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.
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 \( \Rightarrow \) takes time to get out of saturation; avoid

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

- **cut-off**: negligible current: nearly an open circuit; useful.
□ **FORWARD-ACTIVE REGIME:** $V_{BE} > 0$, $V_{BC} < 0$

Minority carrier profiles (*not to scale*):
• 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: \( I_C \sim 0.1 - 1 \ mA, \beta_F \sim 50 - 300. \)

• \( \beta_F \) 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:

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

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

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

• Collector current:

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

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

Reverse Gummel ($V_{EC} = 3 \, V$):
- 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).
**Saturation:** $V_{BE} > 0$, $V_{BC} > 0$

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

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

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

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

- \( I_C \) 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 \( \Rightarrow \) 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-\( \pi \) Model*

\[ \text{C} \]

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

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

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

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

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

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

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

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: $V_{BE} < 0$, $V_{BC} < 0$

Only negligible leakage currents.
3. Output characteristics

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

![Output characteristics diagram 1](image)

Next, common-emitter output characteristics ($I_C$ vs. $V_{CE}$ with $I_B$ as parameter):

![Output characteristics diagram 2](image)
$I_C$ vs. $V_{CB}$ for $0 \leq I_B \leq 100 \, \mu A$:

$IC$ 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: