Lecture 17

The Bipolar Junction Transistor (II)

Regimes of Operation

Outline

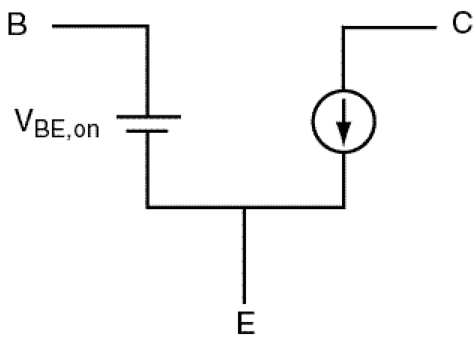
- Regimes of operation
- Large-signal equivalent circuit model
- Output characteristics

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

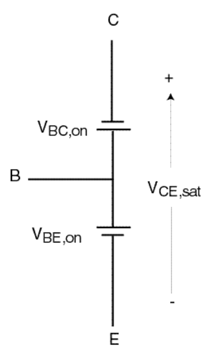
Announcement:
Quiz #2: November 15, 7:30-9:30 PM at Walker.
Calculator Required. Open book.
Quiz Review: Monday, November 13, 7:00PM, _____

Summary of Key Concepts

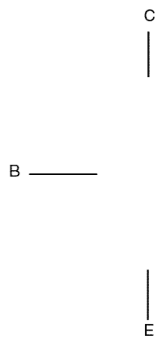
- ***Forward-active regime***: most useful, device has gain and isolation. For bias calculations:



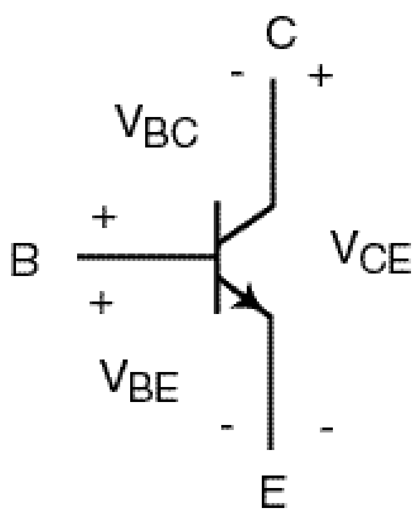
- ***Saturation Regime***: device flooded with minority carriers. Not useful. For bias calculations:

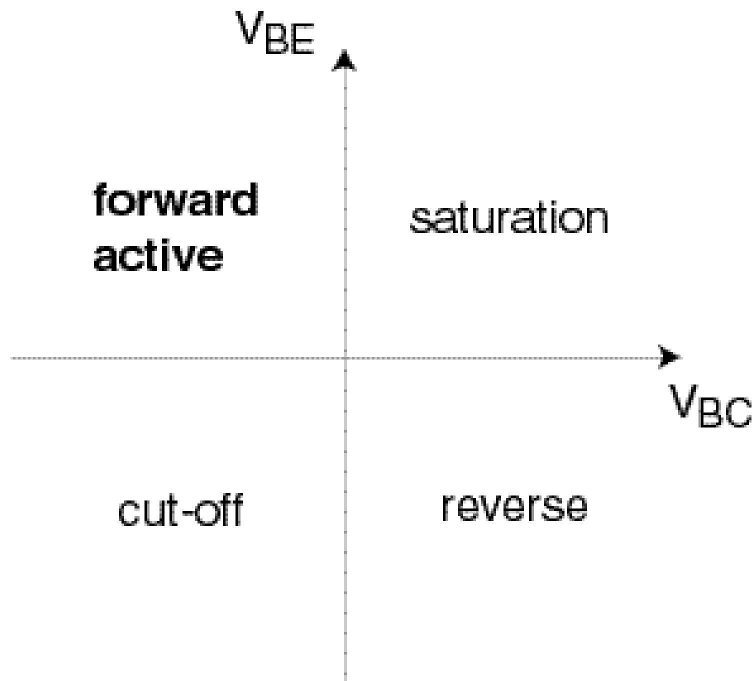


- ***Cut-off Regime***: device open. Useful. For bias calculations:



