Lecture 17
The Bipolar Junction Transistor (I)
Forward Active Regime

Outline

• The Bipolar Junction Transistor (BJT):
  – structure and basic operation
• I-V characteristics in forward active regime

Reading Assignment:
Howe and Sodini; Chapter 7, Sections 7.1, 7.2
1. BJT: structure and basic operation

Bipolar Junction Transistor: excellent for analog and front-end communications applications.
NPN BJT Collector Characteristics

Similar to test circuit as for an n-channel MOSFET …except $I_B$ is the control variable rather than $V_{BE}$

(a)

(b)
Simplified one-dimensional model of intrinsic device:

BJT=two neighboring pn junctions back-to-back

- Close enough for minority carriers to interact
  - ⇒ can diffuse quickly through the base
- Far apart enough for depletion regions not to interact
  - ⇒ prevent “punchthrough”

Regions of operation:

\[ V_{CE} = V_{BE} - V_{BC} \]
Basic Operation: forward-active regime

\[ V_{BE} > 0 \Rightarrow \text{injection of electrons from the } \textit{Emitter} \text{ to the } \textit{Base} \]
\[ \text{injection of holes from the } \textit{Base} \text{ to the } \textit{Emitter} \]

\[ V_{BC} < 0 \Rightarrow \text{extraction of electrons from the } \textit{Base} \text{ to the } \textit{Collector} \]
\[ \text{extraction of holes from the } \textit{Collector} \text{ to the } \textit{Base} \]
Basic Operation: forward-active regime

- Carrier profiles in thermal equilibrium:

- Carrier profiles in forward-active regime:
Basic Operation: forward-active regime

Dominant current paths in forward active regime:

\[ I_C: \text{ electron injection from } \text{Emitter to Base} \text{ and collection by Collector} \]
\[ I_B: \text{ hole injection from Base to Emitter} \]
\[ I_E: I_E = -(I_C + I_B) \]
The Flux Picture - Forward Active Region

- The width of the electron flux “stream” is greater than the hole flux stream.
- The electrons are supplied by the emitter contact injected across the base-emitter SCR and diffuse across the base.
- Electric field in the base-collector SCR extracts electrons into the collector.
- Holes are supplied by the base contact and diffuse across the emitter.
- The reverse injected holes recombine at the emitter ohmic contact.
2. I-V characteristics in forward-active regime

**Collector current**: focus on electron diffusion in base

Boundary conditions:

\[
n_{pB}(0) = n_{pB0} e^{\frac{V_{BE}}{V_{th}}}, \quad n_{pB}(W_B) = 0
\]

Electron profile:

\[
n_{pB}(x) = n_{pB}(0) \left[ 1 - \frac{x}{W_B} \right]
\]
**Electron current density:**

\[ J_{nB} = qD_n \frac{dn_{PB}}{dx} = -qD_n \frac{n_{PB}(0)}{W_B} \]

Collector current scales with area of base-emitter junction \( A_E \):

\[ I_C \propto A_E \]

Collector terminal current:

\[ I_C = -J_{nBAE} = qAE \frac{D_n}{W_B} n_{PB0} \cdot e^{\left[ \frac{V_{BE}}{V_{th}} \right]} \]

or

\[ I_C = I_S e^{\left[ \frac{V_{BE}}{V_{th}} \right] -} \]

\( I_S \equiv \text{transistor saturation current} \)
**Base current:** focus on hole injection and recombination at emitter contact.

\[
p_{nE}(-W_{E} - x_{BE}) = \frac{n_{i}^{2}}{N_{dE}}
\]

Boundary conditions:

\[
p_{nE}(-x_{BE}) = p_{nEo} e^{\frac{-V_{BE}}{V_{th}}}, \quad p_{nE}(-W_{E} - x_{BE}) = p_{nEo}
\]

Hole profile:

\[
p_{nE}(x) = [p_{nE}(-x_{BE}) - p_{nEo}] \cdot \left(1 + \frac{x + x_{BE}}{W_{E}}\right) + p_{nEo}
\]
**Hole current density:**

\[ J_{PE} = -qD_p \frac{dp_{nE}}{dx} = -qD_p \frac{p_{nE}(-x_{BE}) - p_{nEo}}{W_E} \]

Base current scales with area of base-emitter junction \( A_E \):

![diagram](image)

Base terminal current:

\[ I_B = -J_{PE} A_E = qA_E \frac{D_p}{W_E} p_{nEo} \left( e^{\frac{V_{BE}}{V_{th}}} - 1 \right) \]

\[ I_B \approx qA_E \frac{D_p}{W_E} p_{nEo} \cdot e^{\frac{V_{BE}}{V_{th}}} \]

**Emitter current:** \(-(I_B + I_C)\)

\[ I_E = - \left[ \left( qA_E \frac{D_p}{W_E} p_{nEo} \right) + \left( qA_E \frac{D_n}{W_B} n_{pBo} \right) \right] \cdot e^{\frac{V_{BE}}{V_{th}}} \]
Forward Active Region: Current gain

\[ \alpha_F = \frac{I_C}{|I_E|} = \frac{1}{1 + \frac{N_{aB}D_p W_B}{N_dE D_n W_E}} \]

Want \( \alpha_F \) close to unity---\( \rightarrow \) typically \( \alpha_F = 0.99 \)

\[ I_B = -I_E - I_C = \frac{I_C}{\alpha_F} - I_C = I_C \left( \frac{1 - \alpha_F}{\alpha_F} \right) \]

\[ \beta_F = \frac{I_C}{I_B} = \left( \frac{\alpha_F}{1 - \alpha_F} \right) \]

\[ \beta_F = \frac{I_C}{I_B} = \frac{n_{pBo} \cdot \frac{D_n}{W_B}}{\frac{D_p}{W_E}} = \frac{N_dE D_n W_E}{N_{aB} D_p W_B} \]

To maximize \( \beta_F \):

- \( N_{dE} \gg N_{aB} \)
- \( W_E \gg W_B \)
- want npn, rather than pnp design because \( D_n > D_p \)
Plot of $\log I_C$ and $\log I_B$ vs $V_{BE}$
Common-Emitter Output Characteristics
What did we learn today?

Summary of Key Concepts

*npn* BJT in forward active regime:

- **Emitter** “injects” electrons into **Base**, **Collector** “collects” electrons from **Base**
  - $I_C$ controlled by $V_{BE}$, independent of $V_{BC}$
  - *(transistor effect)*
    
    \[
    I_C \propto e^{\frac{V_{BE}}{V_{th}}}
    \]

- **Base**: injects holes into **Emitter** $\Rightarrow I_B$
  
  \[
  I_C \propto I_B
  \]