Lecture 18 - The Bipolar Junction Transistor (II)

Regimes of Operation

April 17, 2003

Contents:

1. Regimes of operation.
2. Large-signal equivalent circuit model.
3. Output characteristics.

Reading assignment:

Howe and Sodini, Ch. 7, §§7.3, 7.4

Announcements:

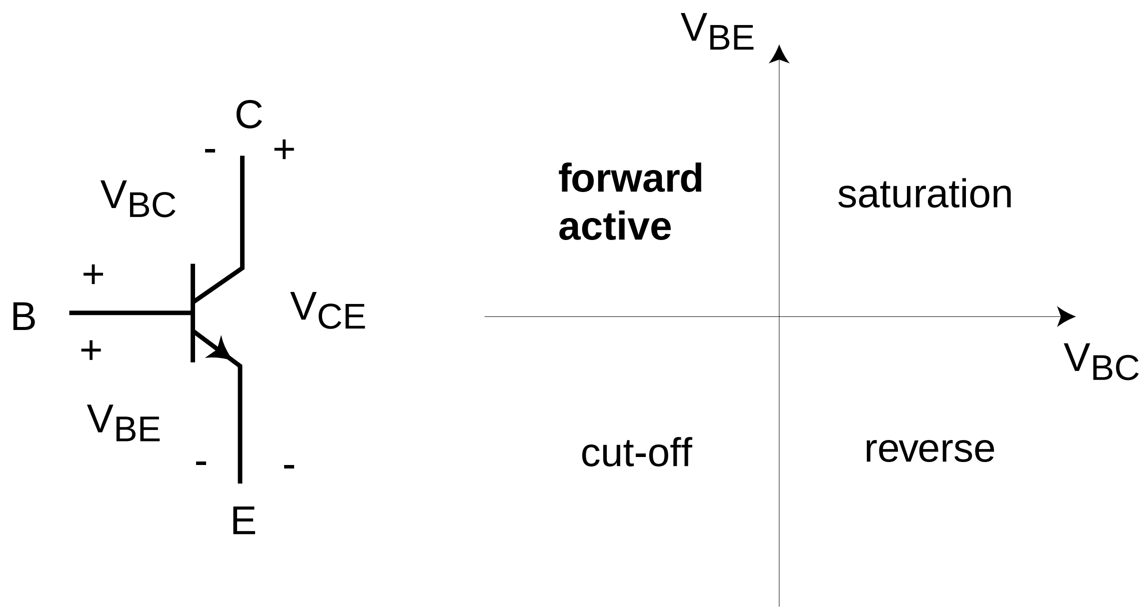
Quiz 2: 4/16, 7:30-9:30 PM, Walker (lectures #10-17) open book, must bring calculator

Extra Office Hours: 4/15, 2-4pm, 38-201; 4/16, 9am-12 & 1-4pm, 24-320

Key questions

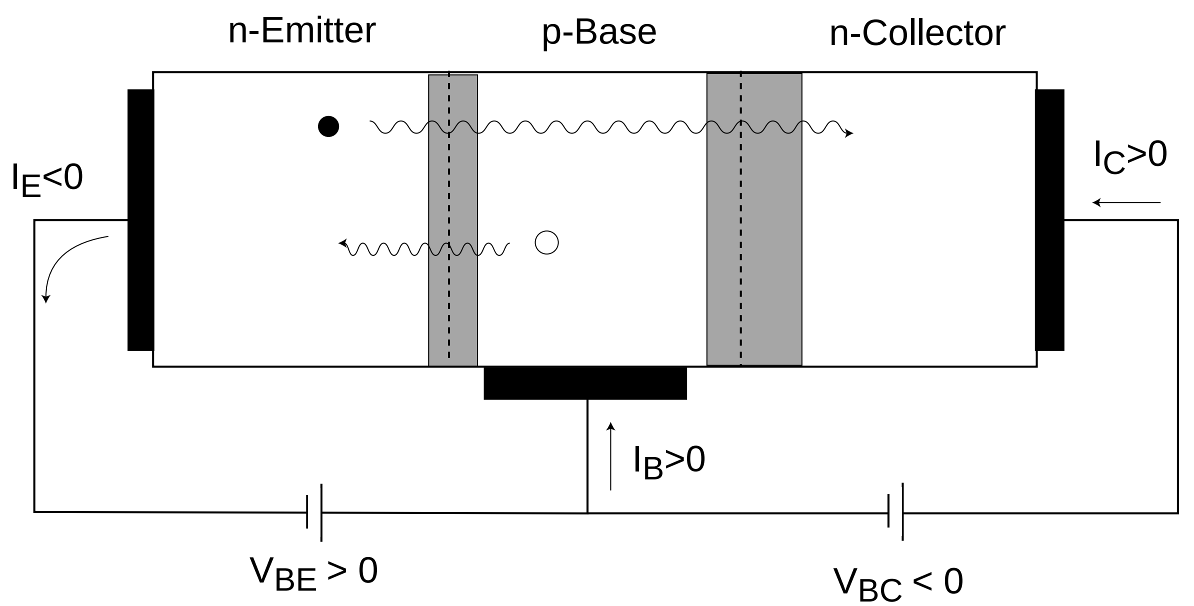
- What other regimes of operation are there for the BJT?
- What is unique about each regime?
- How do equivalent circuit models for the BJT look like?

1. Regimes of operation

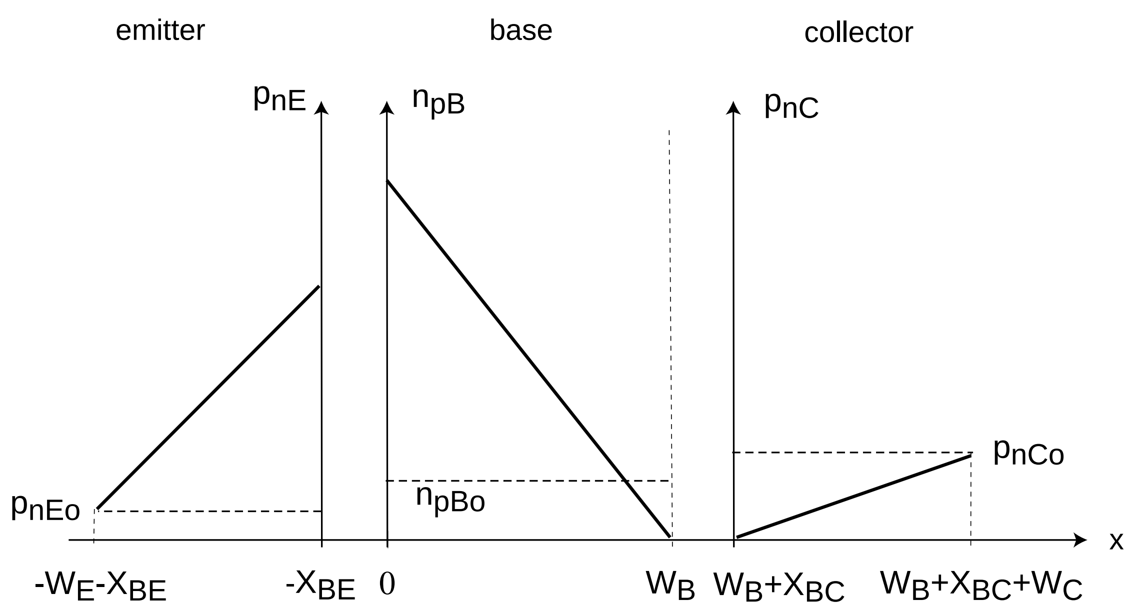


- *forward active*: device has good isolation and high gain; most useful regime;
- *saturation*: device has no isolation and is flooded with minority carriers $\Rightarrow$ takes time to get out of saturation; avoid
- *reverse*: poor gain; not useful;
- *cut-off*: negligible current: nearly an open circuit; useful.

□ Forward-active regime: $V_{BE} > 0$, $V_{BC} < 0$



Minority carrier profiles (*not to scale*):



• Emitter injects electrons into base, collector collects electrons from base:

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

• Base injects holes into emitter, recombine at emitter contact:

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

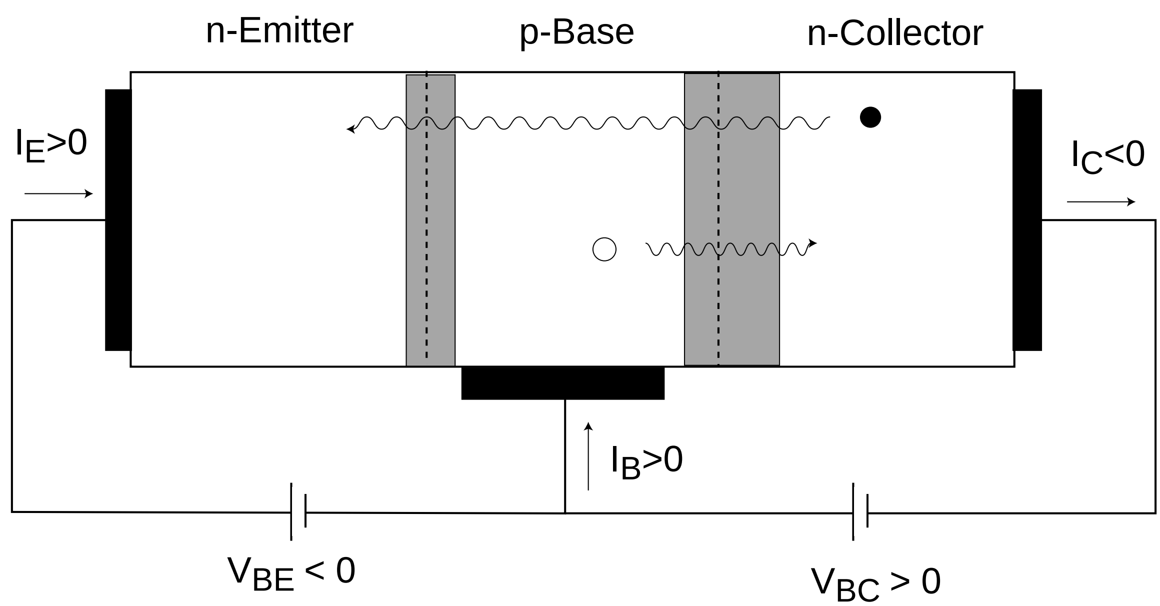
• Emitter current:

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

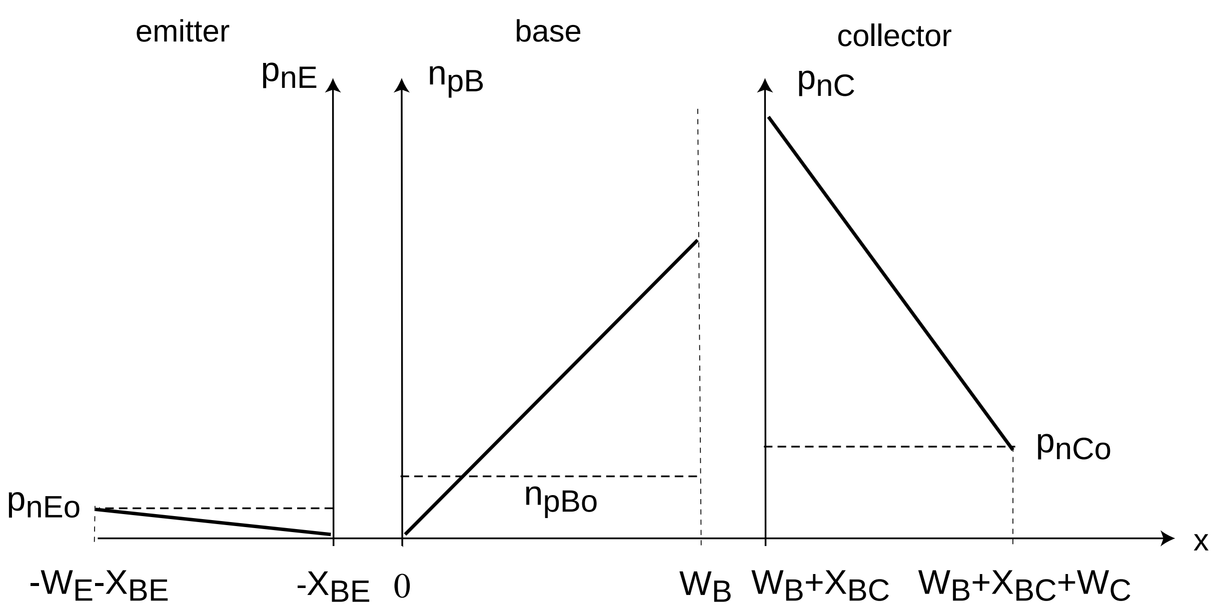
• State-of-the-art IC BJT's today: $I_C \sim 0.1 - 1\ mA$, $\beta_F \simeq 50 - 300$.

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

□ Reverse regime: $V_{BE} < 0$, $V_{BC} > 0$



Minority carrier profiles:



• Collector injects electrons into base, emitter collects electrons from base:

$$I_E = I_S \exp \frac{qV_{BC}}{kT}$$

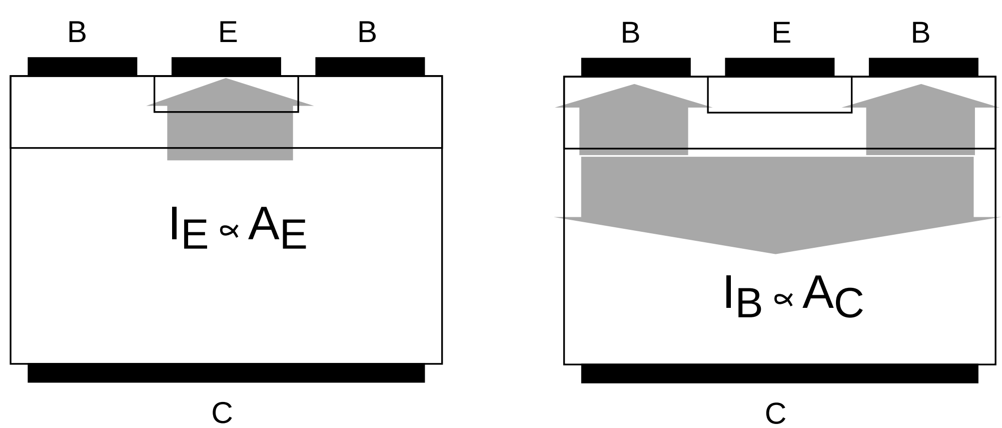
• Base injects holes into collector, recombine at collector contact and buried layer:

