions.

Kirchhoff’s Voltage Law:

\[
0 = \phi_{pm} + \phi_B + \phi_{mn}
\]

therefore, the built-in voltage is given by:

\[
\phi_B = -\phi_{pm} - \phi_{mn}
\]
Potential Plot through pn Junction

- The potential in the metal is the same on both ends of the pn junction in thermal equilibrium, with the metal-semiconductor contact potentials ("batteries") cancelling out the built-in potential.

\[ \phi_n - \phi_p = \phi_{pn} \]

Note: we show potential changes at metal-silicon contacts as vertical, which is not correct. The details are left for an advanced device physics course.

- Now we apply a battery \( V_D \) ... with \( V_D < 0 \) (reverse bias)

\[ I_D \approx 0 \text{ A} \]

\[ V_D (< 0 \text{ V}) \]
pn Junction under Reverse Bias (cont.)

- Potential plot under reverse bias: contact potentials don’t change ... they are ohmic contacts. Only place for change is at the pn junction

- The new potential barrier is called $\phi_j$

\[
\text{KVL:} \quad -V_D - \phi_{pm} - \phi_j - \phi_{mn} = 0
\]

\[
\phi_j = (\phi_{pm} - \phi_{mn}) - V_D = \phi_B - V_D
\]

- The potential barrier is increased over the built-in barrier by the reverse bias ... which widens the depletion region ($x_n > x_{no}$, $x_p > x_{po}$)
Quantitative Results

- Substitute $\phi_j$ for $\phi_B$ in the equilibrium depletion width and we find the depletion width under reverse bias (the math is the same):

\[
x_p(V_D) = \sqrt{\frac{2\varepsilon_s(\phi_B - V_D)}{qN_a}} \left( \frac{N_d}{N_d + N_a} \right) = x_{po} \sqrt{1 - (V_D/\phi_B)}
\]

\[
x_n(V_D) = \sqrt{\frac{2\varepsilon_s(\phi_B - V_D)}{qN_d}} \left( \frac{N_a}{N_d + N_a} \right) = x_{no} \sqrt{1 - (V_D/\phi_B)}
\]

\[
X_d(V_D) = \sqrt{\frac{2\varepsilon_s(\phi_B - V_D)}{q}} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) = X_{do} \sqrt{1 - (V_D/\phi_B)}
\]

- Note $x_{po}$, $x_{no}$, and $X_{do}$ are the widths in thermal equilibrium.
Figure 3.15 - The avalanche breakdown process. (Note that the positive and negative charge carriers will actually be moving in opposite directions in the electric field in the depletion region.)
Zener breakdown diode model

Figure 3.16 - (a) Model for reverse breakdown region of diode  
(b) Zener diode symbol
Depletion Capacitance

- Find the function \( q_J = q_J(v_D) \) from \( x_P(v_D) \):

\[
q_J(v_D) = -qN_a x_P(v_D) = -qN_a x_{Po} \sqrt{1 - \left( \frac{v_D}{\phi_B} \right)}
\]

- Normalized plot:

- To find the depletion capacitance \( C_j \) we simply take the derivative and evaluate it at the particular DC voltage

\[
C_j = C_J(V_D) = \left. \frac{dq_J}{dv_D} \right|_{V_D}
\]

- Math --> no insight into the concept of capacitance!
Graphical Interpretation

- Derivative is the *slope* of the plot of $q_J(v_D)$:

- The small-signal charge is related to the small-signal voltage by the slope at point $(Q_J, V_J)$:

  $$ q_J = \left. \frac{dq_J}{dv_D} \right|_{V_D} \cdot v_d = C_f(V_D) \cdot v_d $$
Physical Interpretation

- Small-signal voltage changes the depletion width ($v_d > 0$ --> reverse bias is reduced --> depletion width is slightly narrower)

\[ v_D = V_D \]

\[ Q_J = -qN_a x_p \]

\[ V_D + v_d > V_D \to x_n' < x_n, |q_j| < |Q_j| \]

\[ q_j = qN_a \Delta x_p \]

\[ q_j = q - Q_j > 0 \]

\[ = -qN_a x_p - (-qN_a x_p) \]

\[ = qN_a (x_p - x_p') \]

\[ = qN_a \Delta x_p \]
Depletion Capacitance Equation

- Derivative can be evaluated (see Chapter 3), but the incremental charge is two sheets separated by a distance $X_d(V_D)$ --> use parallel plate capacitor formula:

$$C_j = \frac{q_j}{V_d} = \frac{\varepsilon_s}{X_d(V_D)} = \frac{\varepsilon_s}{X_{do}\sqrt{1-V_D/\phi_B}} = \frac{C_{jo}}{\sqrt{1-V_D/\phi_B}}$$

- Plot of depletion capacitance (normalized to $C_{jo}$):

![Plot of depletion capacitance](image)

Typical numbers: $X_{do} = 0.4 \, \mu m$ --> $C_{jo} = 2.6 \times 10^{-8} \, F/cm^2 = 0.26 \, fF/\mu m^2$

$\phi_B = 0.8 \, V$ --> $V_D = -6.4 \, V = -8 \, \phi_B$ -->

$$(1 - V_D/\phi_B)^{1/2} = 3 \rightarrow C_j = C_{jo} / 3 = 86 \, aF/\mu m^2$$
Variable capacitor diode

Figure 3.17 - Circuit symbol for the variable capacitance diode (varactor)
Schottky barrier diode

Figure 3.18 - (a) Schottky barrier diode structure  
(b) Schottky diode symbol
Figure 3.19 - Comparison of pn junction (PN) and Schottky diode (SB) i-v characteristics