Lecture 18

The Bipolar Junction Transistor (II)

Regimes of Operation

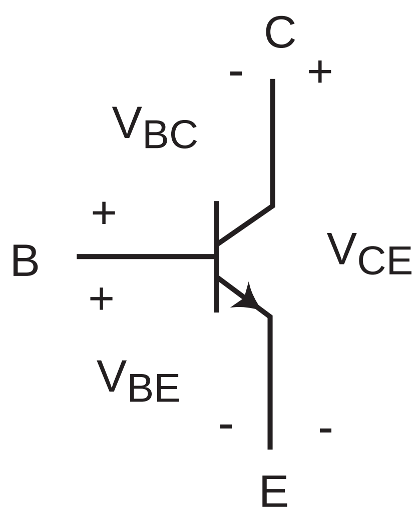
Outline

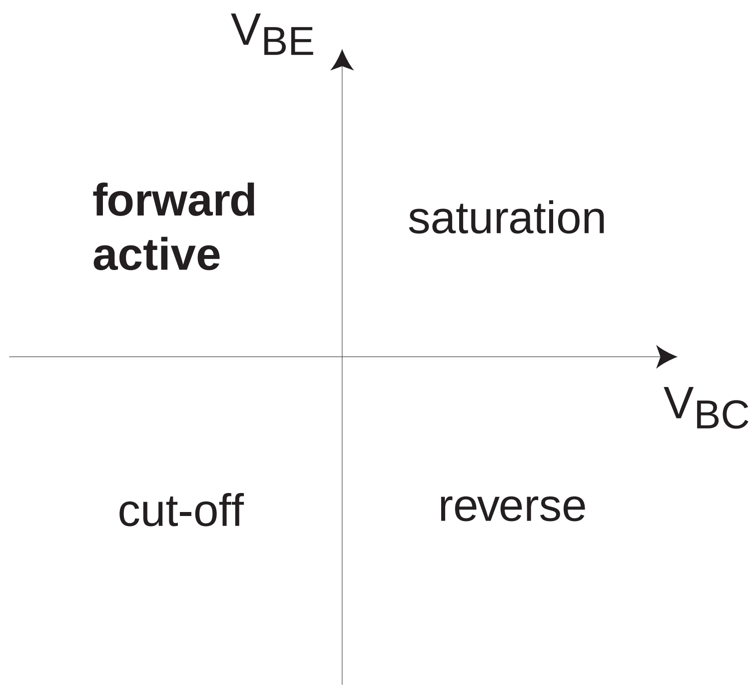
- Regimes of operation
- Large-signal equivalent circuit model
- Output characteristics

Reading Assignment:
Howe and Sodini; Chapter 7, Sections 7.3, 7.4 & 7.5

Announcement:
Quiz #2: April 25, 7:30-9:30 PM at Walker. Calculator Required. Open book.

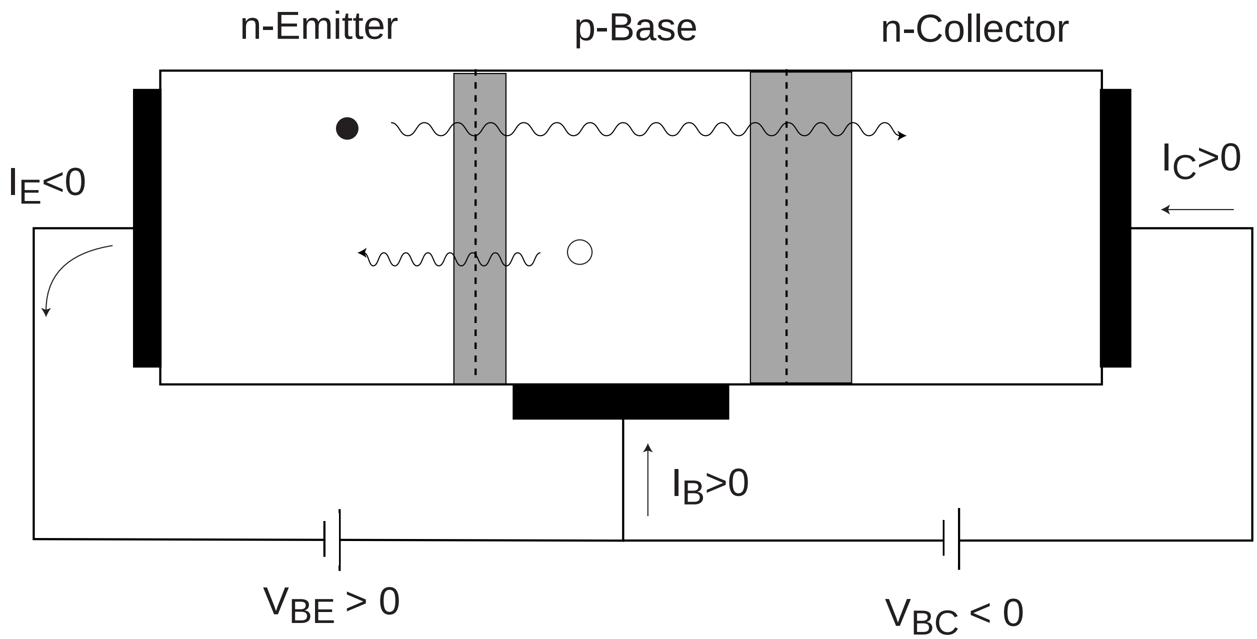
1. BJT: Regions of Operation



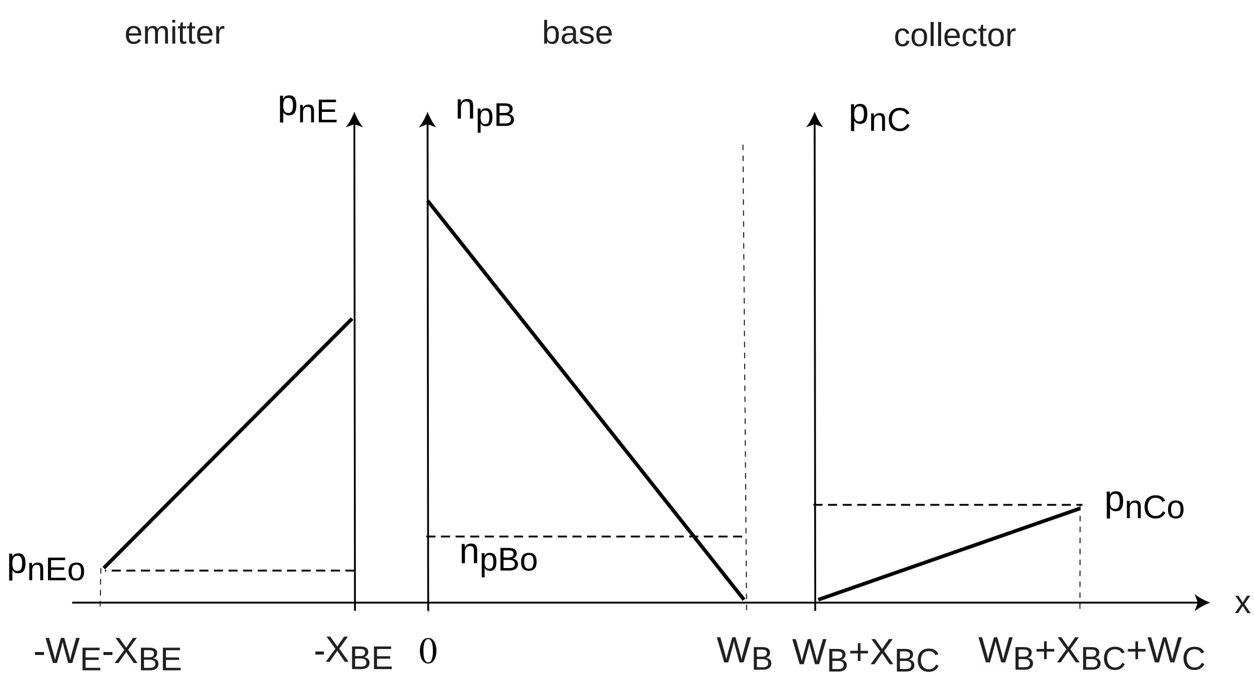


- ***Forward active***: device has high voltage gain and high β;
- ***Reverse active***: poor β; **not useful**;
- ***Cut-off***: negligible current: nearly an open circuit;
- ***Saturation***: device is flooded with minority carriers;
  - ⇒ takes time to get out of saturation

Forward-Active Regime: $V_{BE} > 0$, $V_{BC} < 0$



Minority Carrier profiles (***not to scale***):



Forward-Active Regime: $V_{BE} > 0$, $V_{BC} < 0$

- ***Emitter*** injects **electrons** into ***base***, ***collector*** extracts (collects) **electrons** from ***base***:

$$I_C = I_S e^{\left[\frac{V_{BE}}{V_{th}}\right]}; \qquad I_S = \frac{qA_E n_{pBo} D_n}{W_B}$$

- ***Base*** injects **holes** into ***emitter***, **holes** recombine at ***emitter*** contact:

$$I_B = \frac{I_S}{\beta_F}\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1\right]; \qquad \frac{I_S}{\beta_F} = \frac{qA_E p_{nEo} D_p}{W_E}$$

- ***Emitter*** current:

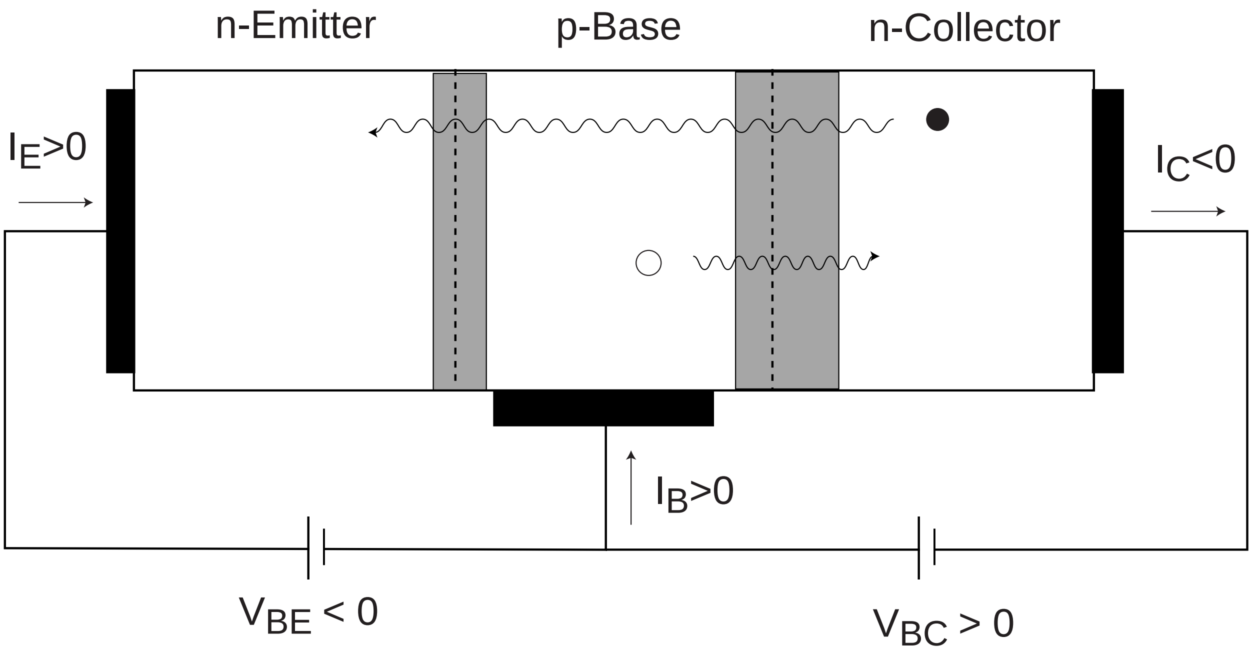
$$I_E = -I_C - I_B = -I_S e^{\left[\frac{V_{BE}}{V_{th}}\right]} - \frac{I_S}{\beta_F}\left(e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1\right)$$

- State-of-the-art IC BJT's today: $I_S \approx 0.1 - 1$ fA
- $\beta_F \approx 50 - 300$.

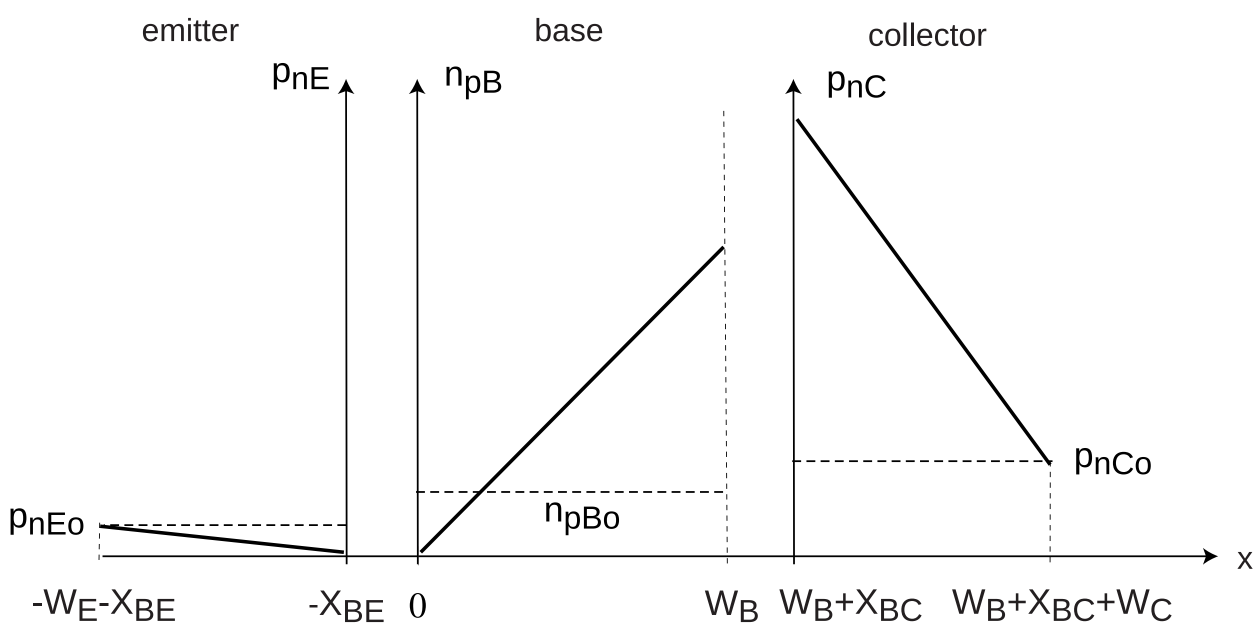
- β_F hard to control tightly: $\Rightarrow$ circuit design techniques required to be insensitive to variations in β_F.

$$\beta_F = \frac{I_C}{I_B} = \frac{n_{pBo} \bullet \frac{D_n}{W_B}}{p_{nEo} \bullet \frac{D_p}{W_E}} = \frac{N_{dE} D_n W_E}{N_{aB} D_p W_B}$$

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



Minority Carrier Profiles (***not to scale***):



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

- ***Collector*** injects electrons into ***base***, ***emitter*** extracts (collects) electrons from ***base***:

$$I_E = I_S e^{\left[\frac{V_{BC}}{V_{th}}\right]}; \qquad I_S = \frac{qA_C n_{pBo} D_n}{W_B}$$

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

$$I_B = \frac{I_S}{\beta_R}\left[e^{\left(\frac{V_{BC}}{V_{th}}\right)} - 1\right]; \qquad \frac{I_S}{\beta_R} = \frac{qA_C p_{nCo} D_p}{W_C}$$

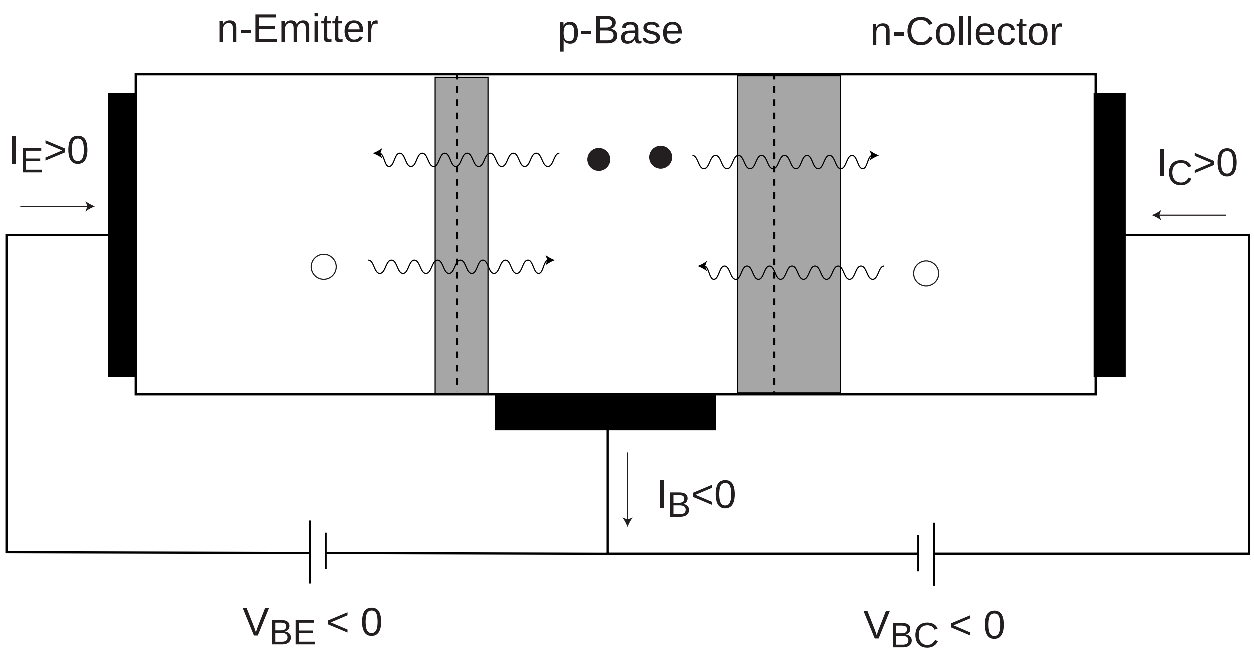
- ***Collector*** current:

$$I_C = -I_E - I_B = -I_S e^{\left[\frac{V_{BC}}{V_{th}}\right]} - \frac{I_S}{\beta_R}\left(e^{\left[\frac{V_{BC}}{V_{th}}\right]} - 1\right)$$

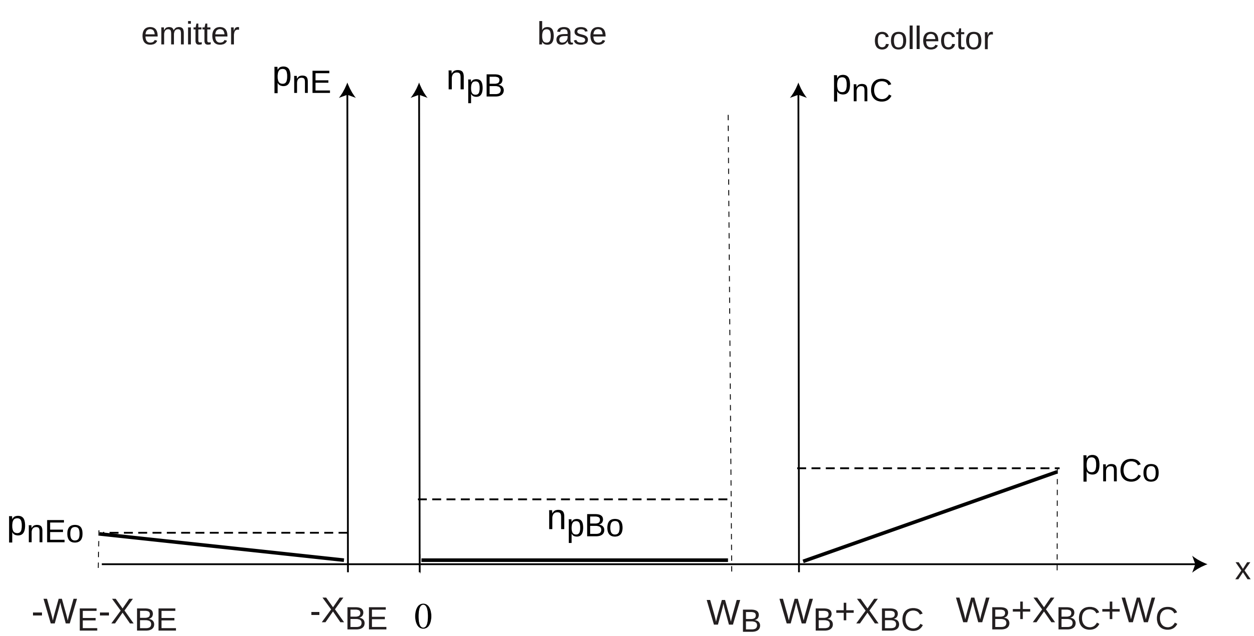
- Typically, $\beta_R \approx 0.1 - 5 << \beta_F$.

$$\beta_R = \frac{I_E}{I_B} = \frac{n_{pBo} \bullet \frac{D_n}{W_B}}{p_{nCo} \bullet \frac{D_p}{W_C}} = \frac{N_{dC} D_n W_C}{N_{aB} D_p W_B}$$

Cut-Off Regime: $V_{BE} < 0$, $V_{BC} < 0$



Minority Carrier Profiles (***not to scale***):



Cut-Off Regime: $V_{BE} < 0$, $V_{BC} < 0$

- ***Base*** extracts holes from ***emitter***:

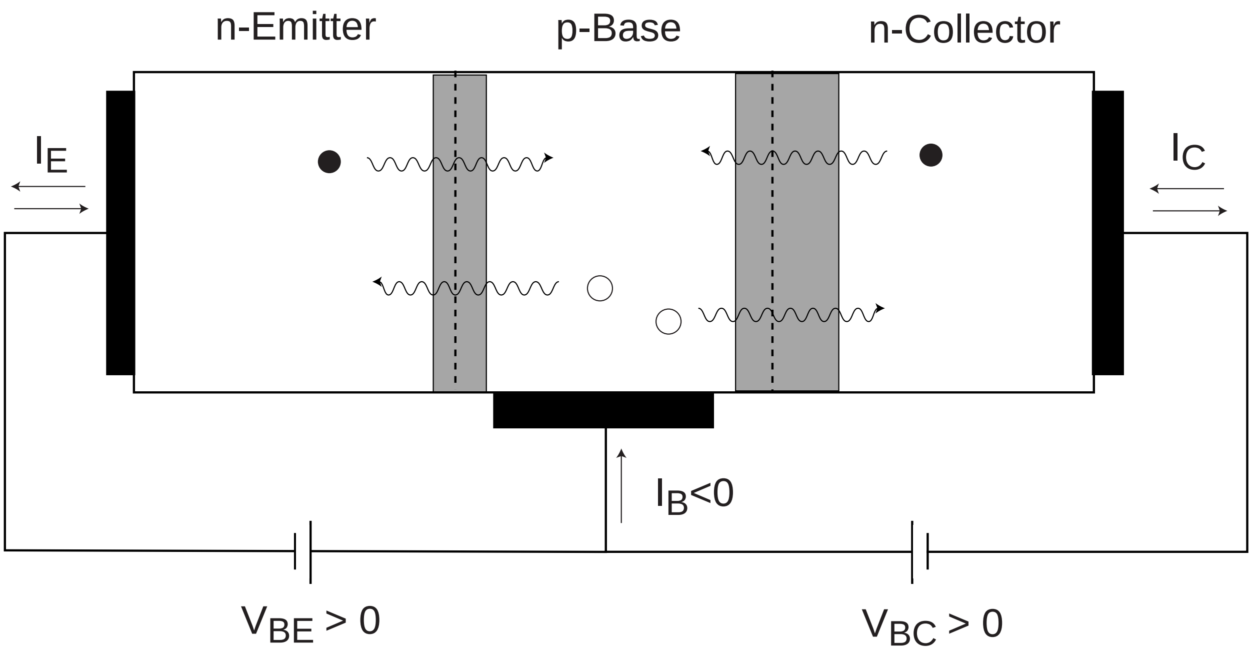
$$I_{B1} = -\frac{I_S}{\beta_F} = -I_E$$

- ***Base*** extracts holes from ***collector***:

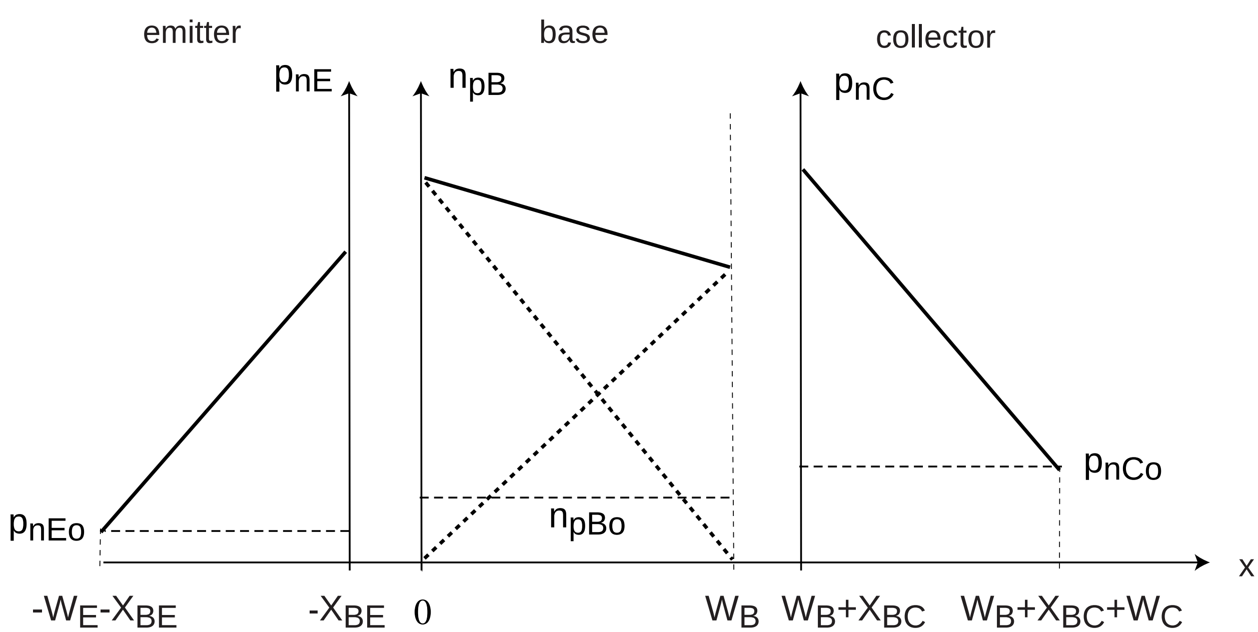
$$I_{B2} = -\frac{I_S}{\beta_R} = -I_C$$

- These are tiny leakage currents ($\approx 10^{-15}$ A).

Saturation Regime: $V_{BE} > 0$, $V_{BC} > 0$



Minority Carrier profiles (***not to scale***):



Saturation Regime: $V_{BE} > 0, V_{BC} > 0$

Saturation is superposition of forward active + reverse active:

$$I_C = I_S\left(e^{\left[\frac{V_{BE}}{V_{th}}\right]} - e^{\left[\frac{V_{BC}}{V_{th}}\right]}\right) - \frac{I_S}{\beta_R}\left(e^{\left[\frac{V_{BC}}{V_{th}}\right]} - 1\right)$$

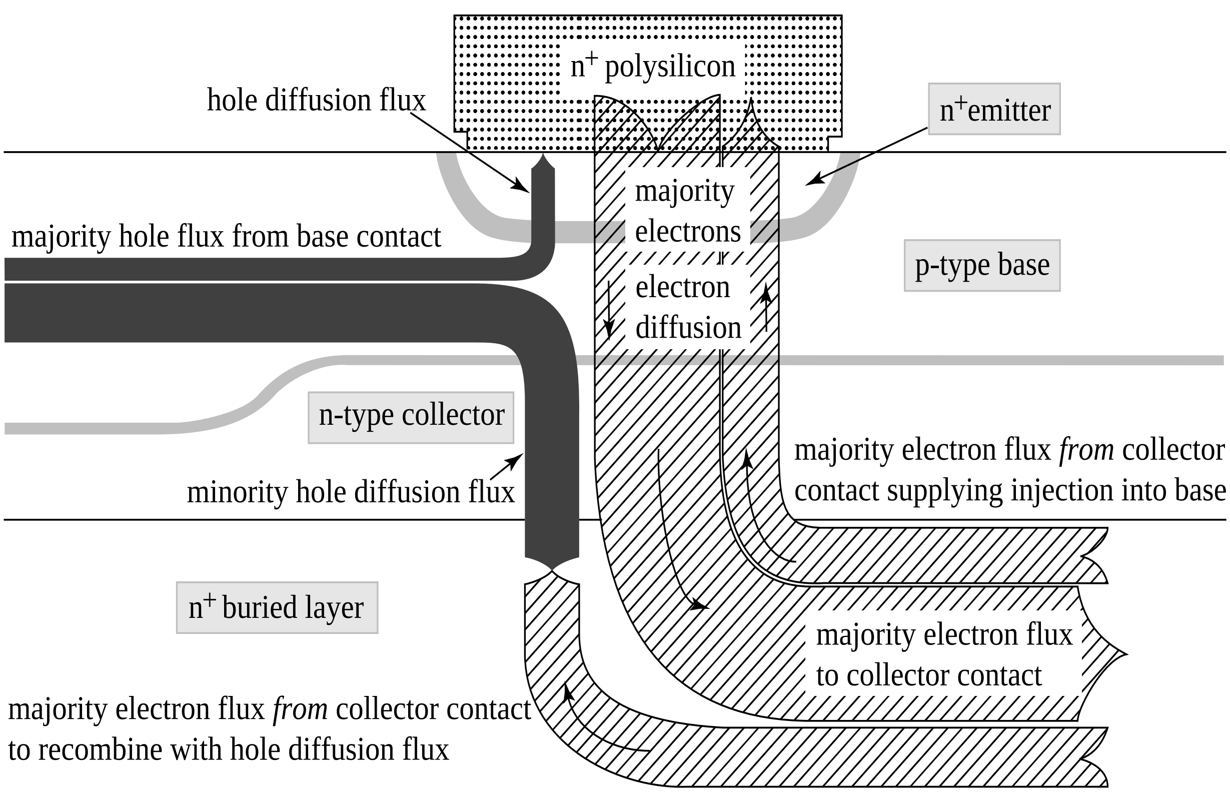
$$I_B = \frac{I_S}{\beta_F}\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1\right] + \frac{I_S}{\beta_R}\left[e^{\left[\frac{V_{BC}}{V_{th}}\right]} - 1\right]$$

$$I_E = -I_S\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - e^{\left[\frac{V_{BC}}{V_{th}}\right]}\right] - \frac{I_S}{\beta_F}\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1\right]$$

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

Saturation - The Flux Picture

- Both junctions are injecting and collecting.
- Electrons injected from emitter into base are collected by the collector as in Forward Active case.
- Electrons injected from collector into the base are collected by the emitter as in Reverse Active case.
- Holes injected into emitter recombine at ohmic contact as in Forward Active case.
- Holes injected into collector recombine with electrons in the n^+ buried layer



2. Large-signal equivalent circuit model

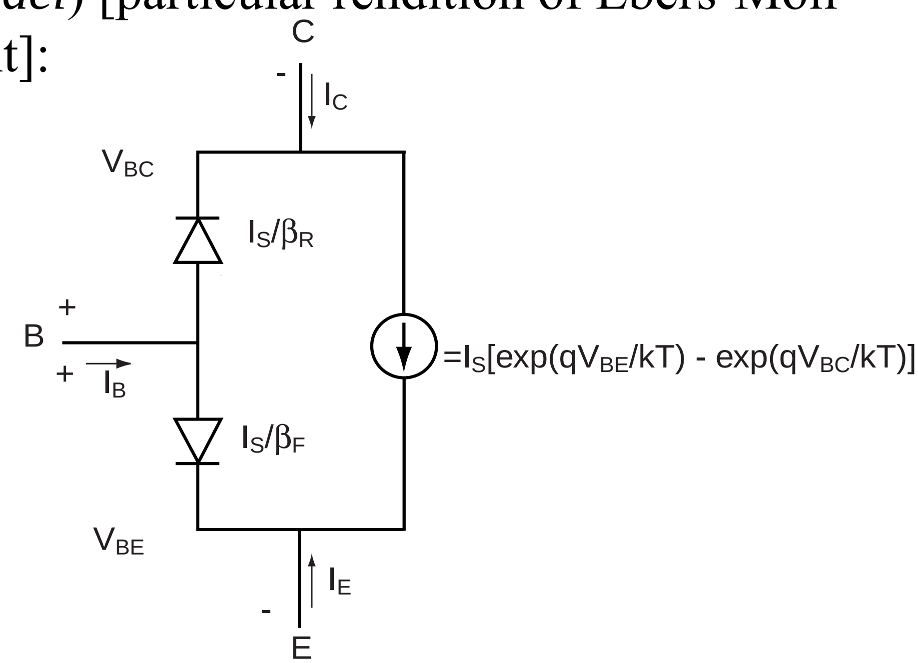
System of equations that describes BJT operation:

$$I_C = I_S\left(e^{\left[\frac{V_{BE}}{V_{th}}\right]} - e^{\left[\frac{V_{BC}}{V_{th}}\right]}\right) - \frac{I_S}{\beta_R}\left(e^{\left[\frac{V_{BC}}{V_{th}}\right]} - 1\right)$$

$$I_B = \frac{I_S}{\beta_F}\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1\right] + \frac{I_S}{\beta_R}\left[e^{\left[\frac{V_{BC}}{V_{th}}\right]} - 1\right]$$

$$I_E = -I_S\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - e^{\left[\frac{V_{BC}}{V_{th}}\right]}\right] - \frac{I_S}{\beta_F}\left[e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1\right]$$

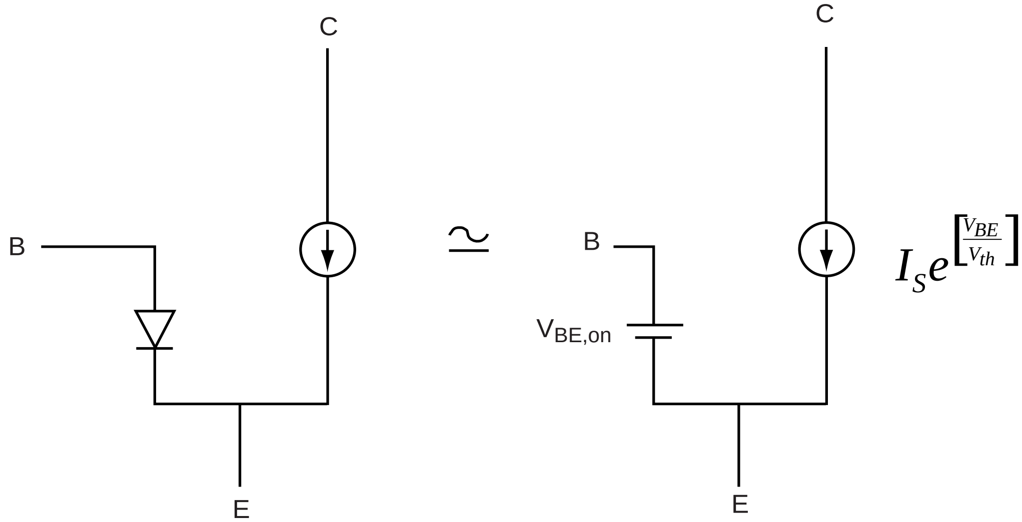
Equivalent-circuit model representation (*non-linear hybrid-π model*) [particular rendition of Ebers-Moll model in text]:



Three parameters in this model: I_S, β_F, and β_R.

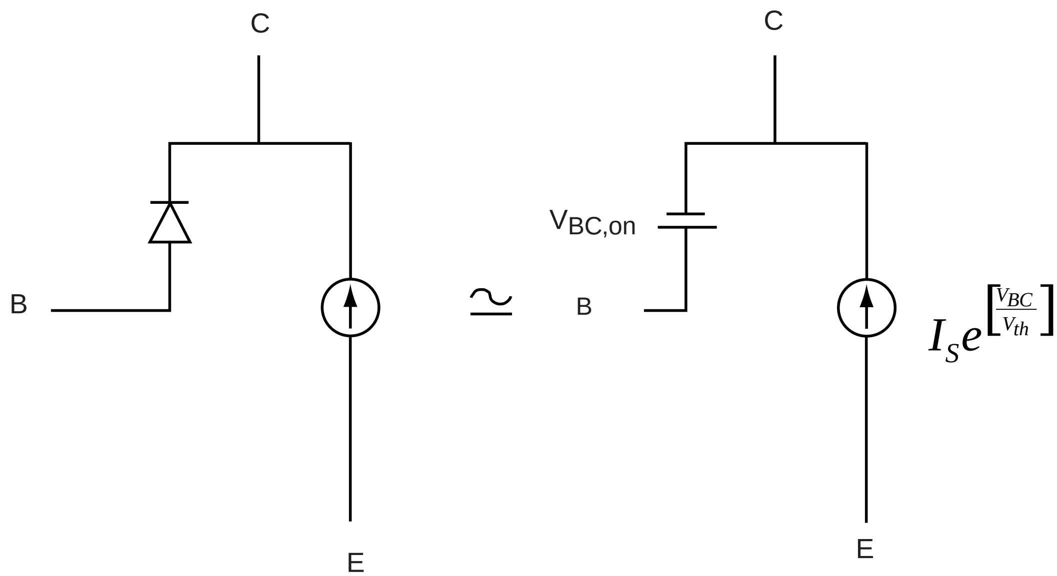
Simplification of equivalent circuit model:

- **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.

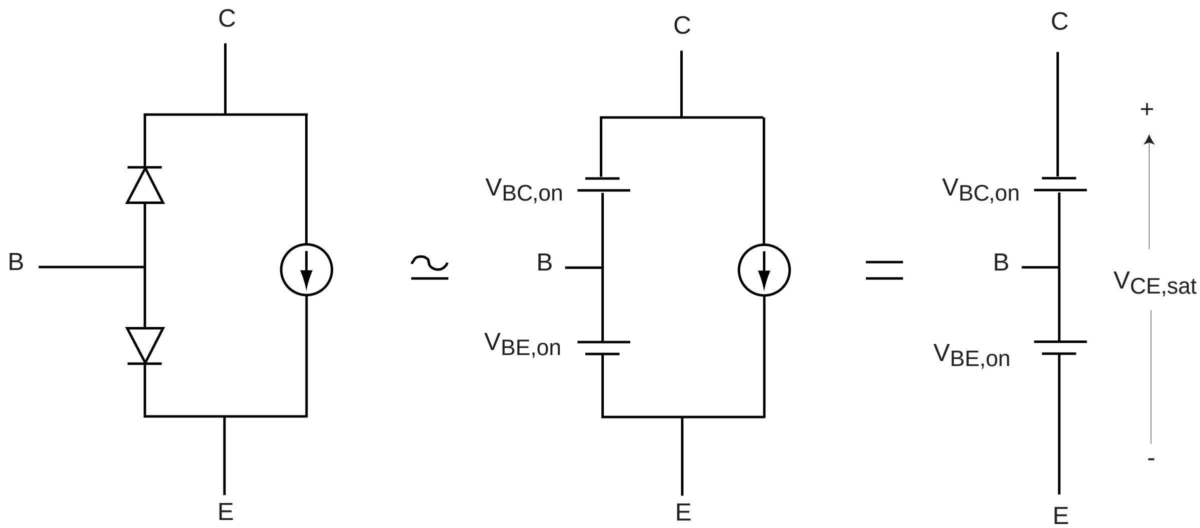
- **Reverse-active regime:** $V_{BE} < 0$, $V_{BC} > 0$



For today's technology: $V_{BC,on} \approx 0.6$ V

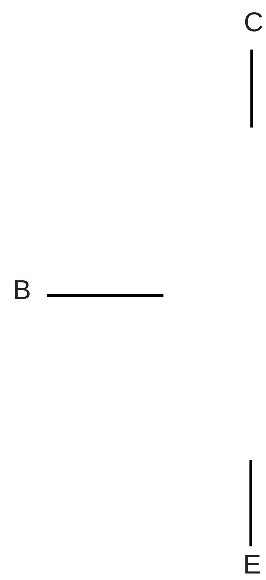
Simplification of equivalent circuit model:

- **Saturation regime:** $V_{BE} > 0$, $V_{BC} > 0$



For today's technology: $V_{CE,sat} \approx 0.1$ V. I_C and I_B depend on outside circuit.

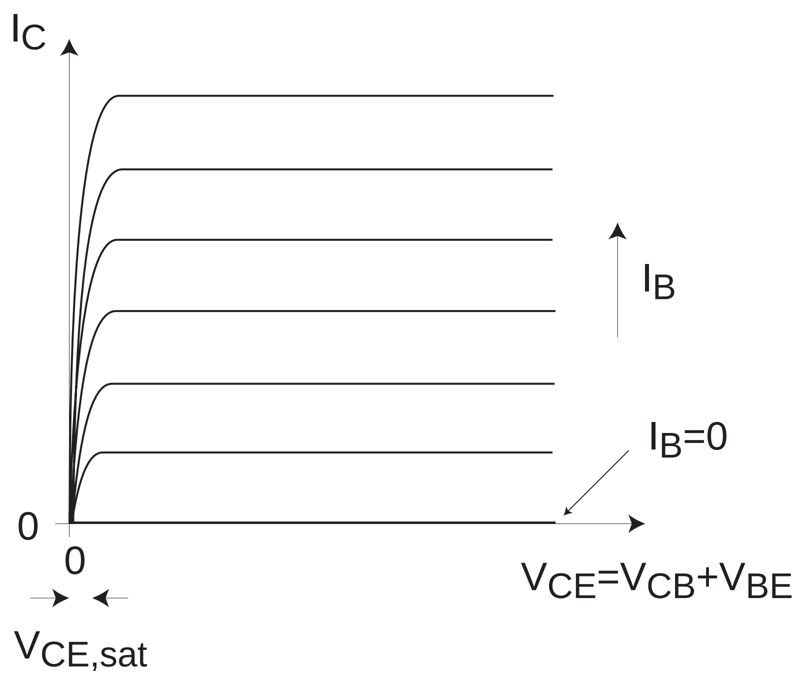
- **Cut-off regime:** $V_{BE} < 0$, $V_{BC} < 0$



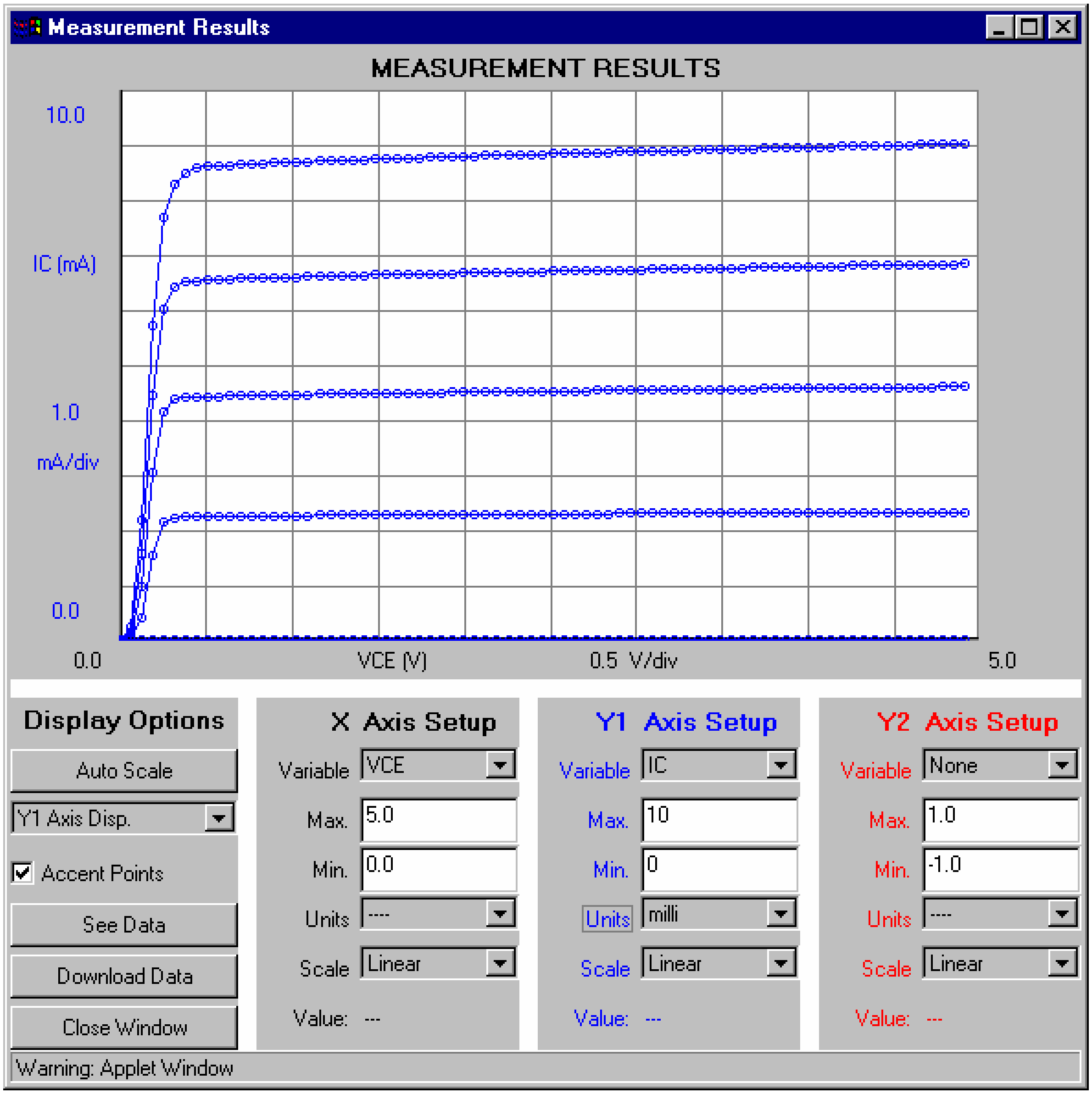
Only negligible leakage currents.

3. Output Characteristics

Common-emitter output characteristics:



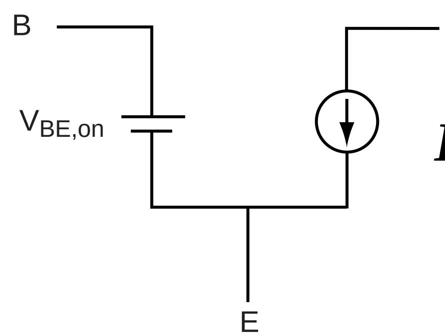
Common-Emitter Output Characteristics



What did we learn today?

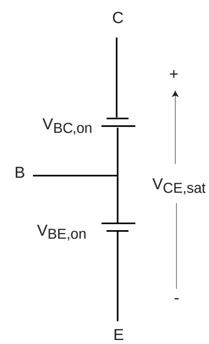
Summary of Key Concepts

- ***Forward-active regime***: For bias calculations:



$$I_S e^{\left[\frac{V_{BE}}{V_{th}}\right]}$$

- ***Saturation Regime***: For bias calculations:



- ***Cut-off Regime***: For bias calculations: