p-n Junction

• p-type semiconductor in contact with n-type

• Basic building blocks of semiconductor devices
  – Diodes,
  – Bipolar junction transistors (BJT),
  – Metal-oxide-semiconductor field effect transistors (MOSFET)
p-n Junction

• When p- and n-type semiconductors are “joined”
  – Holes near junction diffuse to n-side
  – Electrons near junction diffuse to p-side

• “Depletion region” formed near junction
  – No electrons, no holes

• A “built-in” potential is formed to oppose further movement of electrons and holes

\[
\phi(x) = -\int_{x_p}^{x_n} E(x) \, dx = V_{bc} > 0
\]

\[
E = -\frac{d\phi}{dx}
\]
Simplified Analysis of p-n Junction

**Gauss Law:**
\[ \int \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_s} \]

**Electrical potential:**
\[ V = -\int_{-\infty}^{x} E(x')dx' \]

**Built-in potential:**
\[ V_0 = V_T \cdot \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

**Depletion width:**
\[ W = \sqrt{\frac{2\varepsilon_s}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) V_0} \]

Controlled by doping \( N_A, N_D \)

- \( x_n + x_p \) high doping \( \Rightarrow \) large \( N_A, N_D \)
- \( x_n + x_p \) small \( W \)
Built-in Potential

Built-in potential:

\[ V_0 = V_T \cdot \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

\[ V_T = \frac{k_B T}{q} \]: thermal voltage = 26 mV at room temperature

\( N_A \): p-doping (Acceptor)
\( N_D \): n-doping (Donor)
\( n_i \): intrinsic carrier concentration
\( n_i = 1.5 \times 10^{10} \text{ cm}^{-3} \) for Si

Alternative form:

\[ V_0 = 60 \text{ mV} \cdot \log \left( \frac{N_A N_D}{n_i^2} \right) \]

Example:

\( N_A = 1.5 \times 10^{17} \), \( n_D = 1.5 \times 10^{18} \text{ cm}^{-3} \)
\( V_0 = 60 \text{ mV} \cdot \log (10^{15}) = 900 \text{ mV} \)
Carrier Concentration in p-n Junction

At equilibrium:

\[ n \times p = n_i^2 \]

\[ p_p = N_A \]

\[ n_{p0} = \frac{n_i^2}{N_A} \]

\[ n_n = N_D \]

\[ p_{n0} = \frac{n_i^2}{N_D} \]

Depletion

→ No holes

→ No electrons
Depletion Width Under Bias

1. Open circuit (V = 0)
   - Equilibrium
   - Labeled: $P = P_0 e^{\frac{qV_0}{kT}}$

2. Reverse Bias (V < 0)
   - Larger barrier
   - Wider depletion
   - Equations:
     \[ W = \sqrt{\frac{2\epsilon_s}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 - V)} \]

3. Forward Bias (V > 0)
   - Smaller barrier
   - Narrower depletion
   - Applied voltage:
     \[ V > 0 \text{ is forward bias} \]
     \[ V < 0 \text{ is reversed bias} \]
Extra Holes in N Side Under Forward Bias

Excess holes in n-doped side:

\[ p_{n,\text{edge}} = p_{n0} \cdot \left( e^{V/V_T} - 1 \right) \]

Forward Bias Barrier lowered by \( V \)

\[ e^{\frac{V}{kT}} = e^{\frac{V}{V_T}} \]

\[ V_T = \frac{qE}{k} \]
Holes Recombine with Electrons on N Side

Excess holes in n-doped side:
\[ p_{n,\text{edge}} = p_{n0} \cdot \left(e^{V/V_T} - 1\right) \]

Excess holes recombine within diffusion length, \( L_p \):
\[ \frac{dp_{n}(x)}{dx} = -\frac{p_{n,\text{edge}}}{L_p} \]

\[ p_p = N_A \]
\[ n_p0 = \frac{n_i^2}{N_A} \]
\[ n_n = N_D \]
\[ p_{n0} = \frac{n_i^2}{N_D} \]
\[ \Delta p \propto e^{-\frac{x}{L_p}} : L_p = \text{diffusion length} \]
\[ \frac{dP_n(x)}{dx} = -\frac{1}{L_p} P_n(x) \]
Diffusion Currents Under Forward Bias

Excess holes in n-doped side:

\[ p_{n,\text{edge}} = p_{n0} \cdot \left( e^{V/V_T} - 1 \right) \]

Excess holes recombines within diffusion length, \( L_p \):

\[ \frac{dp_n(x)}{dx} = \frac{p_{n,\text{edge}}}{L_p} \]

Diffusion current:

\[ J_p = -qD_p \frac{dp_n(x)}{dx} \]

\[ = \frac{qD_p}{L_p} p_{n0} \cdot \left( e^{V/V_T} - 1 \right) \]

\[ \rightarrow J_p \propto \left( e^{V/T} - 1 \right) \]
Total Currents Under Forward Bias

Hole Diffusion current on N-side

\[ J_p = \frac{qD_p}{L_p} p_{n0} \cdot (e^{V/V_T} - 1) \]

Similarly, Electron Diffusion current on P-side

\[ J_n = \frac{qD_n}{L_n} n_{p0} \cdot (e^{V/V_T} - 1) \]

Total current

\[ I = \text{Area} \cdot (J_p + J_n) \propto (e^{V/V_T} - 1) \]
I-V Curve

\[ I = I_S \left( e^{V/V_T} - 1 \right) \]

where

\[ I_S = A q n_i^2 \left( \frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right) \]

Reverse saturation current

\[ I_S \sim 10^{-15} \text{ Amp} \]

\[ e^{\frac{V}{V_T}} \]

\[ V = 0.8 \text{ V} = 800 \text{ mV} \]

\[ e^{\frac{800}{26}} = e^{32} \approx 10^6 \]
Capacitance in p-n Junction: Depletion Capacitance

Parallel plate capacitance:

\[ C_j = \frac{\varepsilon_s A}{W} \]

Plate separation, \( W \), is voltage dependent:

\[ W = \sqrt{\frac{2\varepsilon_s}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 + |V_R|)} \]

Variable capacitance:

\[ C_j(V_R) = \frac{C_{j0}}{\sqrt{1 + \frac{|V_R|}{V_0}}} \]

\[ C_{j0} = \frac{\varepsilon_s A}{W(V_R=0)} \]
Summary of p-n Junction

Built-in potential: \( V_0 = V_T \ln \left( \frac{N_A N_D}{n^2_i} \right) \)

I-V curve: \( I = I_S \left( e^{V/V_T} - 1 \right) \)

Capacitance: \( C_j = \frac{C_{j0}}{\sqrt{1 + \frac{|V_R|}{V_0}}} \)

Depletion Width: \( W = \sqrt{\frac{2\varepsilon_S}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 - V)} \)