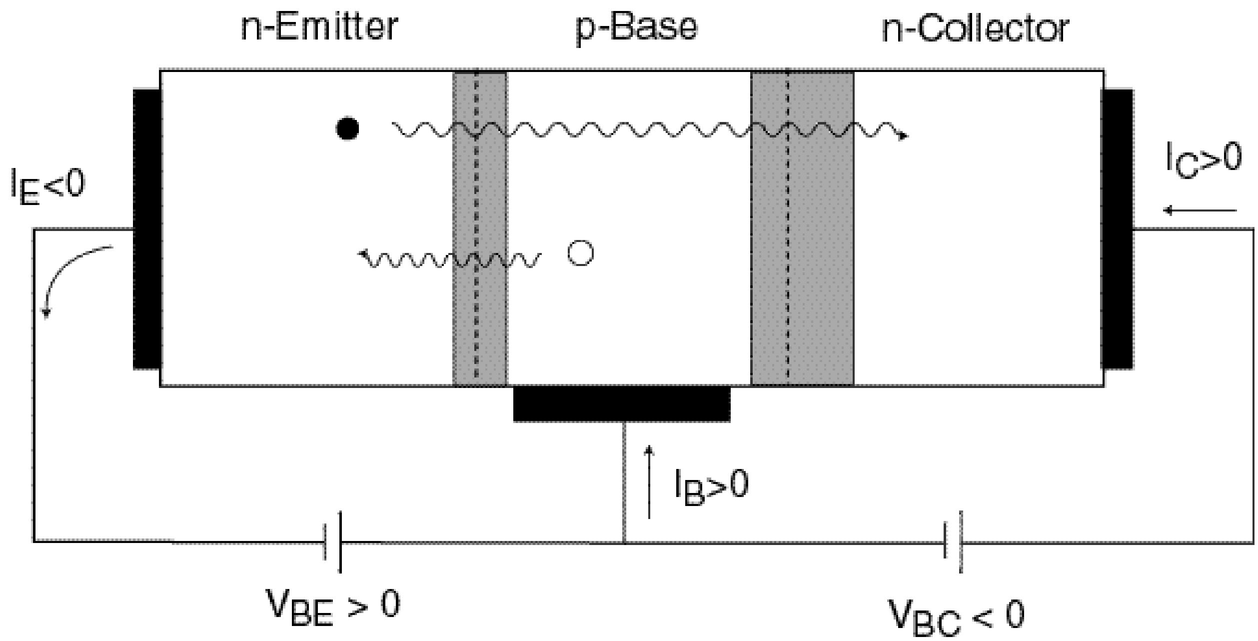
1. BJT: Regimes of Operation



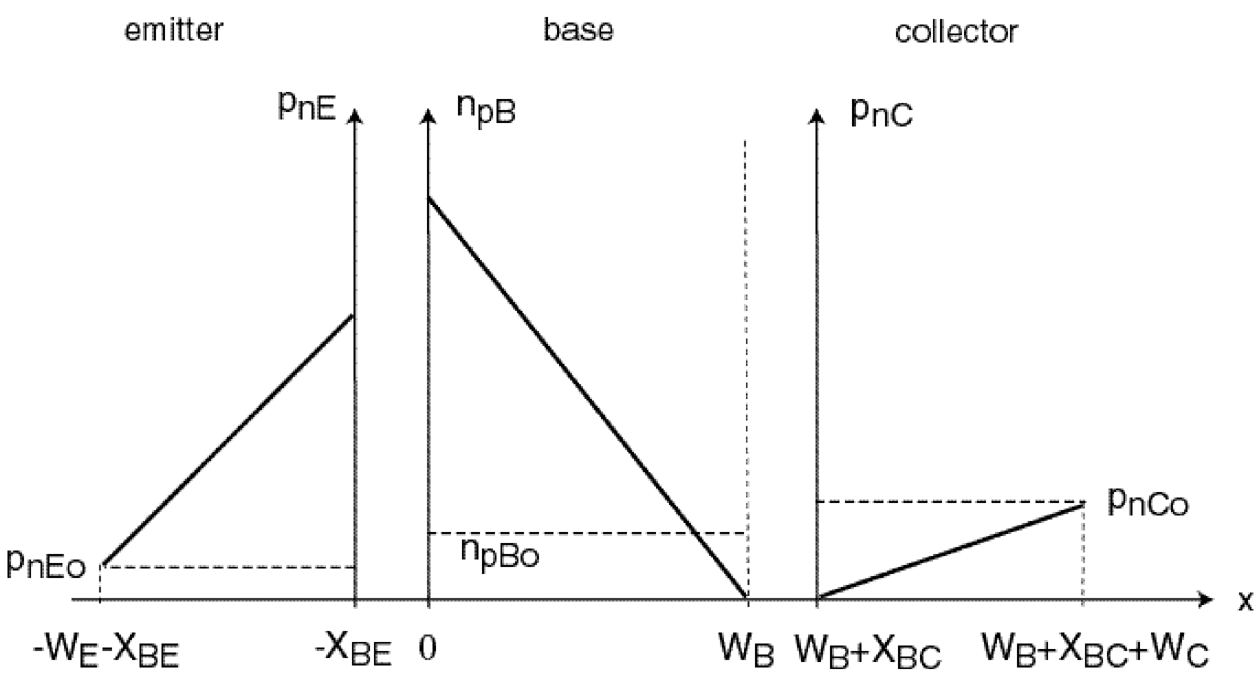


- ***Forward active***: device has good isolation and high gain; **most useful regime**;
- ***Saturation***: device has no isolation and is flooded with minority carriers;
  - takes time to get out of saturation
  - **avoid this regime**
- ***Reverse***: poor gain; **not useful**;
- ***Cut-off***: negligible current: nearly an open circuit; **useful**.

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



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



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

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

$$\mathbf{I_C = I_S \exp\left[\frac{qV_{BE}}{kT}\right]} \qquad \mathbf{I_S = n_{pBo} \cdot \frac{D_n}{W_B}}$$

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

$$\mathbf{I_B = \frac{I_S}{\beta_F}\left[\exp\left(\frac{qV_{BE}}{kT}\right) - 1\right]} \qquad \mathbf{\frac{I_S}{\beta_F} = p_{nEo} \cdot \frac{D_p}{W_E}}$$

- ***Emitter*** current:

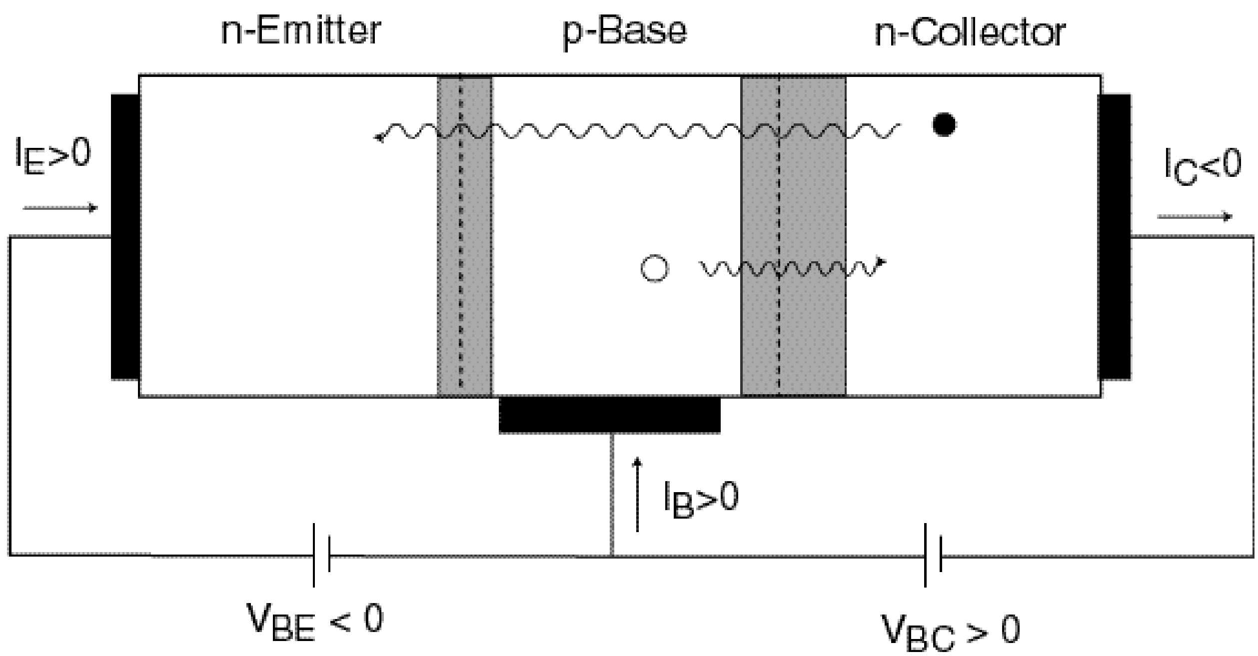
$$I_E = -I_C - I_B = -I_S \exp\left[\frac{qV_{BE}}{kT}\right] - \frac{I_S}{\beta_F}\left[\exp\left(\frac{qV_{BE}}{kT}\right) - 1\right]$$

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

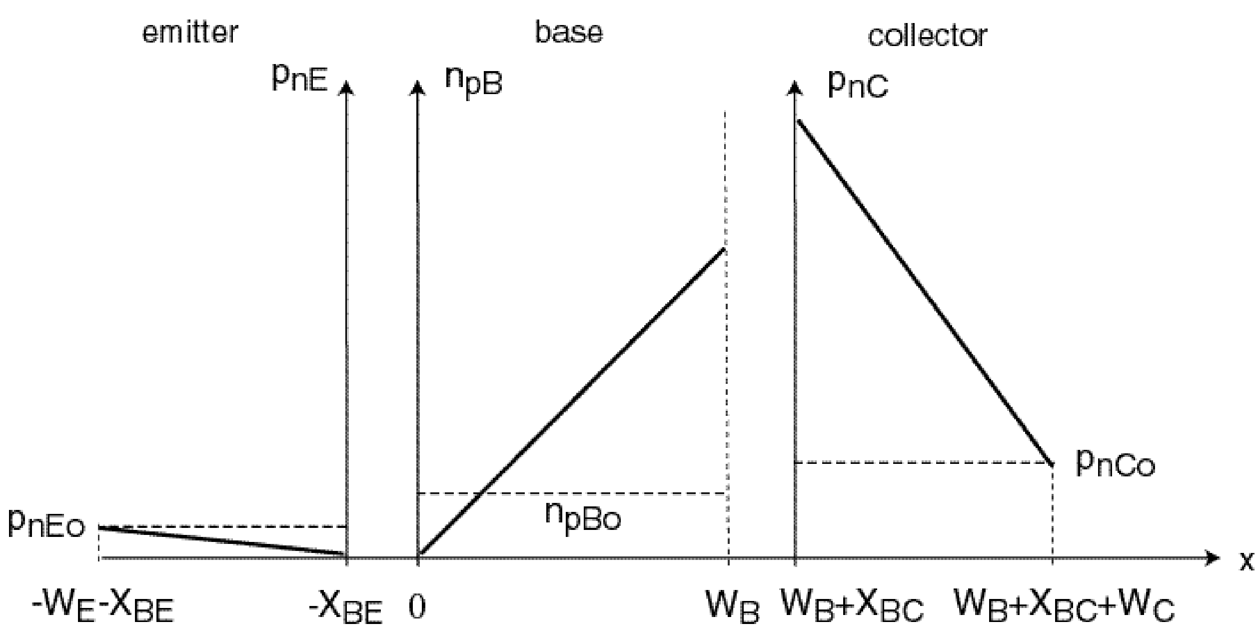
- β_F hard to control tightly: circuit design techniques required to be insensitive to variations in β_F.

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

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***:

$$I_E = I_S \exp\left[\frac{qV_{BC}}{kT}\right] \qquad I_S = n_{pBo} \cdot \frac{D_n}{W_B}$$

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

$$I_B = \frac{I_S}{\beta_R}\left[\exp\left(\frac{qV_{BC}}{kT}\right) - 1\right] \qquad \frac{I_S}{\beta_R} = p_{nCo} \cdot \frac{D_p}{W_C}$$

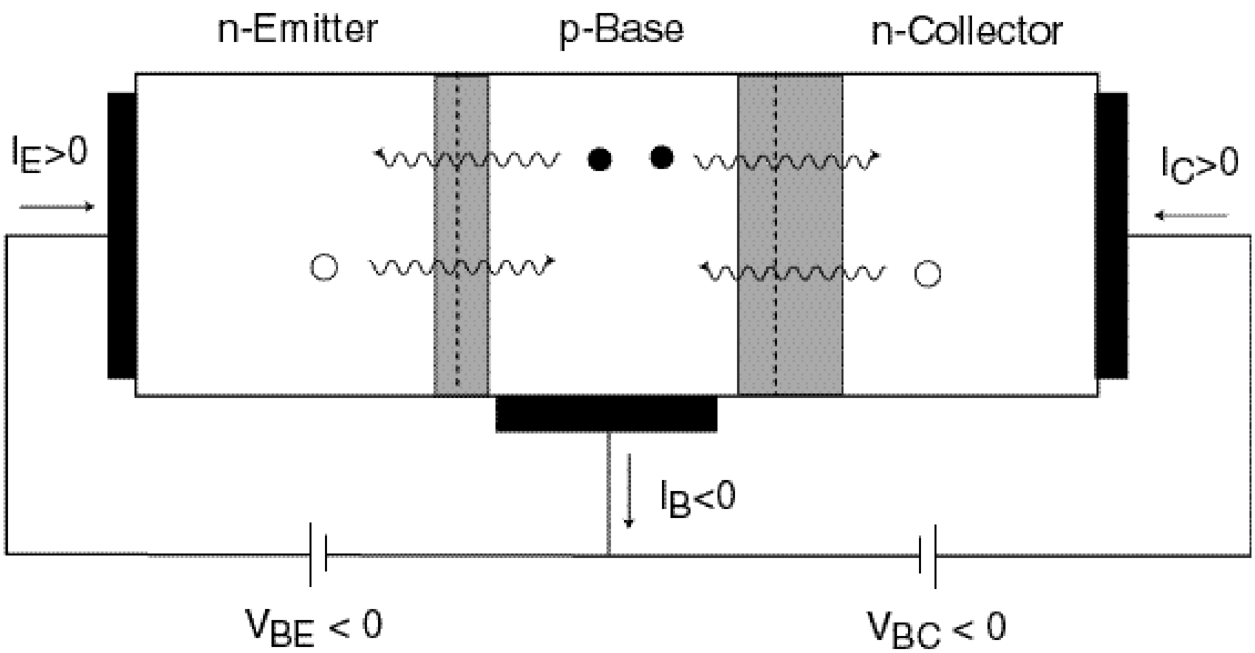
- ***Collector*** current:

