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)

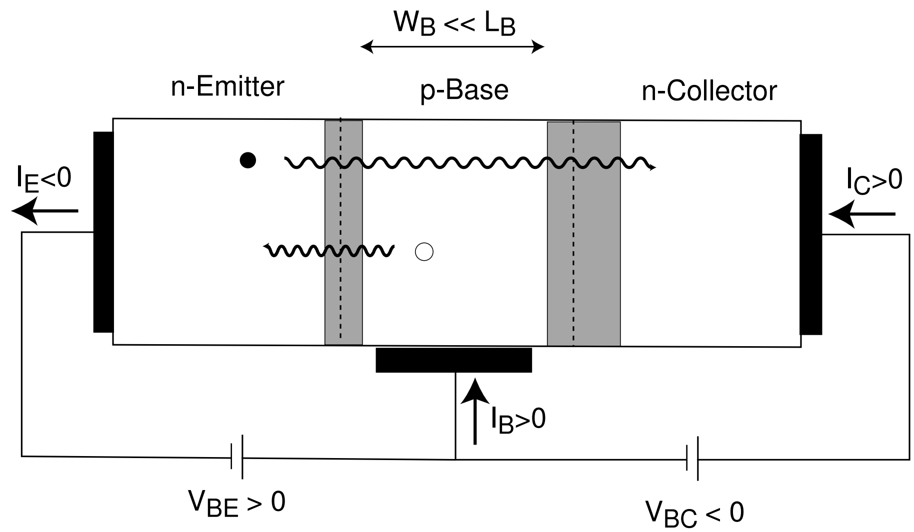
Key questions

- 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:



$$I_C = I_S \exp \frac{qV_{BE}}{kT}$$

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

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

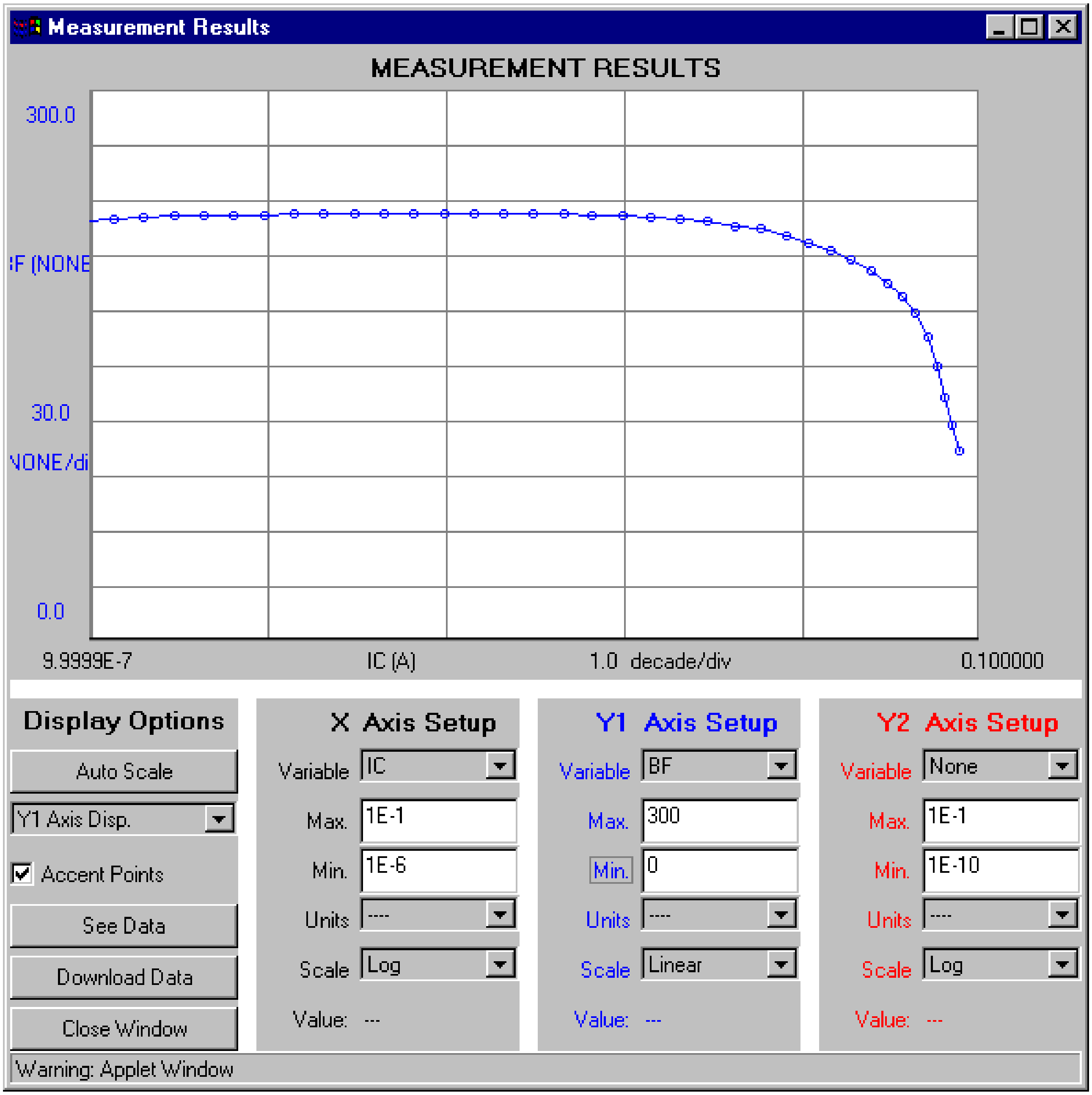
- *Current gain*

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

To maximize β_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 $D_B > D_E$

β_F hard to control $\Rightarrow$ if β_F is high enough (> 50), circuit techniques effectively compensate for this.


Measurement Results
MEASUREMENT RESULTS
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30.0
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9.9999E-7
IC (A)
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See Data
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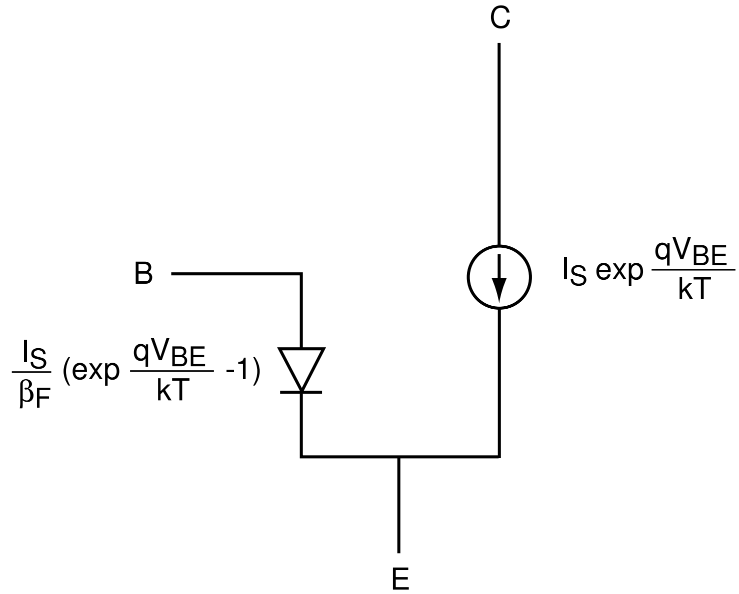
Close Window
X Axis Setup
Variable IC
Max. 1E-1
Min. 1E-6
Units ----
Scale Log
Value: ---
Y1 Axis Setup
Variable BF
Max. 300
Min. 0
Units ----
Scale Linear
Value: ---
Y2 Axis Setup
Variable None
Max. 1E-1
Min. 1E-10
Units ----
Scale Log
Value: ---
Warning: Applet Window

- *Equivalent circuit model*

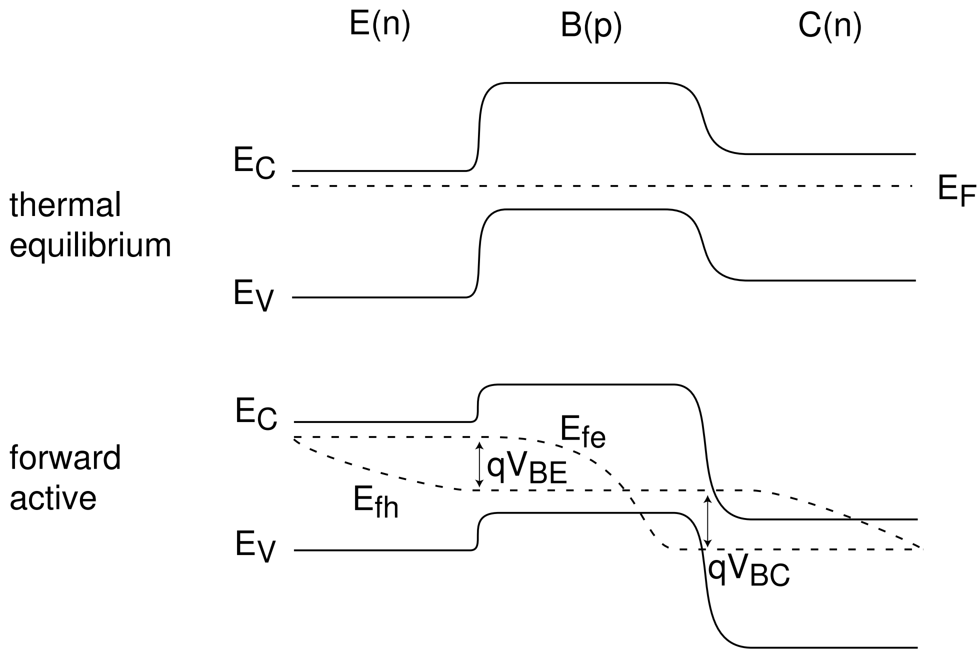


$$I_C = I_S \exp \frac{qV_{BE}}{kT}$$

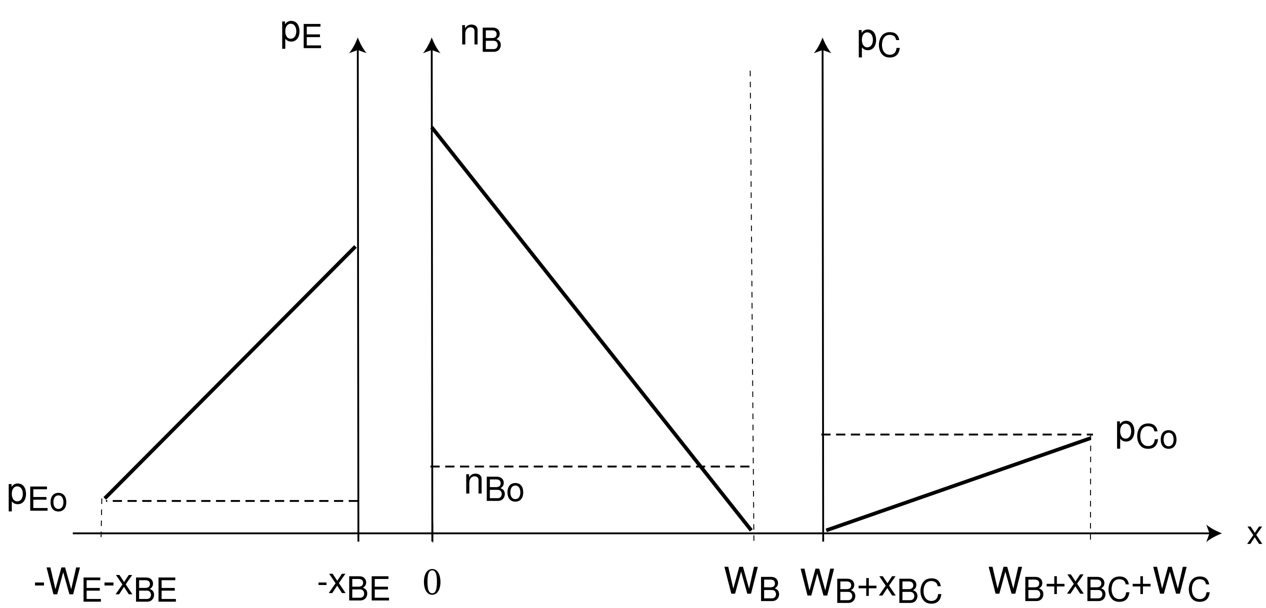
$$I_B = \frac{I_S}{\beta_F}(\exp \frac{qV_{BE}}{kT} - 1)$$

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

- Energy band diagram

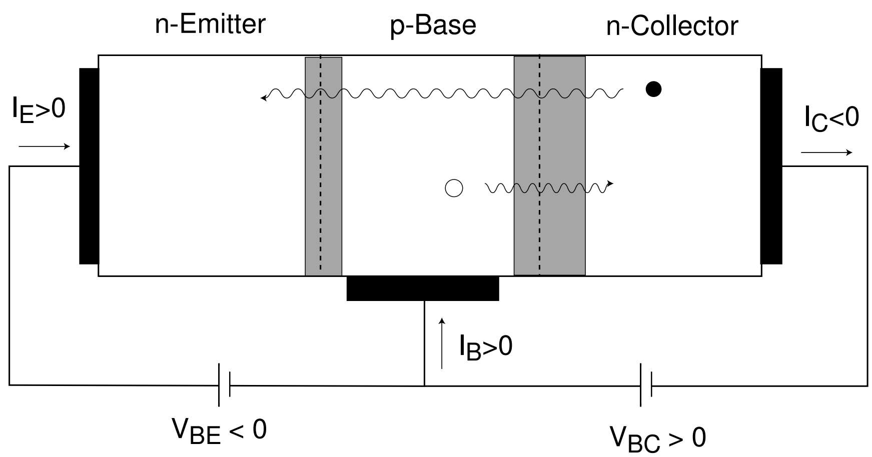


- Summary of minority carrier profiles *(not to scale)*

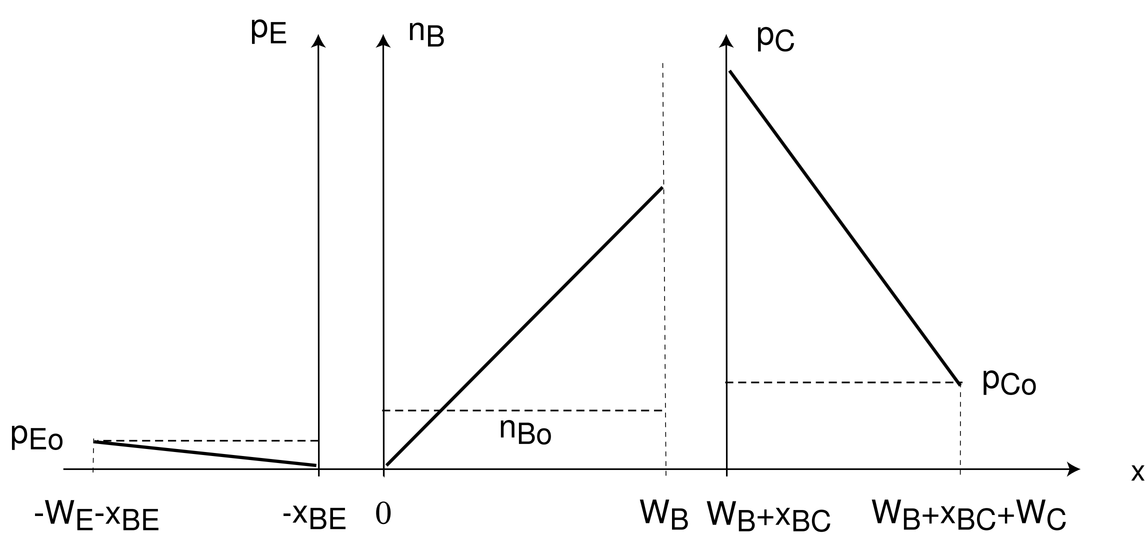


□ **Reverse regime** $(V_{BE} < 0,\ V_{BC} > 0)$

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



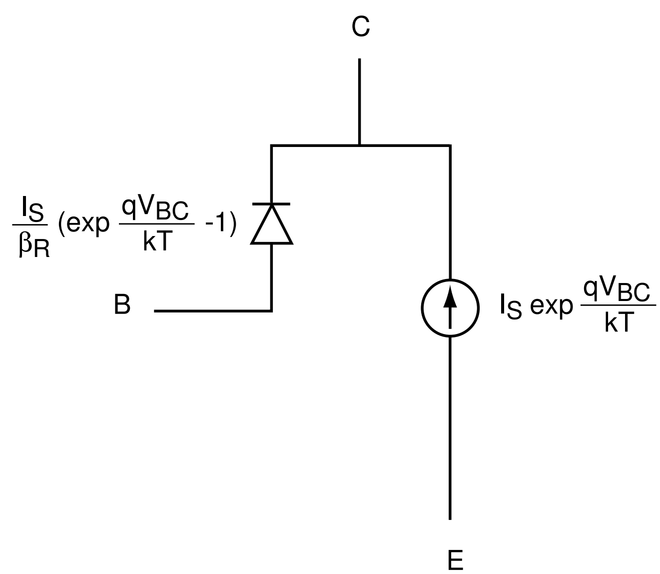
Minority carrier profiles *(not to scale)*:



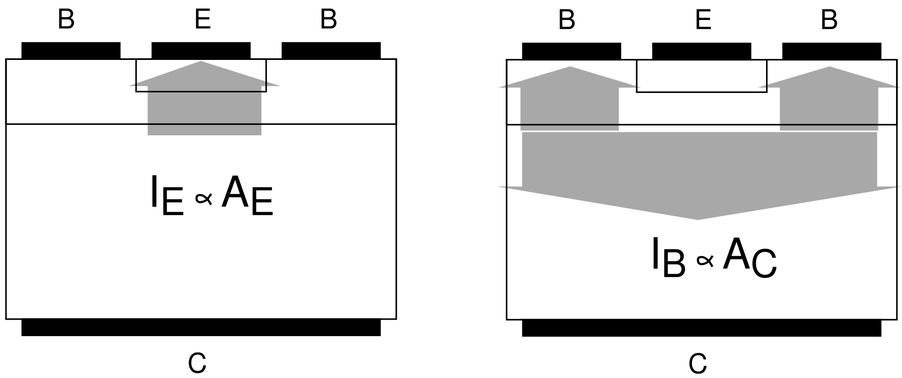
Current equations (just like FAR, but role of collector and emitter reversed):

$$
\begin{aligned}
I_E &= I_S \exp \frac{qV_{BC}}{kT} \\
I_B &= \frac{I_S}{\beta_R}(\exp \frac{qV_{BC}}{kT} - 1) \\
I_C &= -I_E - I_B = -I_S \exp \frac{qV_{BC}}{kT} - \frac{I_S}{\beta_R}(\exp \frac{qV_{BC}}{kT} - 1)
\end{aligned}
$$

Equivalent-circuit model representation:



Prefactor in I_E expression is I_S: emitter current scales with A_E.

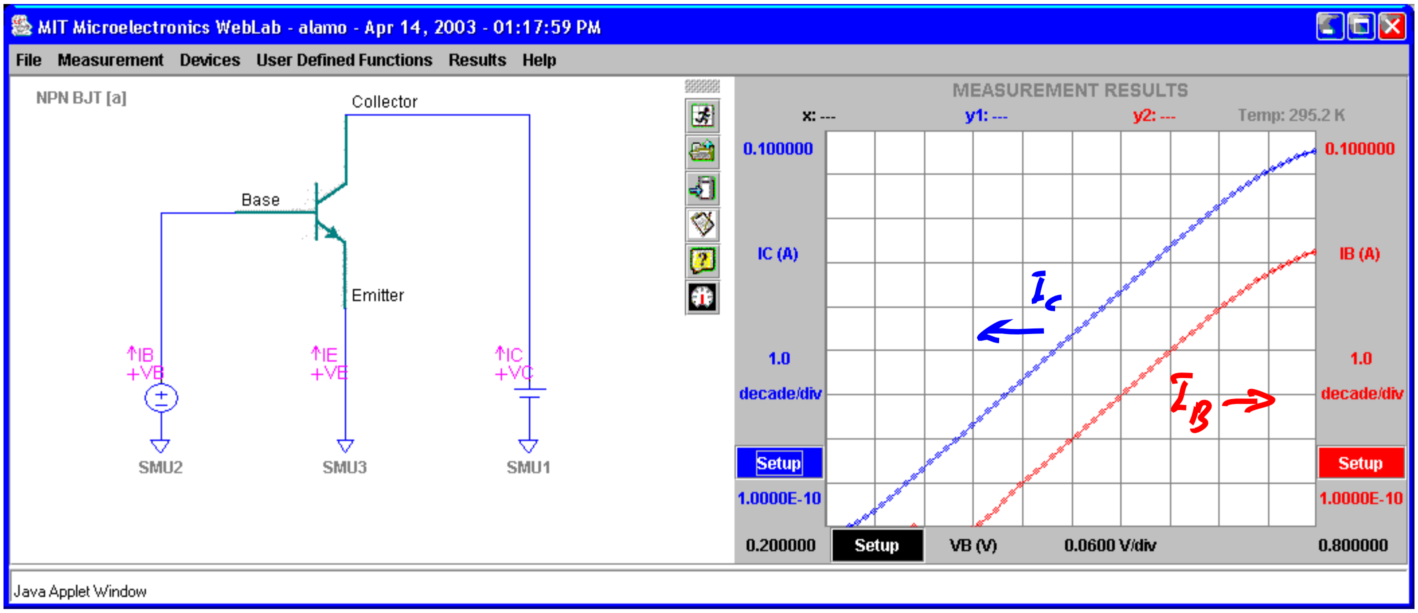


But, I_B scales roughly as A_C:

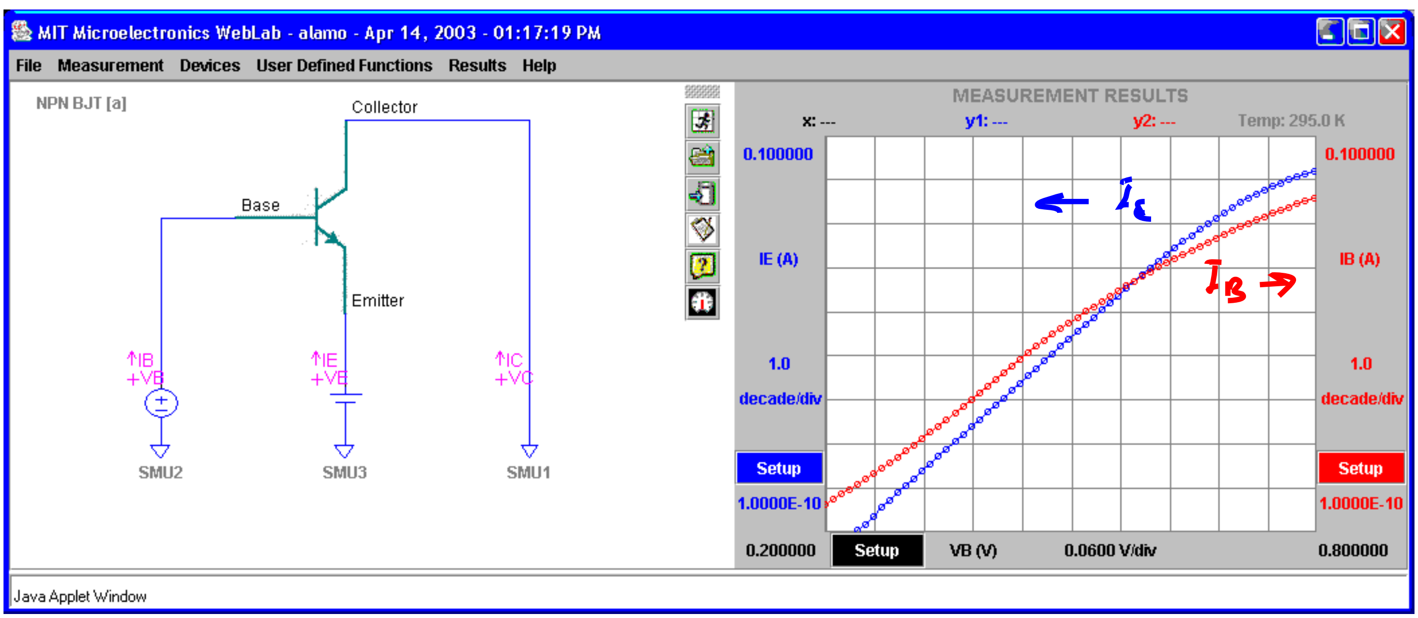
- downward component scales as A_C
- upward component scales as $A_C - A_E \simeq A_C$

Hence, $\beta_R \simeq 0.1 - 5 \ll \beta_F$.

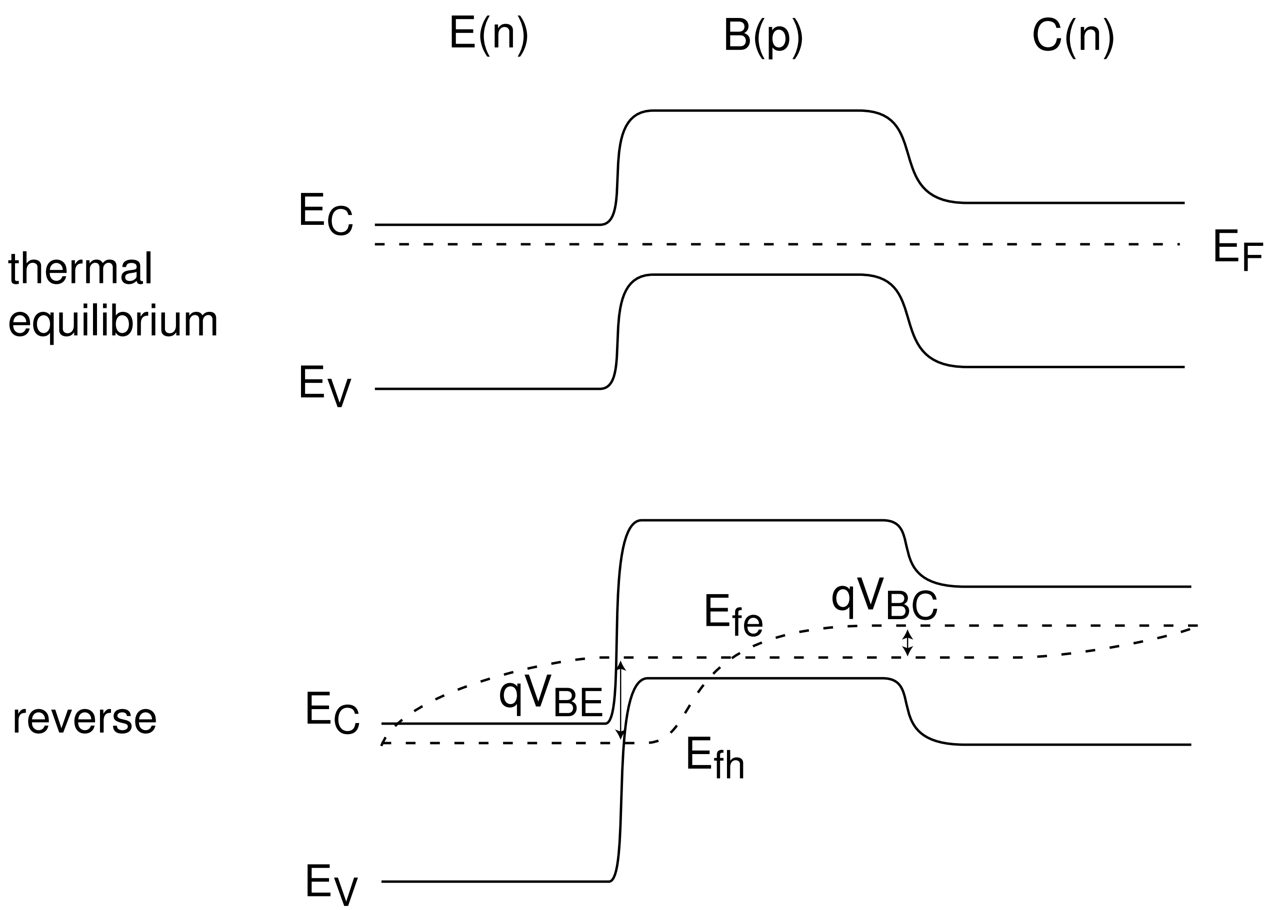
Forward-active Gummel plot ($V_{CE} = 3\ V$):



Reverse Gummel ($V_{EC} = 3\ V$):

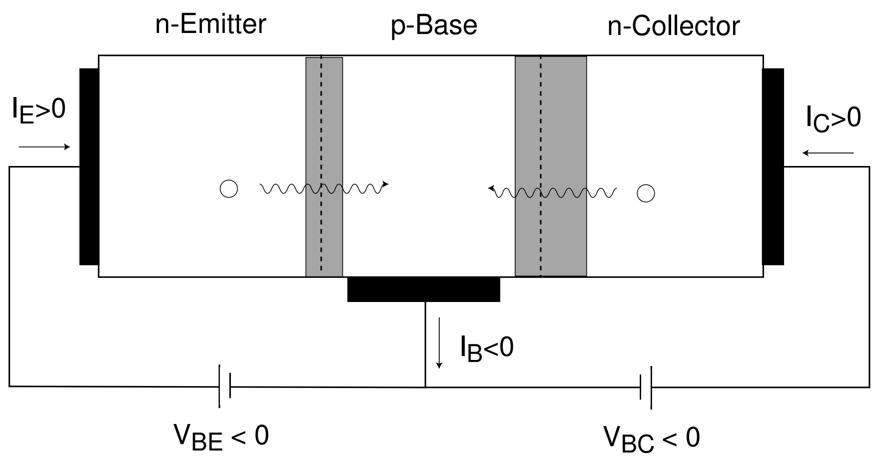


Energy band diagram:

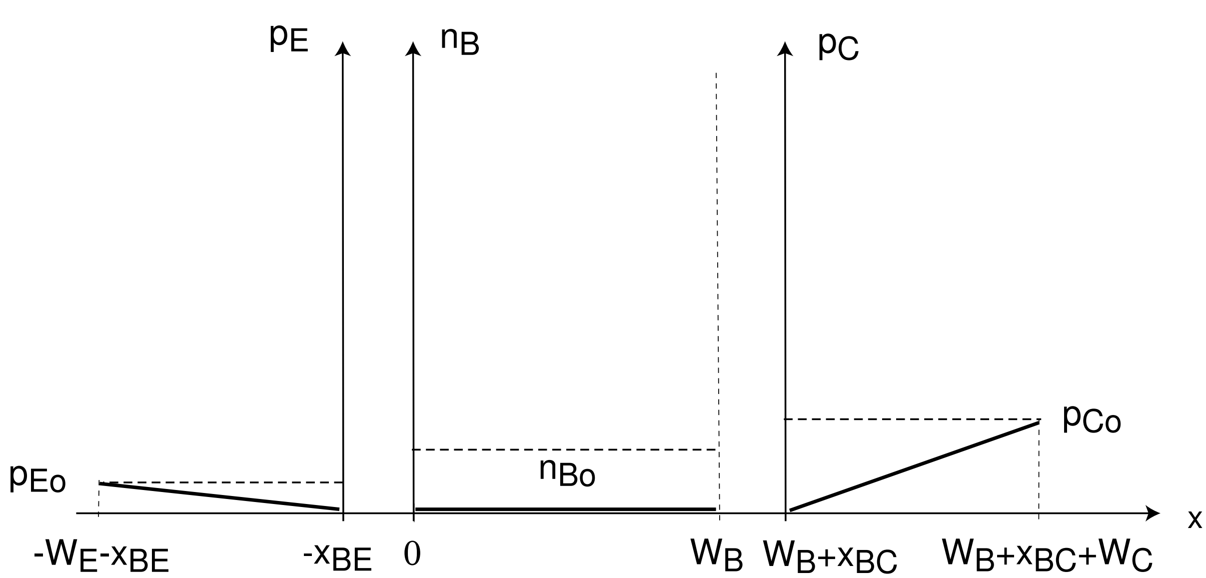


□ **Cut-off regime** $(V_{BE} < 0,\ V_{BC} < 0)$

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:

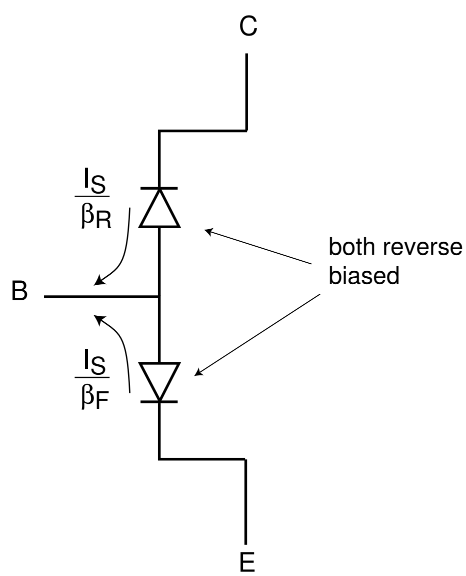
$$I_E = \frac{I_S}{\beta_F}$$

$$I_B = -\frac{I_S}{\beta_F} - \frac{I_S}{\beta_R}$$

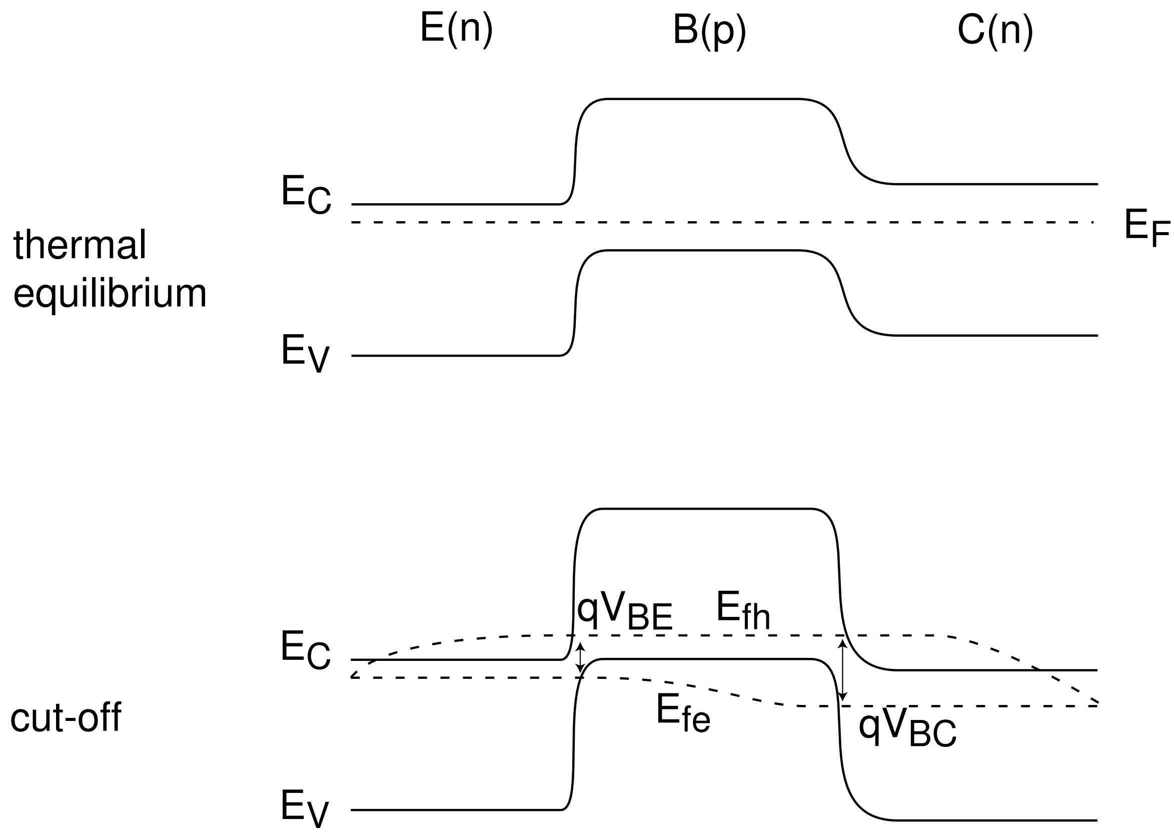
$$I_C = \frac{I_S}{\beta_R}$$

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

Equivalent-circuit model representation:



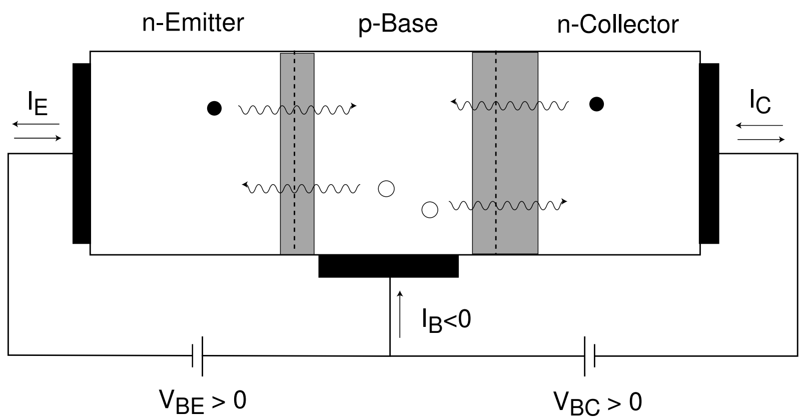
• Energy band diagram



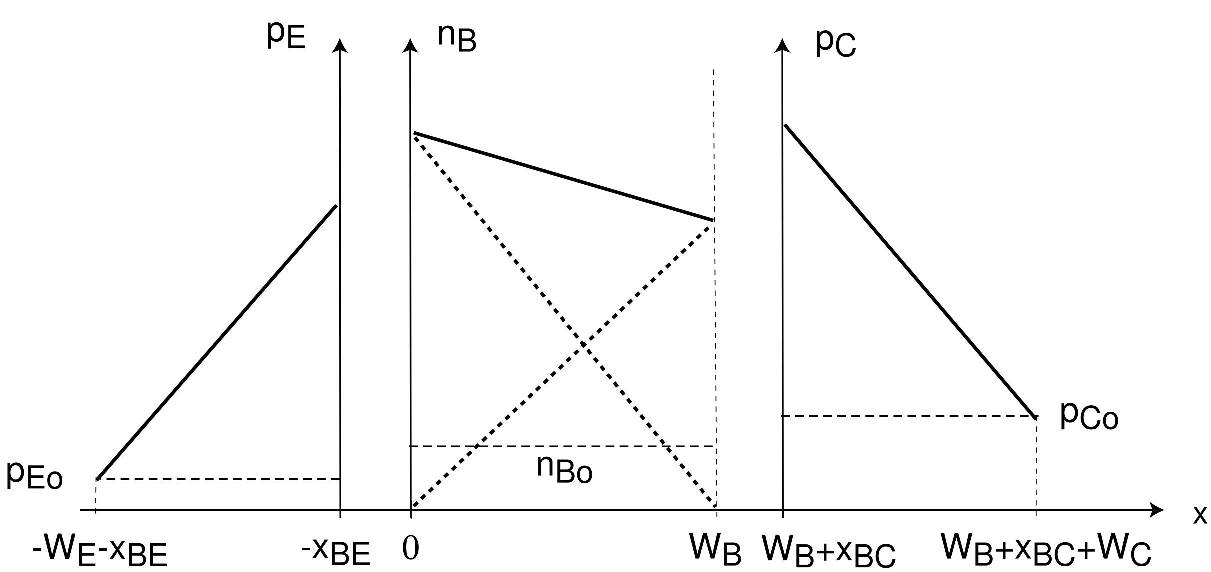
□ **Saturation regime** ($V_{BE} > 0,\ V_{BC} > 0$)

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)*:

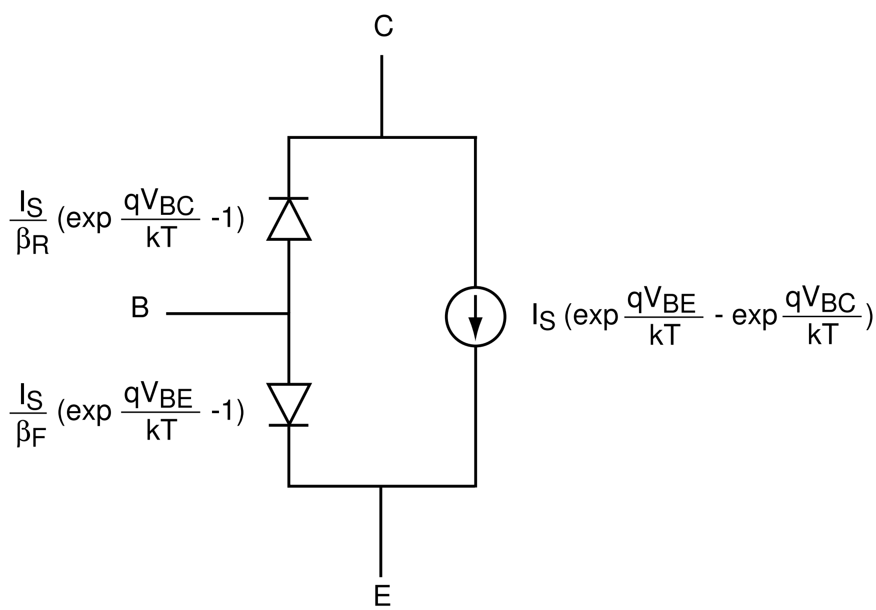


Current equations: superposition of forward active + reverse:

$$
\begin{aligned}
I_C &= I_S(\exp\frac{qV_{BE}}{kT} - \exp\frac{qV_{BC}}{kT}) - \frac{I_S}{\beta_R}(\exp\frac{qV_{BC}}{kT} - 1)\\
I_B &= \frac{I_S}{\beta_F}(\exp\frac{qV_{BE}}{kT} - 1) + \frac{I_S}{\beta_R}(\exp\frac{qV_{BC}}{kT} - 1)\\
I_E &= -\frac{I_S}{\beta_F}(\exp\frac{qV_{BE}}{kT} - 1) - I_S(\exp\frac{qV_{BE}}{kT} - \exp\frac{qV_{BC}}{kT})
\end{aligned}
$$

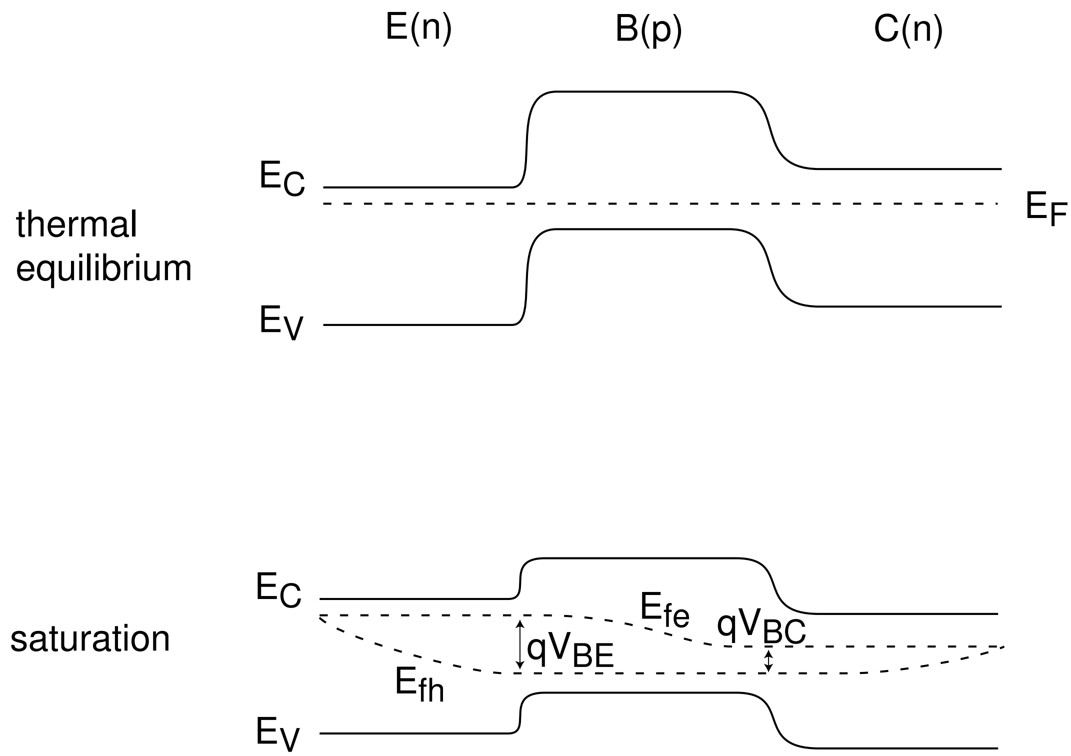
I_C and I_E can have either sign, depending on relative magnitude of V_{BE} and V_{BC} and β_F and β_R.

Equivalent circuit model representation (*Non-Linear Hybrid-π Model*):



Complete model has only three parameters: I_S, β_F, and β_R.

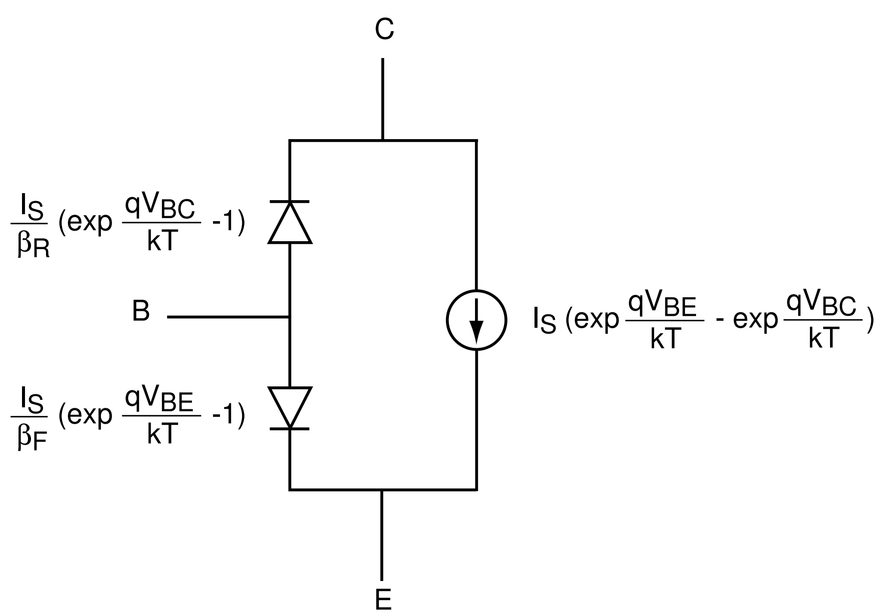
Energy band diagram:



In saturation, collector and base flooded with excess minority carriers $\Rightarrow$ takes lots of time to get transistor out of saturation.

Key conclusions

- In FAR, current gain β_F maximized if $N_E \gg N_B$.
- β_F hard to control precisely: if big enough (> 50), circuit techniques can compensate for variations in β_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-π model: equivalent circuit description of BJT in all regimes:



- Only three parameters needed to describe behavior of BJT in four regimes: I_S, β_F, and β_R.