Lecture 35 - Bipolar Junction Transistor

(cont.)

May 3, 2007

Contents:

1. Current-voltage characteristics of ideal BJT (cont.)

Reading material:

del Alamo, Ch. 11, §11.2 (11.2.1)
Key questions

• How does the BJT operate in other regimes?
• How does a complete model for the ideal BJT look like?
1. Current-voltage characteristics of ideal BJT (cont.)

□ **Forward-active regime** \((V_{BE} > 0, \; V_{BC} < 0)\)

Summary of key results:

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

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

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

\[
\beta_F \approx \frac{I_C}{I_B} \approx \frac{n_i^2 D_B}{N_B W_E} = \frac{N_E D_B W_E}{N_B D_E W_B}
\]

To maximize \(\beta_F\):

• \(N_E \gg N_B\)

• \(W_E \gg W_B\) (for manufacturing reasons, \(W_E \simeq W_B\))

• want npn, rather than pnp because this way \(D_B > D_E\)

\(\beta_F\) hard to control \(\Rightarrow\) if \(\beta_F\) is high enough \((> 50)\), circuit techniques effectively compensate for this.
• Equivalent circuit model

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

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

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

- Summary of minority carrier profiles *(not to scale)*
**Reverse regime** \((V_{BE} < 0, \ V_{BC} > 0)\)

\(I_E\): electron injection from C to B, collection into E  
\(I_B\): hole injection from B to C, recombination in C

Minority carrier profiles *(not to scale)*:
Current equations (just like FAR, but role of collector and emitter reversed):

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

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

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

Equivalent-circuit model representation:
Prefactor in $I_E$ expression is $I_S$: emitter current scales with $A_E$.

But, $I_B$ scales roughly as $A_C$:

- downward component scales as $A_C$
- upward component scales as $A_C - A_E \simeq A_C$

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

Reverse Gummel \((V_{EC} = 3 \, V)\):
Energy band diagram:
\[ \textbf{Cut-off regime} \ (V_{BE} < 0, \ V_{BC} < 0) \]

\( I_E \): hole generation in E, extraction into B
\( I_C \): hole generation in C, extraction into B

Minority carrier profiles \((\text{not to scale})\):
Current equations:

\[ I_E = \frac{I_S}{\beta_F} \]
\[ I_B = -\frac{I_S}{\beta_F} - \frac{I_S}{\beta_R} \]
\[ I_C = \frac{I_S}{\beta_R} \]

These are tiny leakage currents (\(\sim 10^{-12} \, A\))

Equivalent-circuit model representation:
• Energy band diagram

![Energy Band Diagram](image-url)
Saturation regime \((V_{BE} > 0, \ V_{BC} > 0)\)

\(I_C, I_E\): balance of electron injection from E/C into B  
\(I_B\): hole injection into E/C, recombination in E/C, respectively

Minority carrier profiles \((not \ to \ scale)\):
Current equations: 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 \(\beta_R\).

Equivalent circuit model representation (Non-Linear Hybrid-\(\pi\) Model):

![Equivalent Circuit Model](image)

Complete model has only three parameters: \(I_S\), \(\beta_F\), and \(\beta_R\).
Energy band diagram:

In saturation, collector and base flooded with excess minority carriers ⇒ takes lots of time to get transistor out of saturation.
Key conclusions

- In FAR, current gain $\beta_F$ maximized if $N_E \gg N_B$.

- $\beta_F$ hard to control precisely: if big enough (> 50), circuit techniques can compensate for variations in $\beta_F$.

- BJT design optimized for operation in forward-active regime ⇒ operation in inverse regime is poor: $\beta_R \ll \beta_F$.

- In saturation, BJT flooded with minority carriers ⇒ takes time to get BJT out of saturation.

- Hybrid-$\pi$ model: equivalent circuit description of BJT in all regimes:

\[
\begin{align*}
I_S & \left( \exp \frac{qV_{BC}}{kT} - 1 \right) \\
I_S & \left( \exp \frac{qV_{BE}}{kT} - 1 \right) \\
I_S & \left( \exp \frac{qV_{BE}}{kT} \cdot \exp \frac{qV_{BC}}{kT} \right)
\end{align*}
\]

- Only three parameters needed to describe behavior of BJT in four regimes: $I_S$, $\beta_F$, and $\beta_R$. 

Cite as: Jesús del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].