Bipolar Transistor and Related Devices

MATS-535, Lecture 8

- The transistor action
- Static characteristics
- MOS diode
Bipolar Transistor

Perspective view of a silicon $p$-$n$-$p$ bipolar transistor.
Bipolar Transistor

(a) Idealized one-dimensional schematic of a p-n-p bipolar transistor and (b) its circuit symbol. (c) Idealized one-dimensional schematic of an n-p-n bipolar transistor and (d) its circuit symbol.
Bipolar Transistor (no bias)

(a) A $p$-$n$-$p$ transistor with all leads grounded (at thermal equilibrium). (b) Doping profile of a transistor with abrupt impurity distributions. (c) Electric-field profile. (d) Energy band diagram at thermal equilibrium.
Bipolar Transistor
Active mode operation under bias

(a) The transistor is shown in this Figure under the active mode of operation.
(b) Doping profiles and the depletion regions under biasing conditions.
(c) Electric-field profile.
(d) Energy band diagram.
Bipolar Transistor
Current gain

Various current components in a p-n-p transistor under active mode of operation. The electron flow is in the opposite direction to the electron current.
Carrier Distribution in Each Region

**Base Region**

\[ D_p \left( \frac{d^2 p_n}{dx^2} \right) - \frac{p_n - p_{n0}}{\tau_p} = 0 \]

\[ p_n(x) = p_n + C_1 e^{x/L_p} + C_2 e^{-x/L_p}, \quad L_p = \sqrt{D_p \tau_p} \]

\[ p_n(0) = p_{n0} e^{eV_{EB}/kT}, \quad p_n(W) = 0 \]

\[ p_n(x) = p_{n0} \left( e^{eV_{EB}} - 1 \right) \left( \frac{\sinh \left( \frac{W-x}{L_p} \right)}{\sinh \left( \frac{W}{L_p} \right)} \right) + p_{n0} \left[ 1 - \frac{\sinh \left( \frac{x}{L_p} \right)}{\sinh \left( \frac{W}{L_p} \right)} \right], \]

\[ p_n(x) = p_{n0} \left( e^{eV_{EB}} - 1 \right) \left( 1 - \frac{x}{W} \right) = p_n(0) \left( 1 - \frac{x}{W} \right), \quad W / L_p \ll 1. \]
Carrier Distribution in Each Region

Emitter and Collector Region

\[ n_E(x = -x_E) = n_{E0} e^{eV_{EB}/kT}, \]
\[ n_C(x = -x_C) = n_{C0} e^{-e|V_{CB}|/kT} = 0 \]
\[ n_E(x) = n_{E0} + n_{E0} (e^{eV_{EB}/kT} - 1) e^{(x+x_E)/L_E}, \quad x \leq -x_E, \]
\[ n_C(x) = n_{C0} - n_{C0} e^{-(x-x_C)/L_C}, \quad x \geq x_C. \]

Boundary conditions

Emitter region

Collector region
Minority carrier distribution in various regions of a p-n-p transistor under the active mode of operation.
Ideal Transistor

Current-Voltage Characteristics

\[ I_{Ep} = A \left( -eD_p \frac{dp_n}{dx} \right) \approx \frac{eAD_p p_{n0}}{W} e^{eV_{EB}/kT}, \quad x = 0 \]

\[ I_{Cp} = A \left( -eD_p \frac{dp_n}{dx} \right) \approx \frac{eAD_p p_{n0}}{W} e^{eV_{EB}/kT}, \quad x = W \]

\[ I_{Ep} \approx I_{Cp}, \quad W / L_p << 1 \]

Hole current
Ideal Transistor
Current-Voltage Characteristics

\[ I_{E_n} = A \left( -eD_E \frac{dp_E}{dx} \right) \approx \frac{eAD_E n_{E0}}{L_E} \left( e^{V_{EB}/kT} - 1 \right), \quad x = -x_E \]

\[ I_{C_n} = A \left( -eD_C \frac{dn_C}{dx} \right) \approx \frac{eAD_C n_{C0}}{L_C}, \quad x = x_C \]

Electron current
Ideal Transistor
Current-Voltage Characteristics

\[ I_E = a_{11} \left( e^{eV_{EB}/kT} - 1 \right) + a_{12}, \]
\[ a_{11} = eA \left( \frac{D_p p_{n0}}{W} + \frac{D_E n_{E0}}{L_E} \right), \]
\[ a_{12} = eA \frac{D_p p_{n0}}{W}, \]
\[ I_C = a_{21} \left( e^{eV_{EB}/kT} - 1 \right) + a_{22}, \]
\[ a_{22} = eA \left( \frac{D_p p_{n0}}{W} + \frac{D_C n_{C0}}{L_C} \right), \]
\[ a_{21} = eA \frac{D_p p_{n0}}{W}. \]
Bipolar Transistor
Common base configuration

(a) Common base circuit

(b) Characteristics of the common base configuration
- Saturation
- Active
- Cutoff

$V_{EB}$, $V_{CB}$, $I_E = 6mA$, $I_CBO$, $BV_{CBO}$
Bipolar Transistor
Common emitter configuration

\[ I_C = \alpha_C (I_B + I_C) + I_{CBO}. \]

\[ I_C = \frac{\alpha_0}{1 - \alpha_0} I_B + \frac{I_{CBO}}{1 - \alpha_0}. \]

\[ \beta_0 = \frac{\Delta I_C}{\Delta I_B} = \frac{\alpha_0}{1 - \alpha_0}, \text{ current gain} \]

\[ \alpha_0 = \gamma \alpha_T \approx 1 \]

\[ \beta_0 >> 1 \]

Common emitter circuit