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

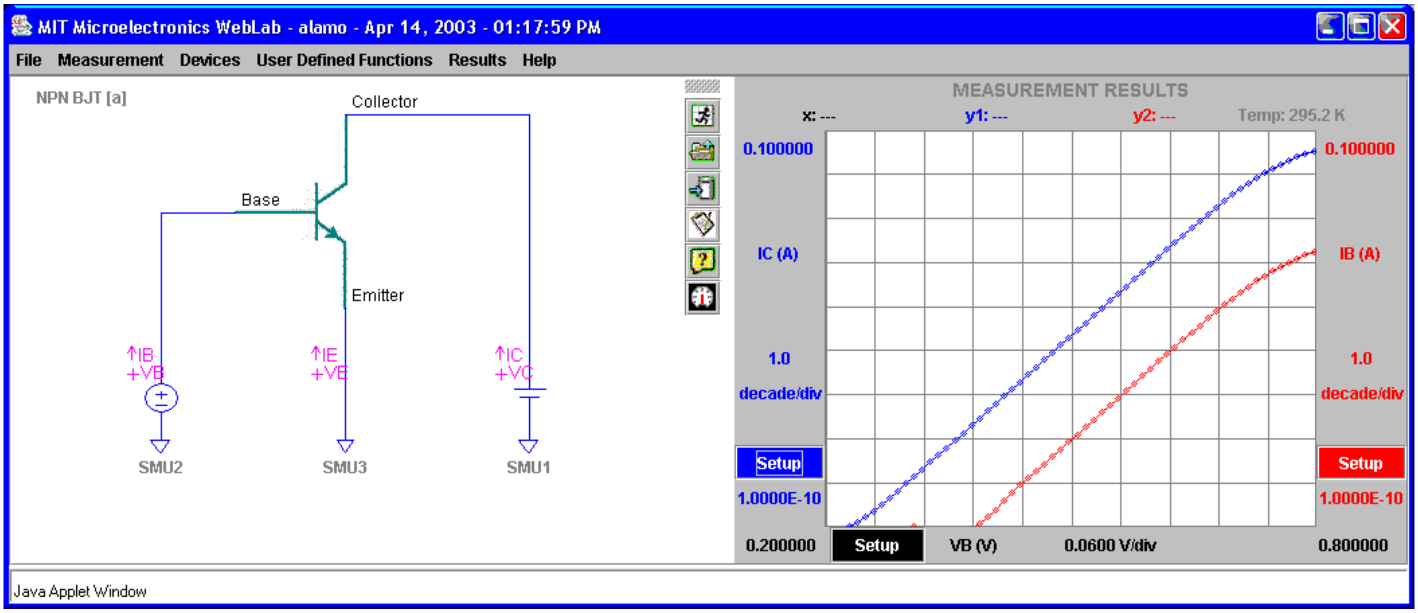
• Collector current:

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

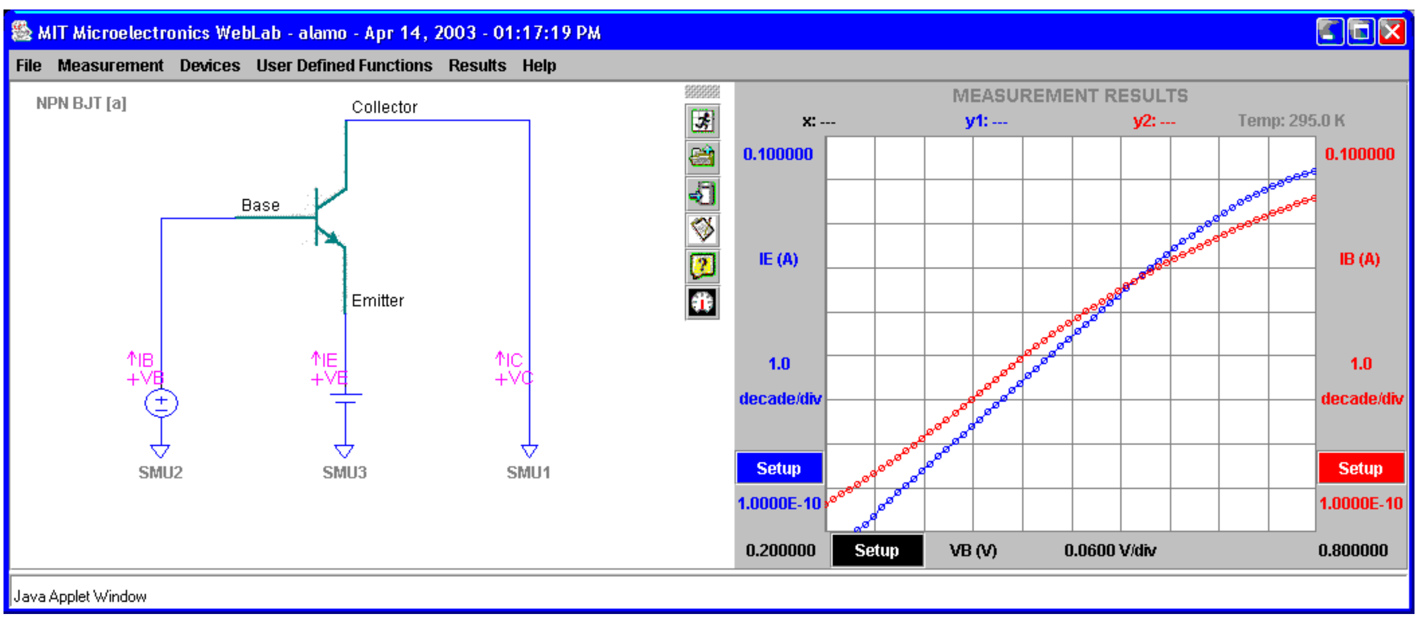
• Typically, $\beta_R \simeq 0.1 - 5 \ll \beta_F$.



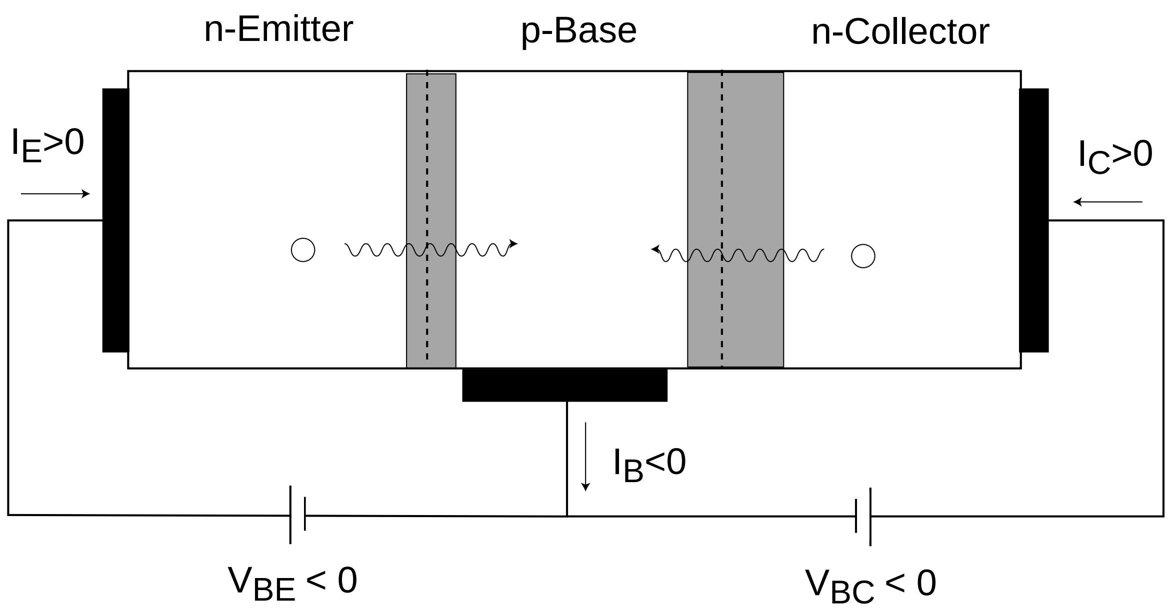
Forward-active Gummel plot ($V_{CE} = 3\ V$):



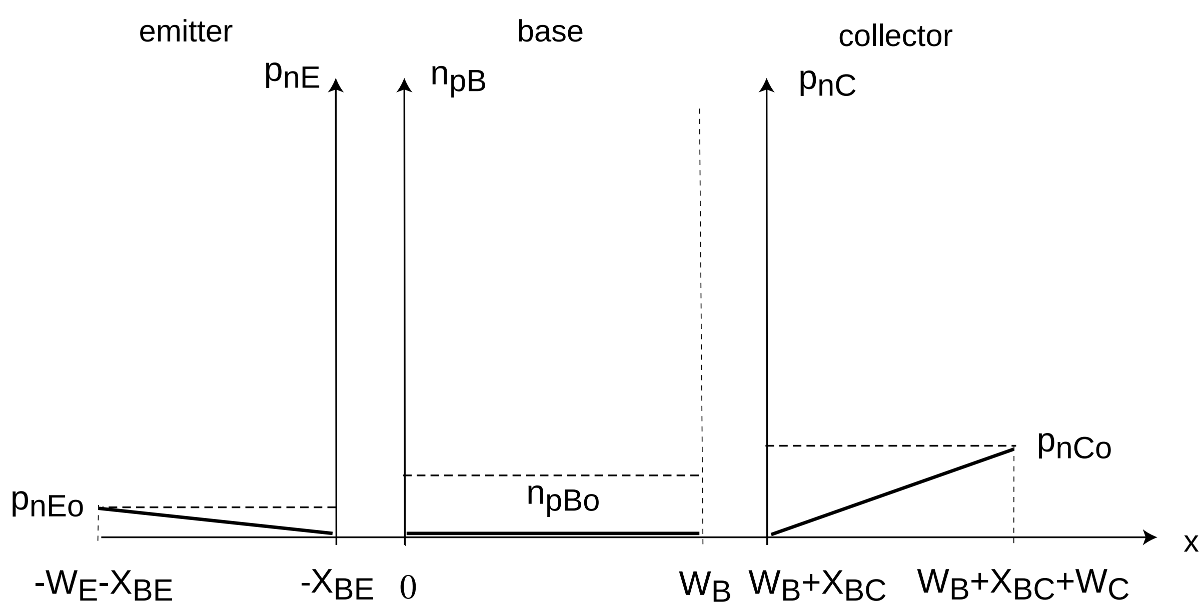
Reverse Gummel ($V_{EC} = 3\ V$):



□ Cut-off: $V_{BE} < 0$, $V_{BC} < 0$



Minority carrier profiles:



- Base extracts holes from emitter:

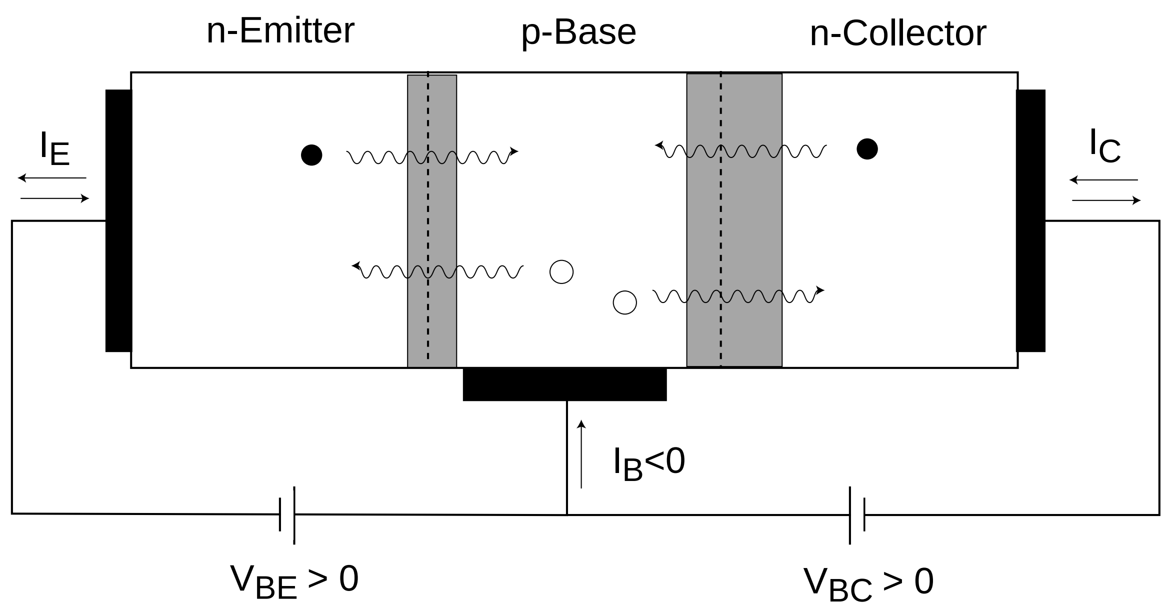
$$I_{B1} = -\frac{I_S}{\beta_F} = -I_E$$

- Base extracts holes from collector:

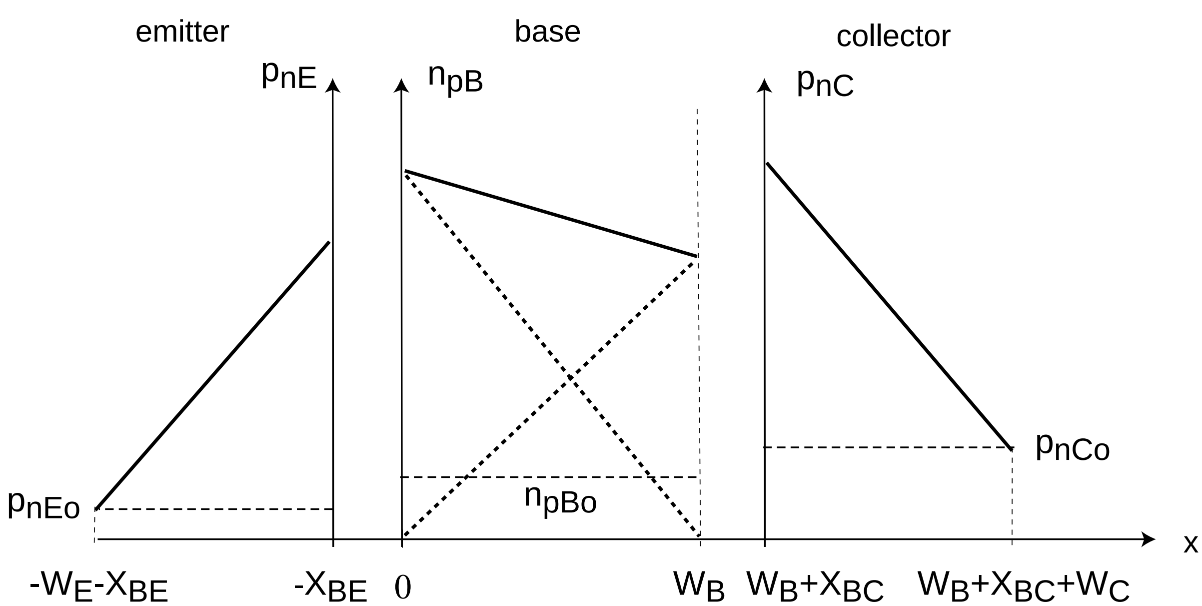
$$I_{B2} = -\frac{I_S}{\beta_R} = -I_C$$

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

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



Minority carrier profiles:



Saturation is superposition of forward active + reverse:

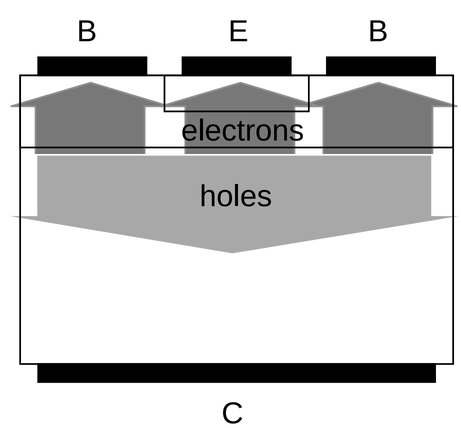
$$I_C = I_S(\exp\frac{qV_{BE}}{kT} - \exp\frac{qV_{BC}}{kT}) - \frac{I_S}{\beta_R}(\exp\frac{qV_{BC}}{kT} - 1)$$

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

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

- 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.

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



2. Large-signal equivalent circuit model

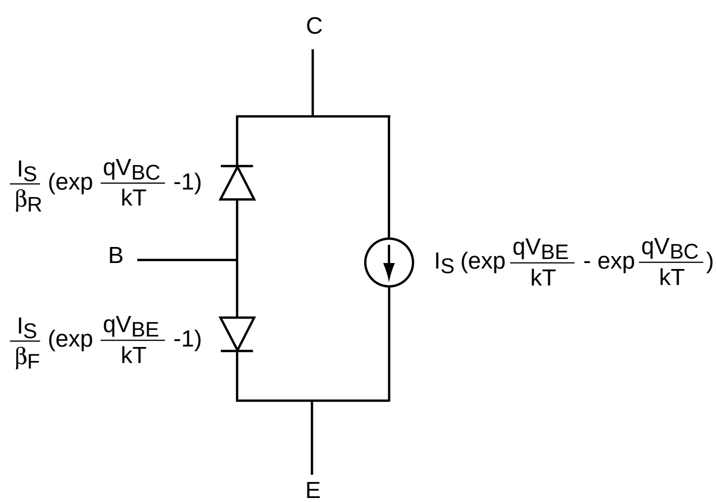
System of equations that describes BJT operation:

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

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

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

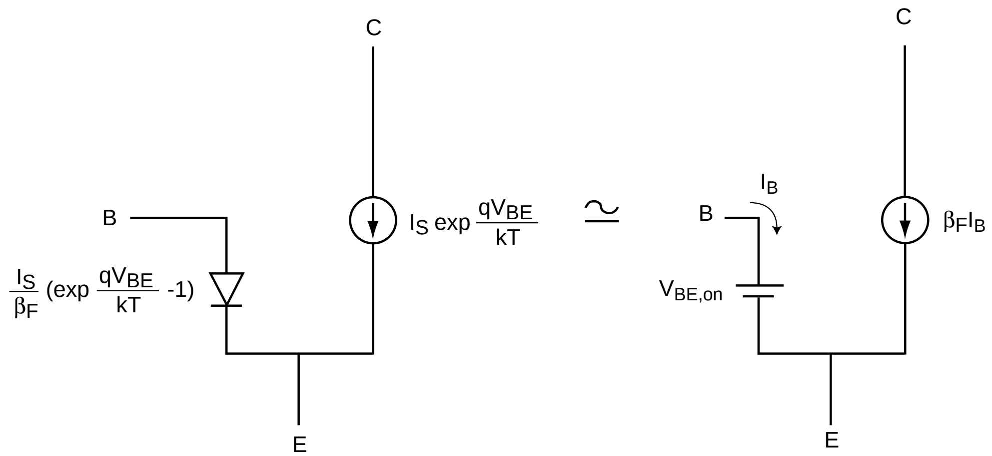
Equivalent-circuit model representation:
Non-Linear Hybrid-π Model



Three parameters in this model: I_S, β_F, and β_R.
Model equivalent to Ebers-Moll model in text.

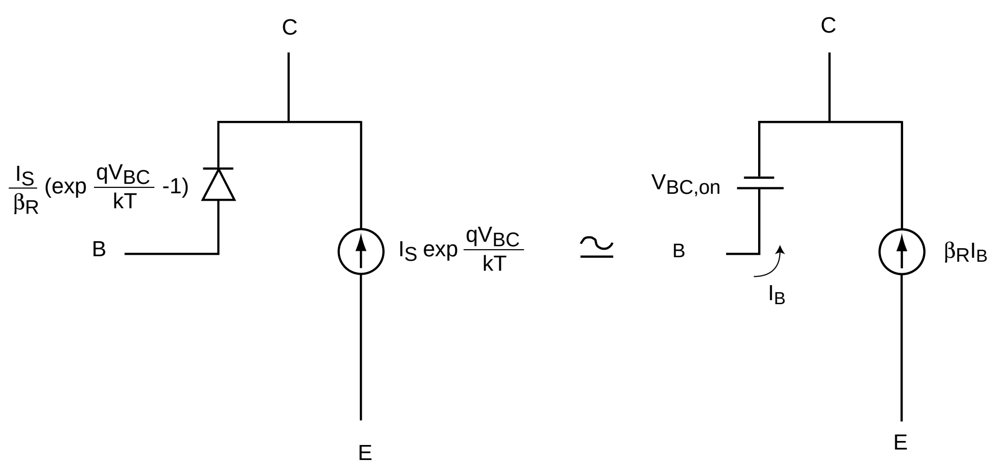
Simplifications of equivalent-circuit model:

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



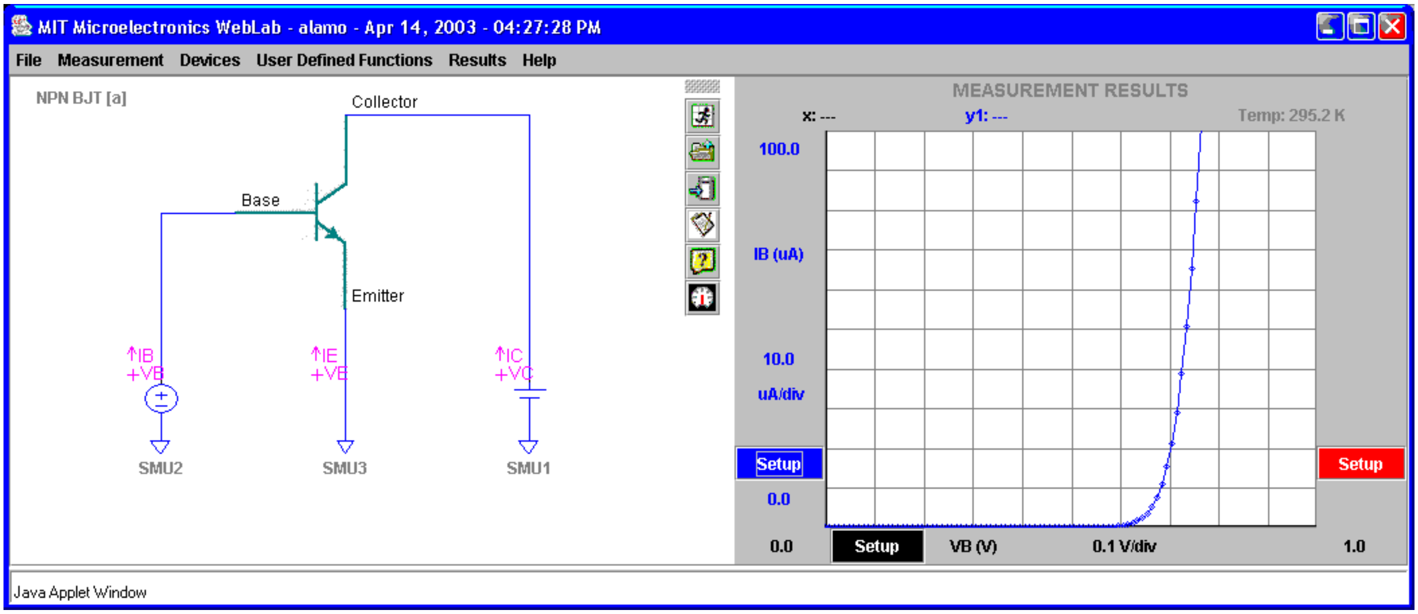
For today's technology: $V_{BE,on} \simeq 0.7\ V$.
I_B depends on outside circuit.

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

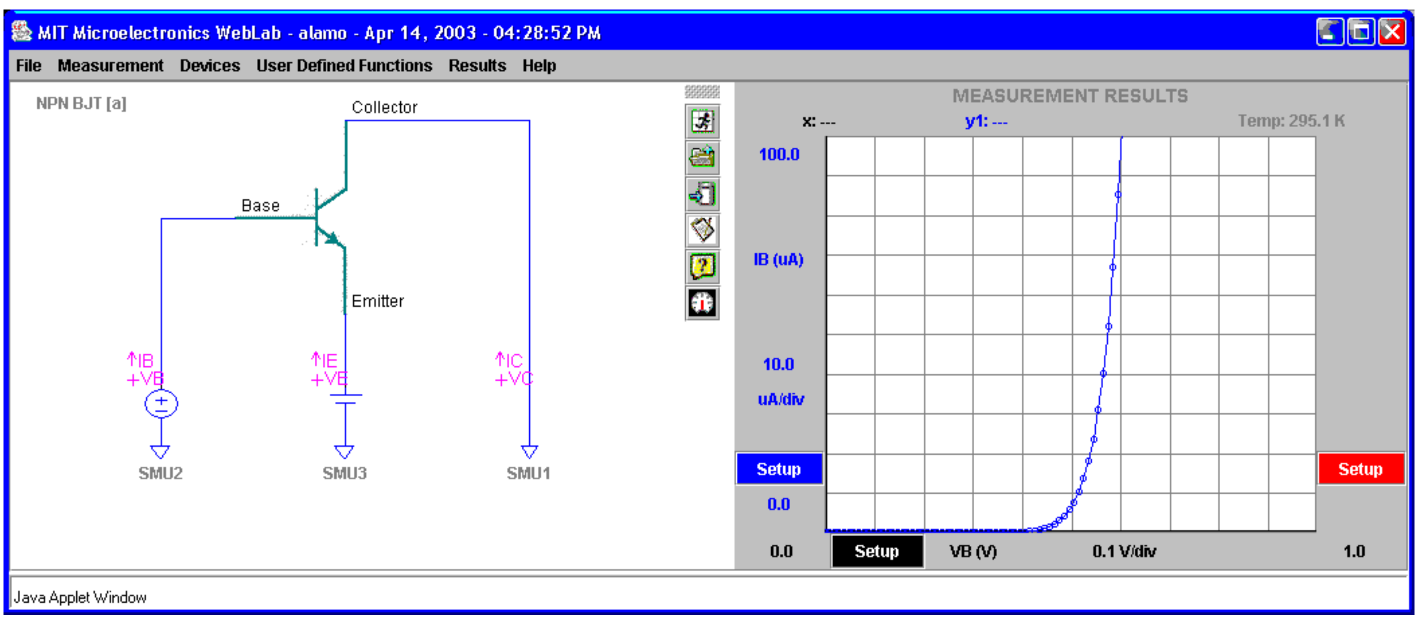


For today's technology: $V_{BC,on} \simeq 0.5\ V$.
I_B also depends on outside circuit.

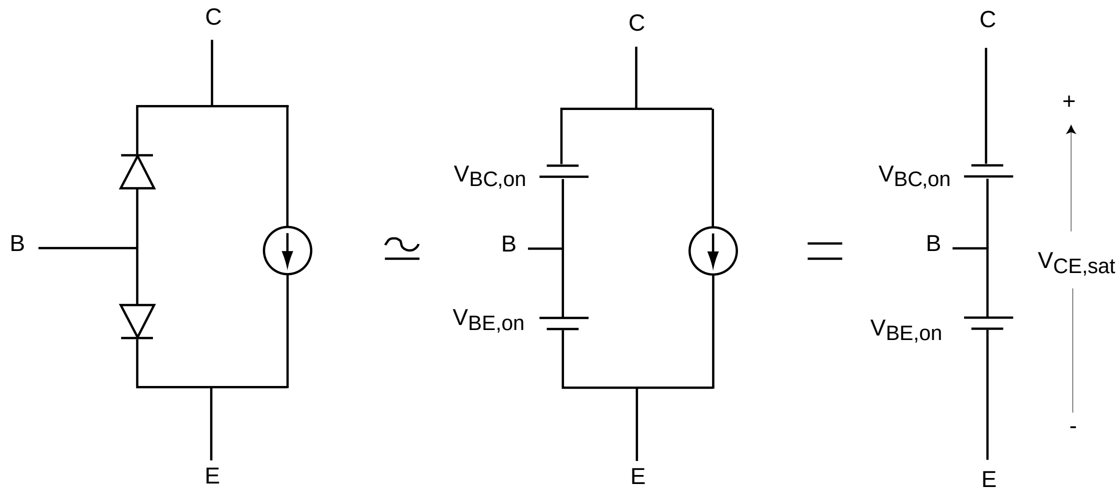
I_B vs. V_{BE} for $V_{CE} = 3\ V$:



I_B vs. V_{BC} for $V_{EC} = 3\ V$:

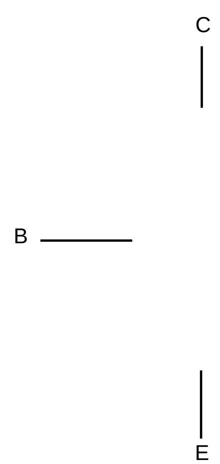


- Saturation: $V_{BE} > 0$, $V_{BC} > 0$



Today's technology: $V_{CE,sat} = V_{BE,on} - V_{BC,on} \simeq 0.2\ V$. I_B and I_C depend on outside circuit.

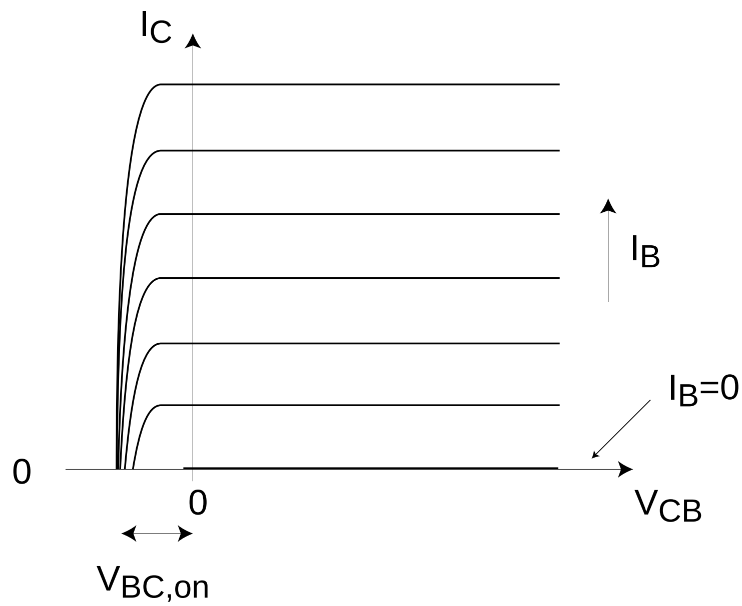
- Cut-off: $V_{BE} < 0$, $V_{BC} < 0$



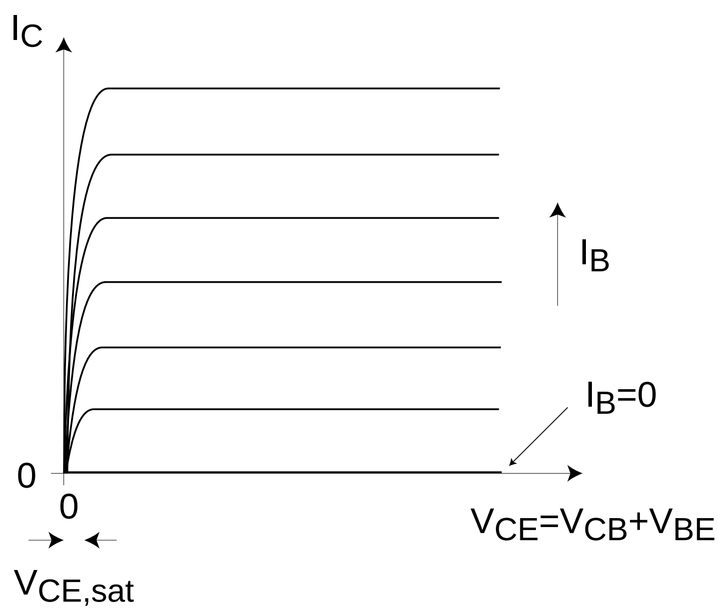
Only negligible leakage currents.

3. Output characteristics

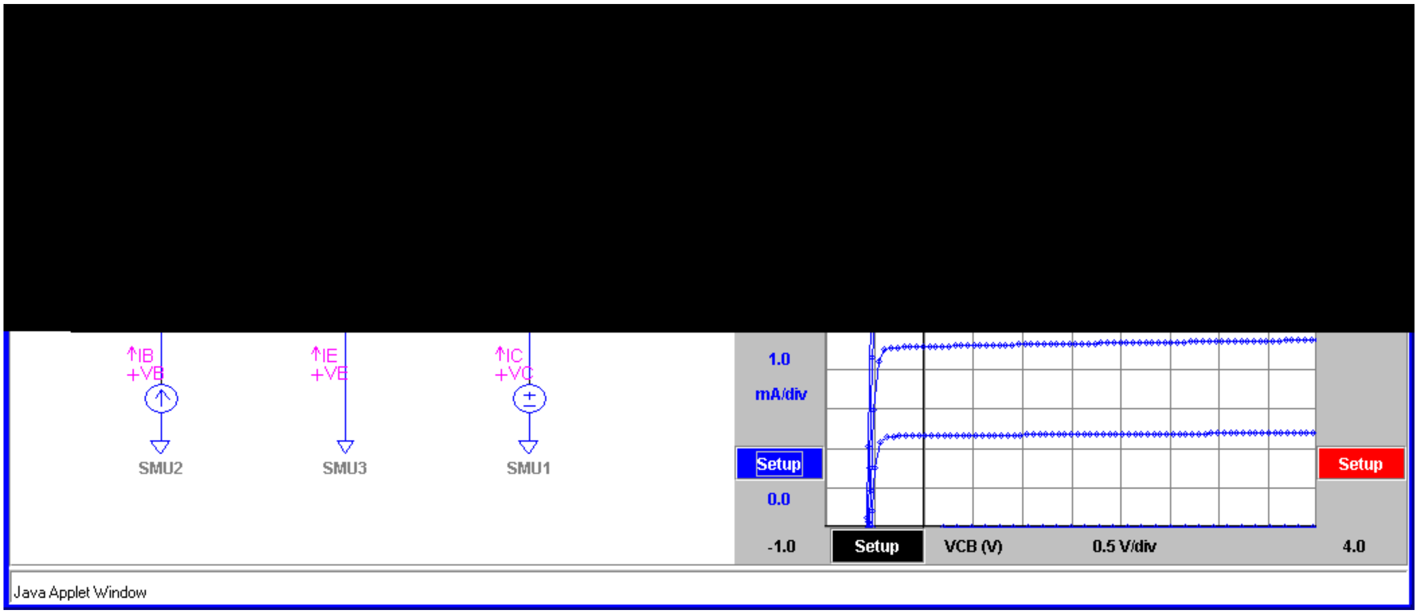
First, I_C vs. V_{CB} with I_B as parameter:



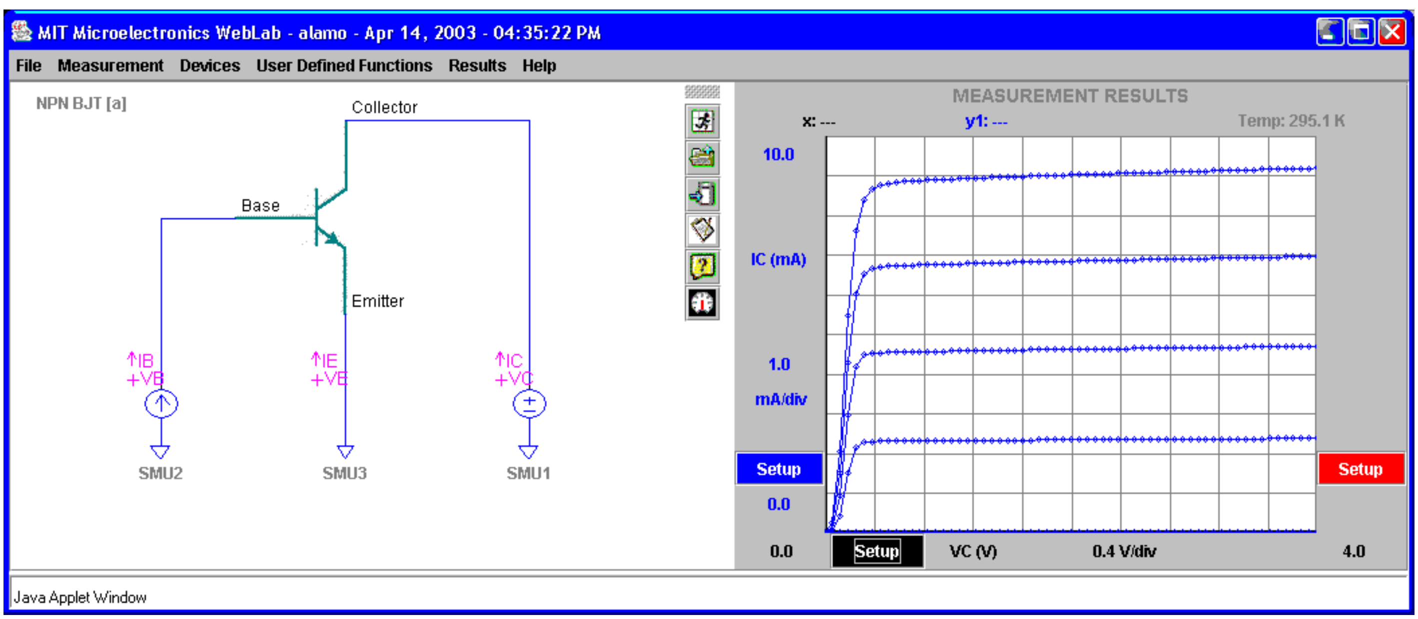
Next, *common-emitter output characteristics* (I_C vs. V_{CE} with I_B as parameter):



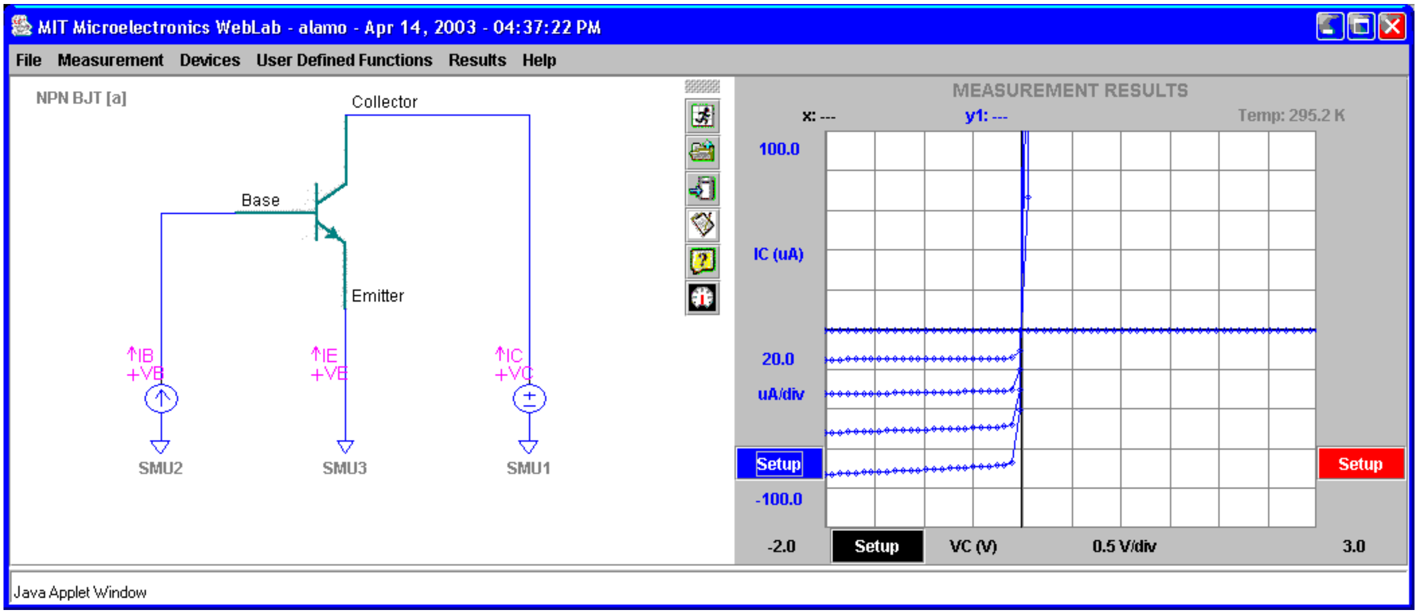
I_C vs. V_{CB} for $0 \leq I_B \leq 100\ \mu A$:



I_C vs. V_{CE} for $0 \leq I_B \leq 100\ \mu A$:

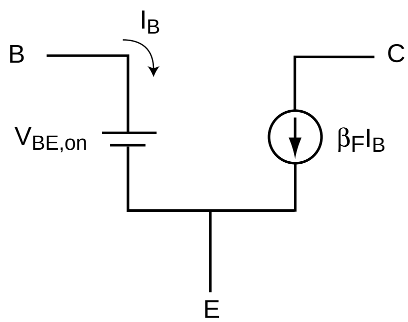


I_C vs. V_{CE} for $0 \leq I_B \leq 100\ \mu A$:

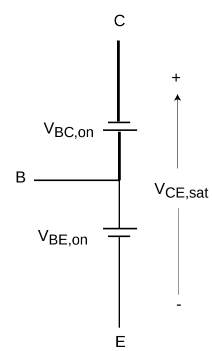


Key conclusions

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



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



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