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

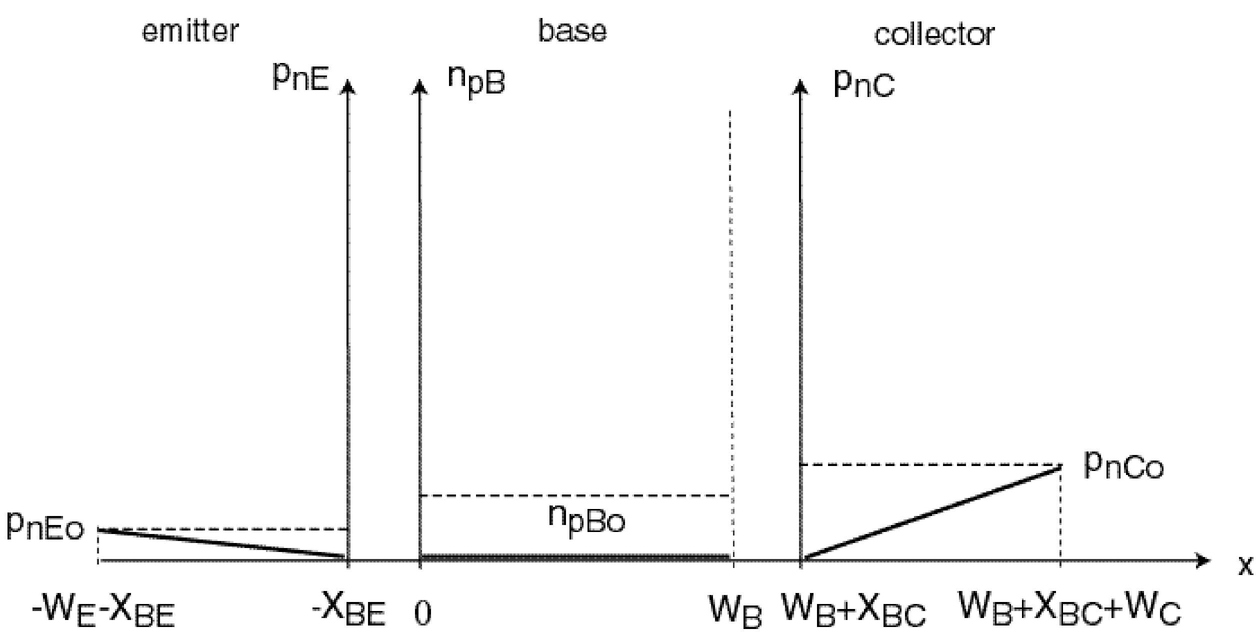
- Typically, $\beta_R \approx 0.1 - 5 << \beta_F$.

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

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***:

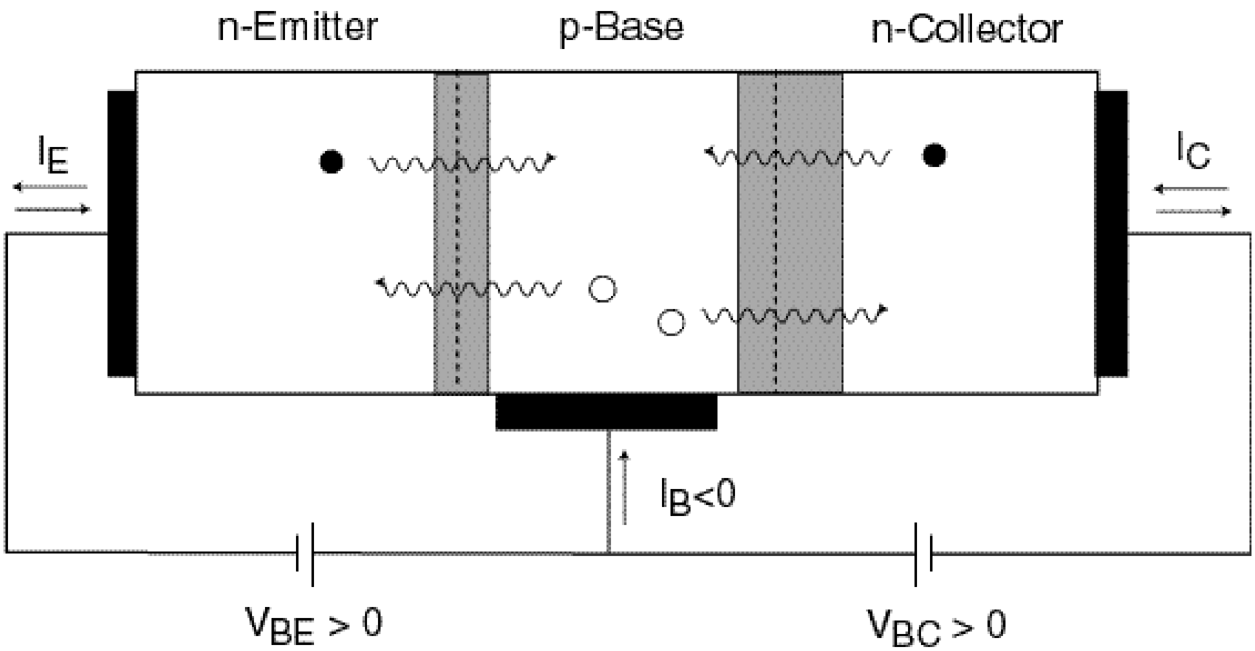
$$I_{B1} = -\frac{I_S}{\beta_F} = -I_E$$

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

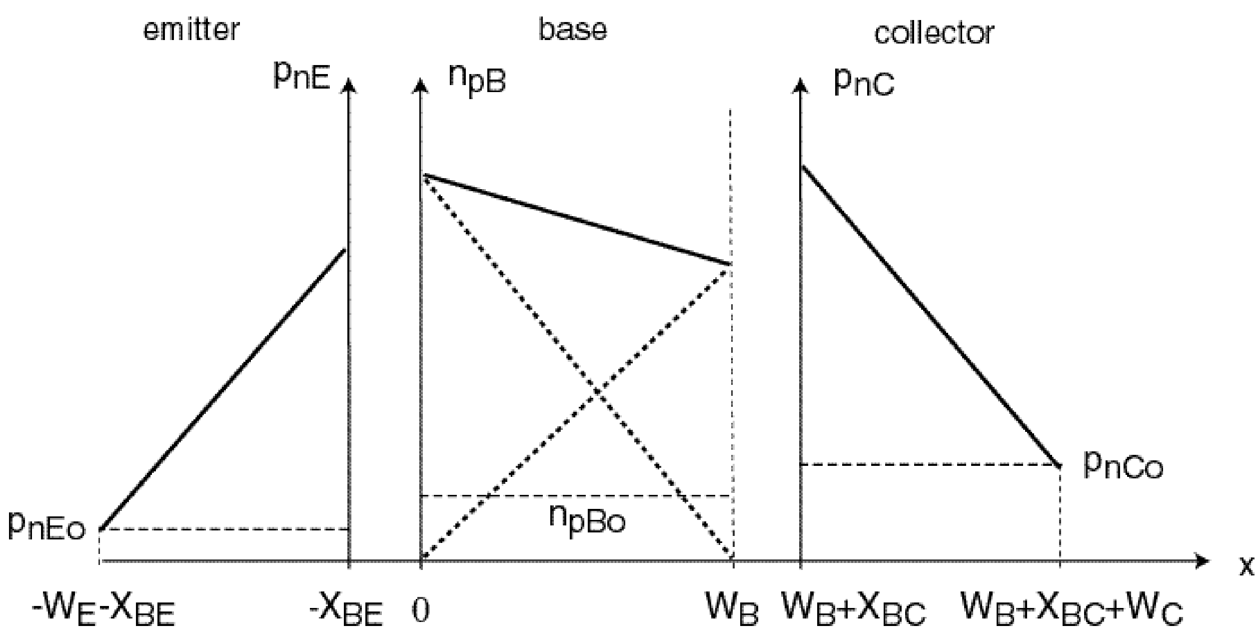
$$I_{B2} = -\frac{I_S}{\beta_R} = -I_C$$

- These are tiny leakage currents ($\approx 10^{-12}$ 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:

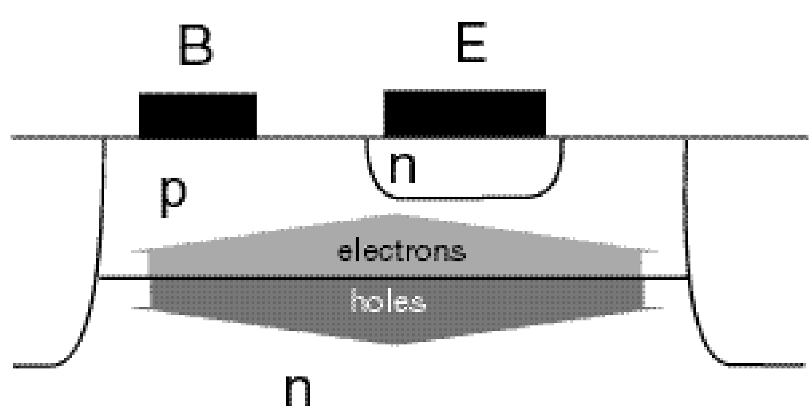
$$I_C = I_S\left(\exp\left[\frac{qV_{BE}}{kT}\right] - \exp\left[\frac{qV_{BC}}{kT}\right]\right) - \frac{I_S}{\beta_R}\left(\exp\left[\frac{qV_{BC}}{kT}\right] - 1\right)$$

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

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

- 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.

- In saturation, collector and base are flooded with excess minority carriers   it takes lots of time to get transistor out of saturation.



2. Large-signal equivalent circuit model

System of equations that describes BJT operation:

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

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

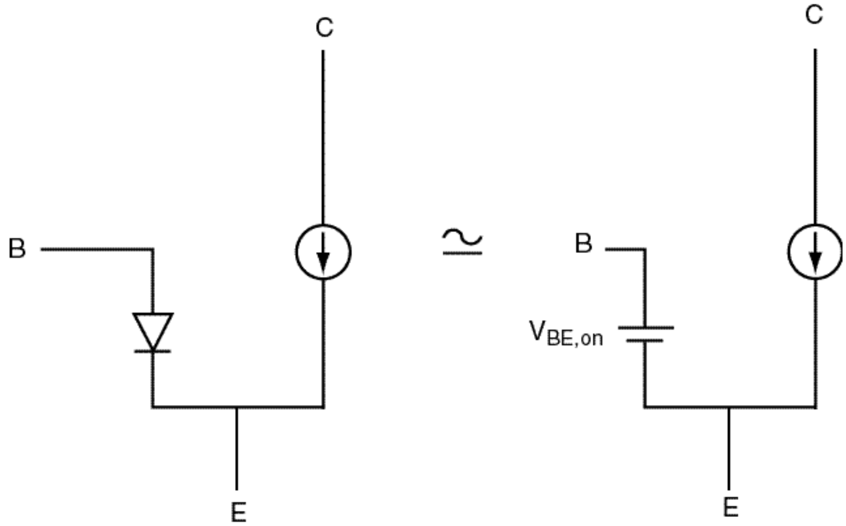
$$I_E = -I_S\left[\exp\left(\frac{qV_{BE}}{kT}\right) - \exp\left(\frac{qV_{BC}}{kT}\right)\right] - \frac{I_S}{\beta_F}\left[\exp\left(\frac{qV_{BE}}{kT}\right) - 1\right]$$

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.

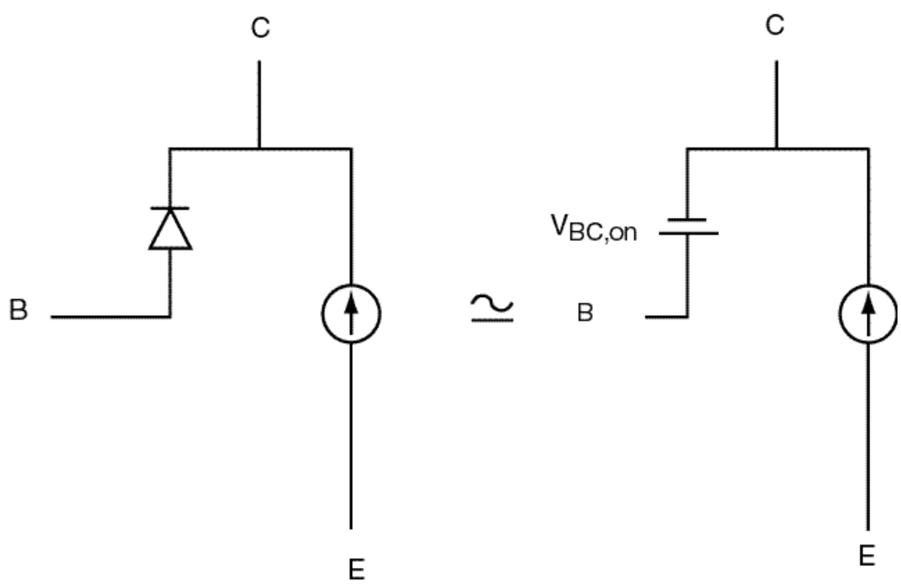
Simplification of equivalent circuit model:

- **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.

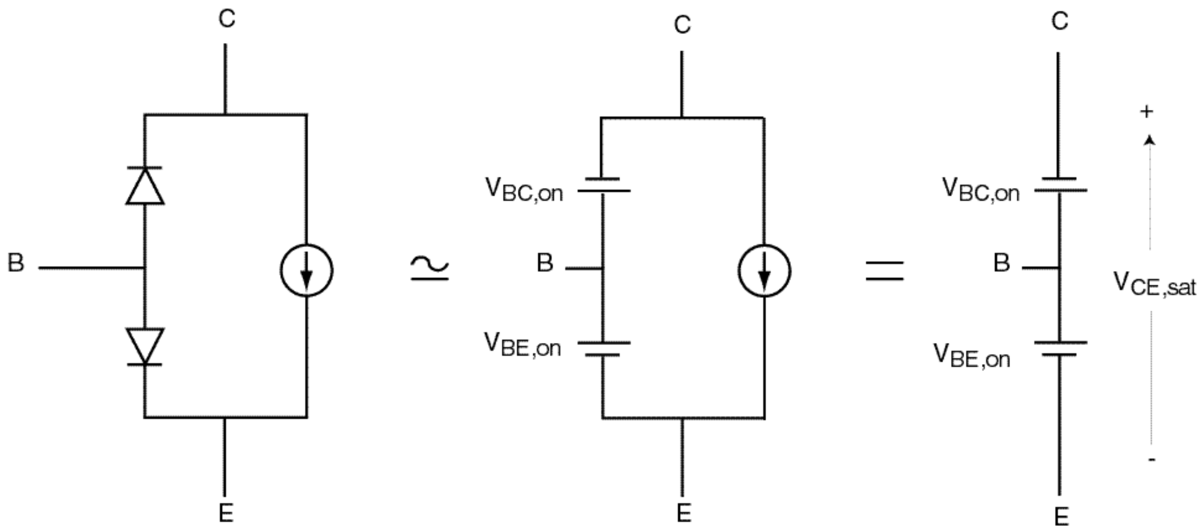
- **Reverse-active regime:** $V_{BE} < 0$, $V_{BC} > 0$



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

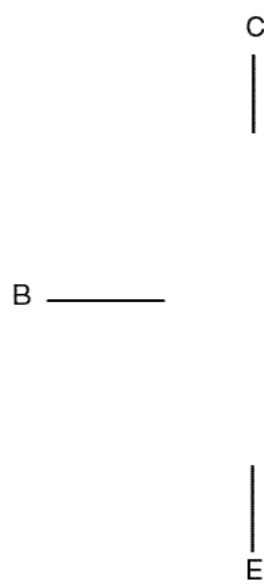
Simplification of equivalent circuit model:

- **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.

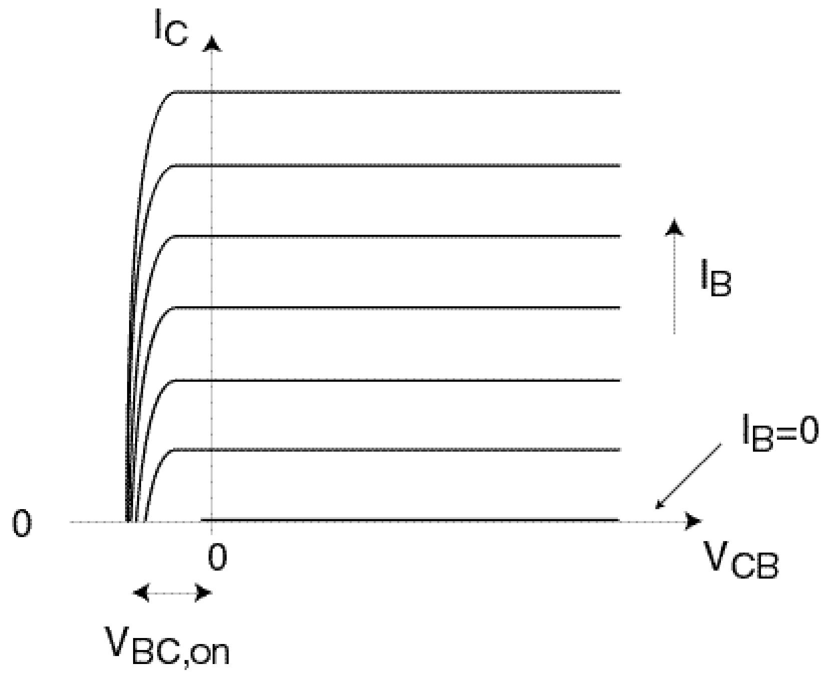
- **Cut-off regime:** $V_{BE} < 0$, $V_{BC} < 0$



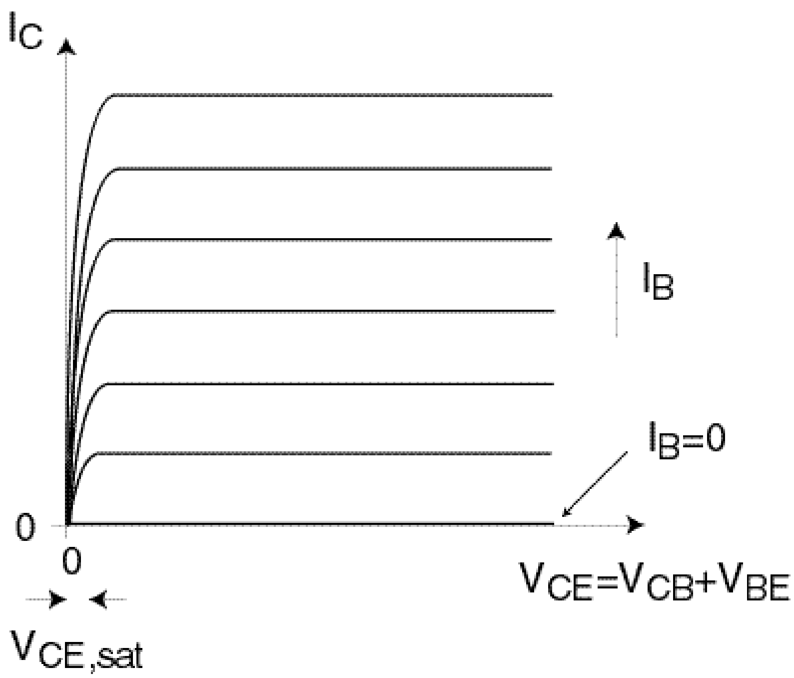
Only negligible leakage currents.

3. Output Characteristics

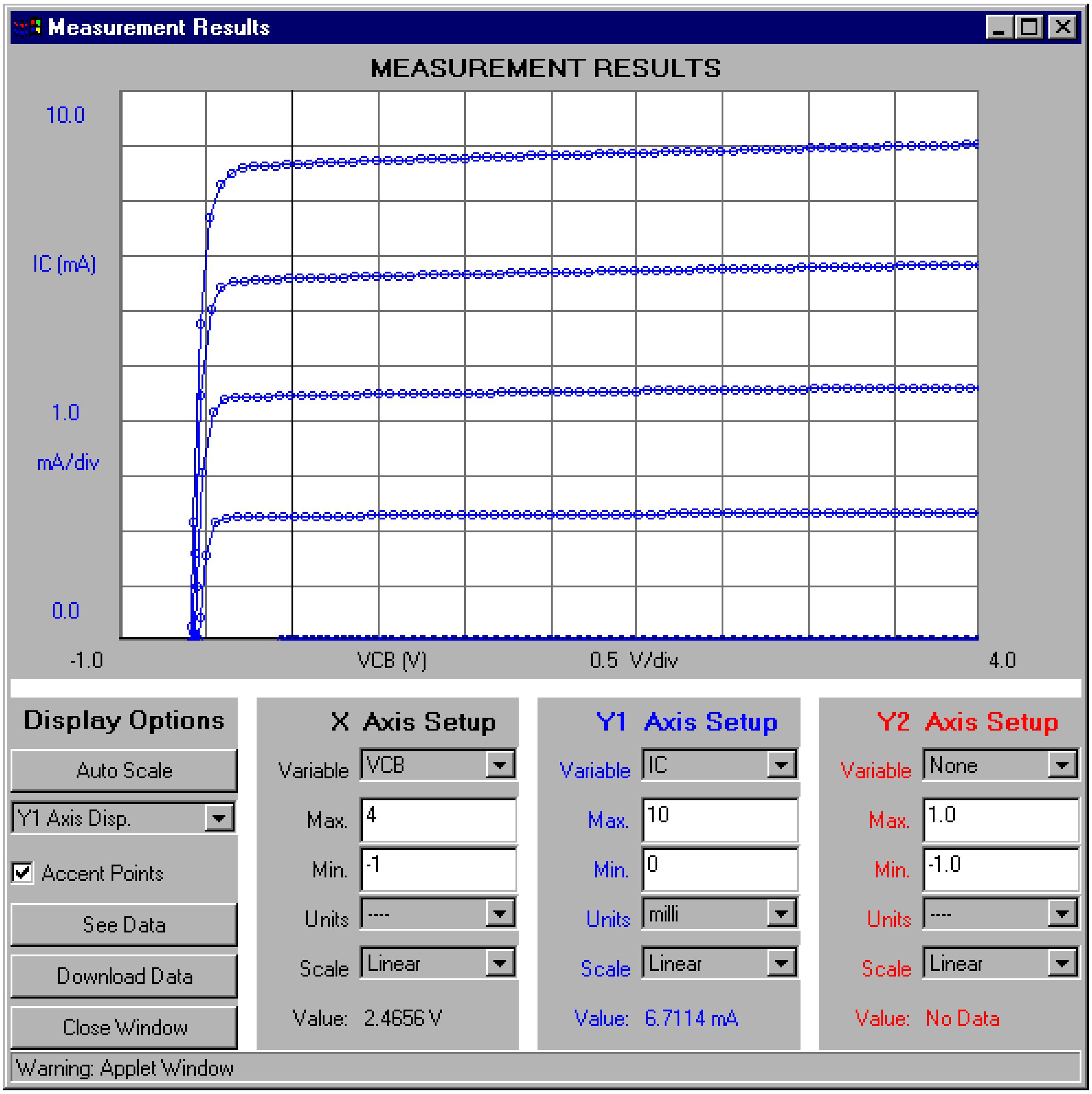
Common-base output characteristics:



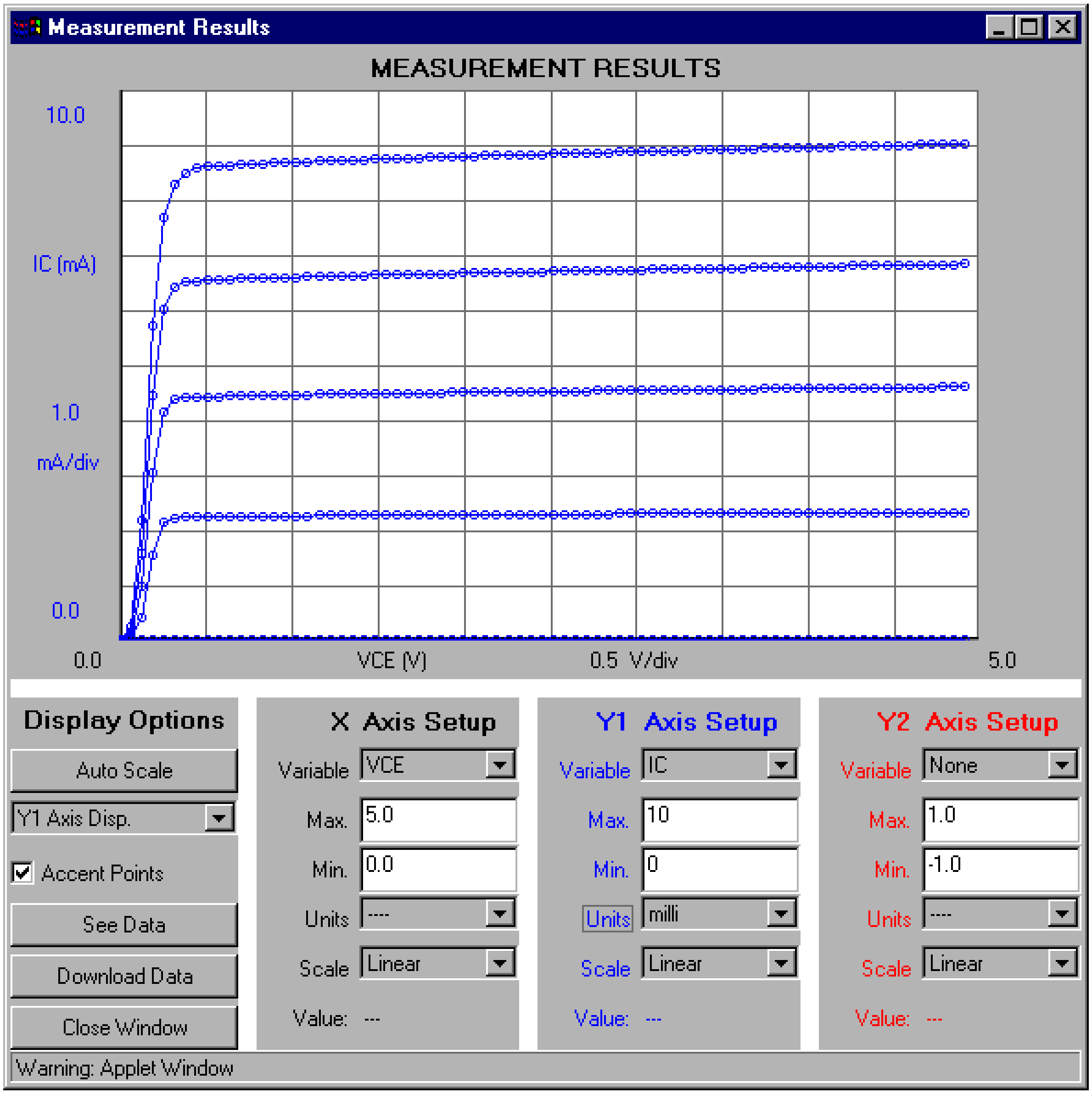
Common-emitter output characteristics:



Common-base output characteristics



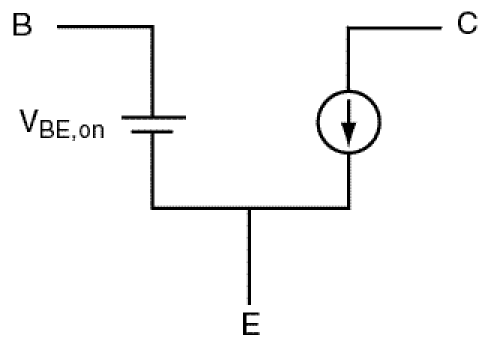
Common-Emitter Output Characteristics



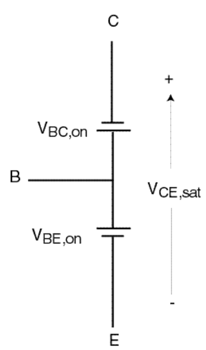
What did we learn today?

Summary of Key Concepts

- ***Forward-active regime***: most useful, device has gain and isolation. For bias calculations:



- ***Saturation Regime***: device flooded with minority carriers. Not useful. For bias calculations:



- ***Cut-off Regime***: device open. Useful. For bias calculations: