Lecture 18 - The Bipolar Junction Transistor (II)

Regimes of Operation

November 10, 2005

Contents:

1. Regimes of operation.
2. Large-signal equivalent circuit model.
3. Output characteristics.

Reading assignment:

Howe and Sodini, Ch. 7, §§7.3, 7.4

Announcements:

Quiz 2: 11/16, 7:30-9:30 PM, open book, must bring calculator; lectures #10-18.

Review session: 11/15, 7:30-9:30, place TBA
Cross-sectional diagram of the original point-contact semiconductor amplifier.
Key questions

• What other regimes of operation are there for the BJT?

• What is unique about each regime?

• How do equivalent circuit models for the BJT look like?
1. Regimes of operation

- **forward active**: device has good isolation and high gain; most useful regime;

- **saturation**: device has no isolation and is flooded with minority carriers ⇒ takes time to get out of saturation; avoid

- **reverse**: poor gain; not useful;

- **cut-off**: negligible current: nearly an open circuit; useful.
\[ \text{FORWARD-ACTIVE REGIME: } V_{BE} > 0, \ V_{BC} < 0 \]
• Emitter injects electrons into base, collector collects electrons from base:

\[ I_C = I_S \exp \frac{qV_{BE}}{kT} \]

• Base injects holes into emitter, recombine at emitter contact:

\[ I_B = \frac{I_S}{\beta_F} (\exp \frac{qV_{BE}}{kT} - 1) \]

• Emitter current:

\[ I_E = -I_C - I_B = -I_S \exp \frac{qV_{BE}}{kT} - \frac{I_S}{\beta_F} (\exp \frac{qV_{BE}}{kT} - 1) \]

• State-of-the-art IC BJT’s today: \( I_C \sim 0.1 - 1 \text{ mA}, \beta_F \simeq 50 - 300. \)

• \( \beta_F \) hard to control tightly \( \Rightarrow \) circuit design techniques required to be insensitive to variations in \( \beta_F \).
□ **Reverse regime:** $V_{BE} < 0$, $V_{BC} > 0$

Minority carrier profiles:
• Collector injects electrons into base, emitter collects electrons from base:

\[ I_E = I_S \exp \frac{qV_{BC}}{kT} \]

\[ I_C = I_S \exp \frac{qV_{BC}}{kT} \]

• Base injects holes into collector, recombine at collector contact and buried layer:

\[ I_B = \frac{I_S}{\beta_R} (\exp \frac{qV_{BC}}{kT} - 1) \]

• Collector current:

\[ I_C = -I_E - I_B = -I_S \exp \frac{qV_{BC}}{kT} - \frac{I_S}{\beta_R} (\exp \frac{qV_{BC}}{kT} - 1) \]

• Typically, \( \beta_R \approx 0.1 - 5 \ll \beta_F \).
Forward-active Gummel plot ($V_{CE} = 3 \, V$):

Reverse Gummel ($V_{EC} = 3 \, V$):
\[ \text{Cut-off: } V_{BE} < 0, \ V_{BC} < 0 \]

Minority carrier profiles:
• Base extracts holes from emitter:

\[ I_{B1} = -\frac{I_S}{\beta_F} = -I_E \]

• Base extracts holes from collector:

\[ I_{B2} = -\frac{I_S}{\beta_R} = -I_C \]

• These are tiny leakage currents (\( \sim 10^{-12} \) A).
\[ \textbf{Saturation: } V_{BE} > 0, \ V_{BC} > 0 \]

Minority carrier profiles:
Saturation is superposition of forward active + reverse:

\[
I_C = I_S \left( \exp \frac{qV_{BE}}{kT} - \exp \frac{qV_{BC}}{kT} \right) - \frac{I_S}{\beta_R} \left( \exp \frac{qV_{BC}}{kT} - 1 \right)
\]

\[
I_B = \frac{I_S}{\beta_F} \left( \exp \frac{qV_{BE}}{kT} - 1 \right) + \frac{I_S}{\beta_R} \left( \exp \frac{qV_{BC}}{kT} - 1 \right)
\]

\[
I_E = -\frac{I_S}{\beta_F} \left( \exp \frac{qV_{BE}}{kT} - 1 \right) - I_S \left( \exp \frac{qV_{BE}}{kT} - \exp \frac{qV_{BC}}{kT} \right)
\]

- \(I_C\) and \(I_E\) can have either sign, depending on relative magnitude of \(V_{BE}\) and \(V_{BC}\), and \(\beta_F\) and \(\beta_R\).
- In saturation, collector and base flooded with excess minority carriers ⇒ takes lots of time to get transistor out of saturation.
2. Large-signal equivalent circuit model

System of equations that describes BJT operation:

\[ I_C = I_S \left( \exp \left( \frac{qV_{BE}}{kT} \right) - \exp \left( \frac{qV_{BC}}{kT} \right) \right) - \frac{I_S}{\beta_R} \left( \exp \left( \frac{qV_{BC}}{kT} \right) - 1 \right) \]

\[ I_B = \frac{I_S}{\beta_F} \left( \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right) + \frac{I_S}{\beta_R} \left( \exp \left( \frac{qV_{BC}}{kT} \right) - 1 \right) \]

\[ I_E = -\frac{I_S}{\beta_F} \left( \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right) - I_S \left( \exp \left( \frac{qV_{BE}}{kT} \right) - \exp \left( \frac{qV_{BC}}{kT} \right) \right) \]

Equivalent-circuit model representation:

**Non-Linear Hybrid-π Model**

Three parameters in this model: \( I_S, \beta_F, \) and \( \beta_R \).
Model equivalent to Ebers-Moll model in text.
Simplifications of equivalent-circuit model:

- **Forward-active regime:** $V_{BE} > 0$, $V_{BC} < 0$

  \[
  I_B = \frac{I_S}{\beta_F} \left( \exp \left( \frac{qV_{BE}}{kT} \right) - 1 \right)
  \]

  For today’s technology: $V_{BE,\text{on}} \approx 0.7 \, V$.
  $I_B$ depends on outside circuit.

- **Reverse:** $V_{BE} < 0$, $V_{BC} > 0$

  \[
  I_B = \frac{I_S}{\beta_R} \left( \exp \left( \frac{qV_{BC}}{kT} \right) - 1 \right)
  \]

  For today’s technology: $V_{BC,\text{on}} \approx 0.5 \, V$.
  $I_B$ also depends on outside circuit.
$I_B$ vs. $V_{BE}$ for $V_{CE} = 3 \text{ V}$:

$I_B$ vs. $V_{BC}$ for $V_{EC} = 3 \text{ V}$:
• **Saturation:** $V_{BE} > 0, V_{BC} > 0$

![Diagrams]

Today’s technology: $V_{CE, sat} = V_{BE, on} - V_{BC, on} \approx 0.2 \, V$. $I_B$ and $I_C$ depend on outside circuit.

• **Cut-off:** $V_{BE} < 0, V_{BC} < 0$

![Diagrams]

Only negligible leakage currents.
3. Output characteristics

First, $I_C$ vs. $V_{CB}$ with $I_B$ as parameter:

Next, common-emitter output characteristics ($I_C$ vs. $V_{CE}$ with $I_B$ as parameter):
$I_C$ vs. $V_{CB}$ for $0 \leq I_B \leq 100 \, \mu A$:

$I_C$ vs. $V_{CE}$ for $0 \leq I_B \leq 100 \, \mu A$:
$I_C$ vs. $V_{CE}$ for $0 \leq I_B \leq 100 \ \mu A$: 
Key conclusions

- Forward-active regime: most useful, device has gain and isolation. For bias calculations:

- Saturation: device flooded with minority carriers. Not useful. For bias calculations:

- Cut-off: device open. Useful. For bias calculations: