Lecture 35 - Bipolar Junction Transistor

(cont.)

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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**

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

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

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

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

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

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

\[ I_E: \text{ electron injection from C to B, collection into E} \]
\[ I_B: \text{ hole injection from B to C, recombination in C} \]

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

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

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

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

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, $\beta_R \simeq 0.1 - 5 \ll \beta_F$. 
Energy band diagram:
□ **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 \((not\ to\ scale)\):
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
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:

\[
\begin{align*}
I_C &= I_S \left( \exp \frac{qV_{BE}}{kT} - \exp \frac{qV_{BC}}{kT} \right) - \frac{I_S}{\beta_R} \left( \exp \frac{qV_{BC}}{kT} - 1 \right) \\
I_B &= \frac{I_S}{\beta_F} \left( \exp \frac{qV_{BE}}{kT} - 1 \right) + \frac{I_S}{\beta_R} \left( \exp \frac{qV_{BC}}{kT} - 1 \right) \\
I_E &= -\frac{I_S}{\beta_F} \left( \exp \frac{qV_{BE}}{kT} - 1 \right) - I_S \left( \exp \frac{qV_{BE}}{kT} - \exp \frac{qV_{BC}}{kT} \right)
\end{align*}
\]

\(I_C\) 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 diagram]

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 \(\implies\) 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 $\Rightarrow$ operation in inverse regime is poor: $\beta_R \ll \beta_F$.

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

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

![Hybrid-\pi model](image)

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