

# Lecture 18 - The Bipolar Junction Transistor (II)

## REGIMES OF OPERATION

November 10, 2005

### Contents:

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

### Reading assignment:

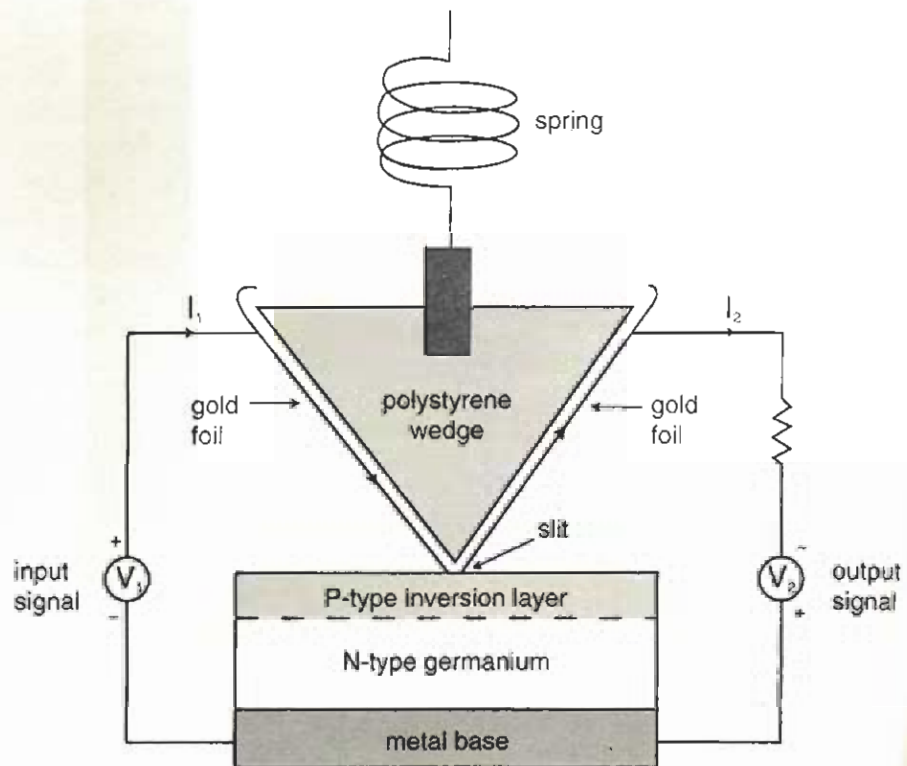
Howe and Sodini, Ch. 7, §§7.3, 7.4

### Announcements:

Quiz 2: 11/16, 7:30-9:30 PM,  
open book, must bring calculator; lectures #10-18.

Review session: 11/15, 7:30-9:30, place TBA

Cross-sectional diagram of the original point-contact semiconductor amplifier.

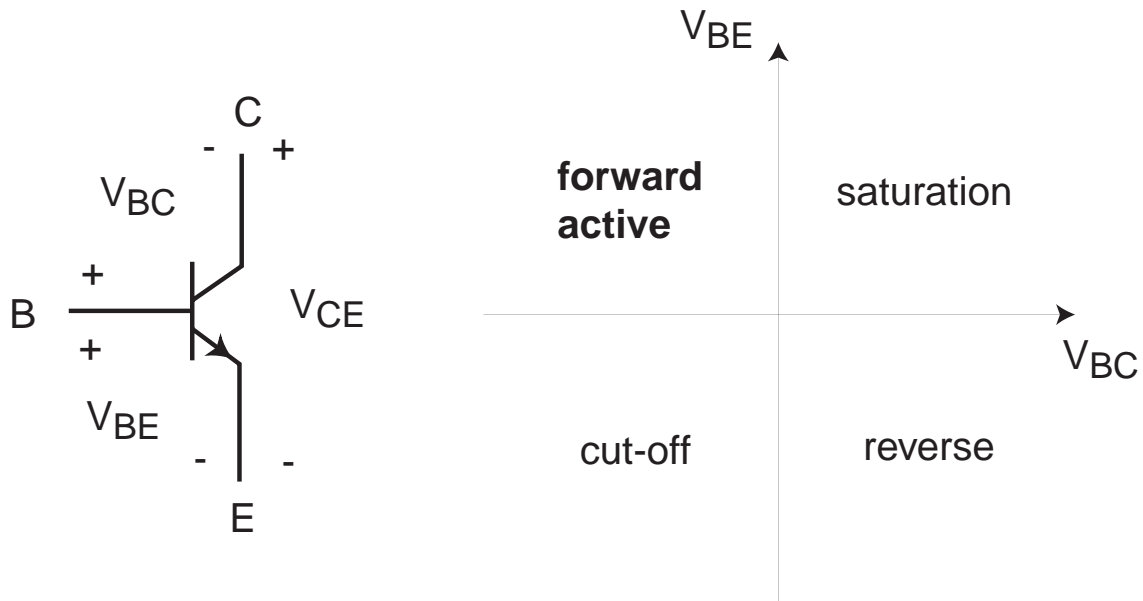


from Riordan and Moddeson, "Crystal Fire",  
November 1997

## Key questions

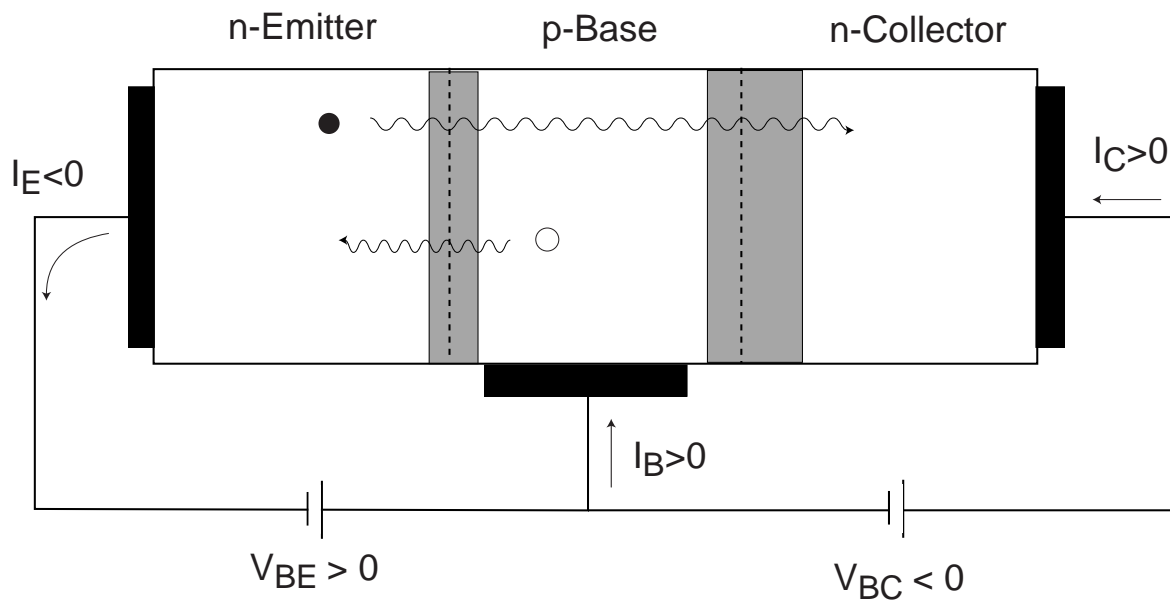
- What other regimes of operation are there for the BJT?
- What is unique about each regime?
- How do equivalent circuit models for the BJT look like?

# 1. Regimes of operation

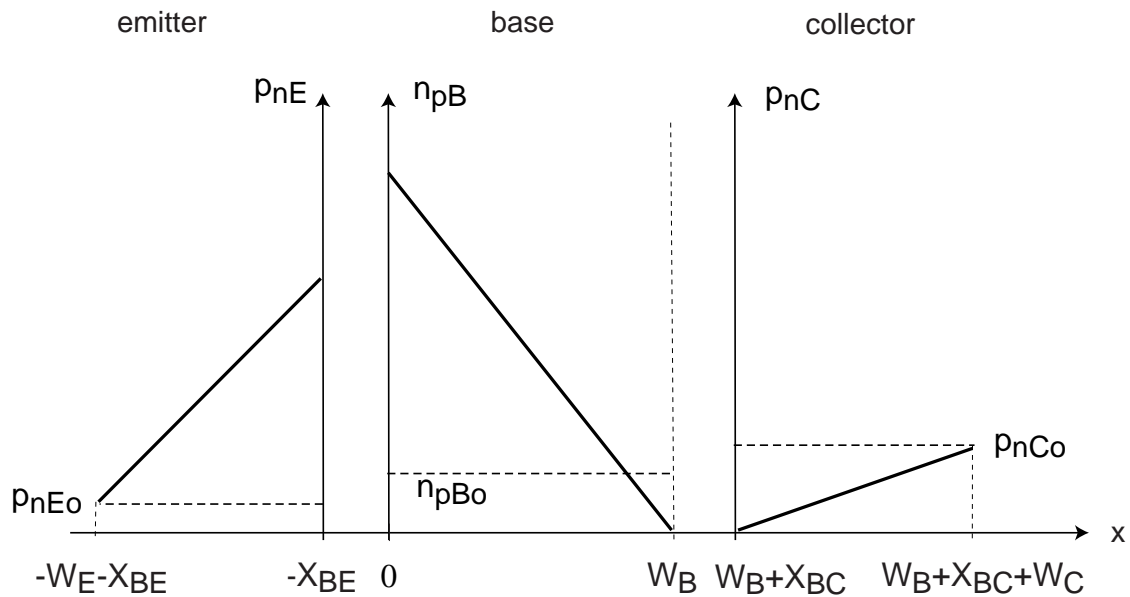


- *forward active*: device has good isolation and high gain; most useful regime;
- *saturation*: device has no isolation and is flooded with minority carriers  $\Rightarrow$  takes time to get out of saturation; avoid
- *reverse*: poor gain; not useful;
- *cut-off*: negligible current: nearly an open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

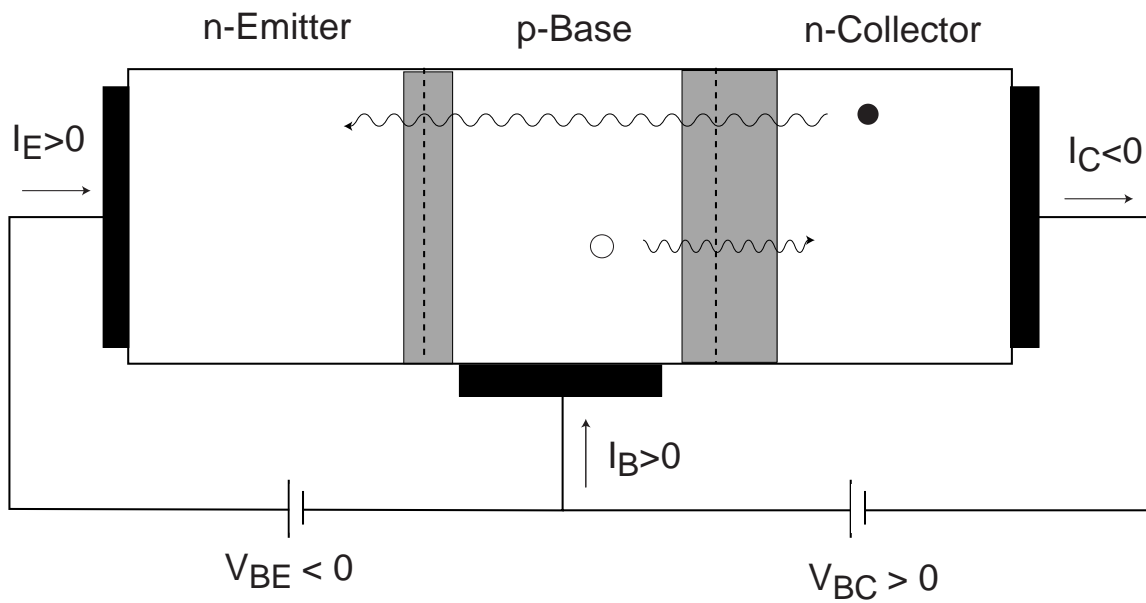
$$I_B = \frac{I_S}{\beta_F} \left( \exp \frac{qV_{BE}}{kT} - 1 \right)$$

- Emitter current:

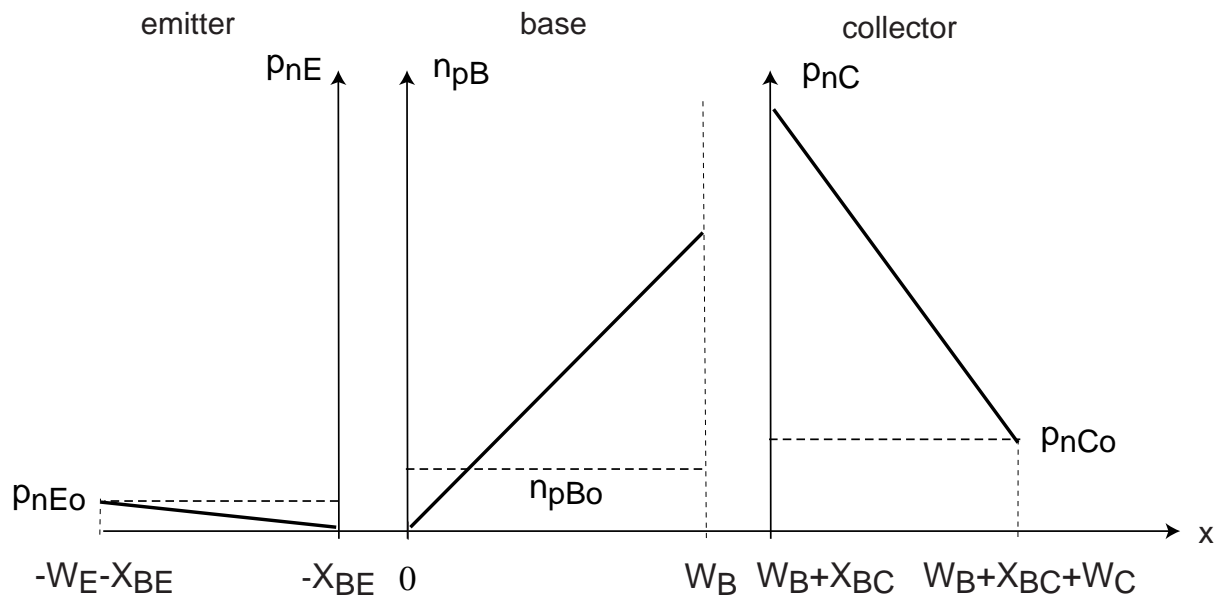
$$I_E = -I_C - I_B = -I_S \exp \frac{qV_{BE}}{kT} - \frac{I_S}{\beta_F} \left( \exp \frac{qV_{BE}}{kT} - 1 \right)$$

- State-of-the-art IC BJT's today:  $I_C \sim 0.1 - 1 \text{ mA}$ ,  $\beta_F \simeq 50 - 300$ .
- $\beta_F$  hard to control tightly  $\Rightarrow$  circuit design techniques required to be insensitive to variations in  $\beta_F$ .

□ REVERSE REGIME:  $V_{BE} < 0$ ,  $V_{BC} > 0$



Minority carrier profiles:



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

FAR:

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

identical!

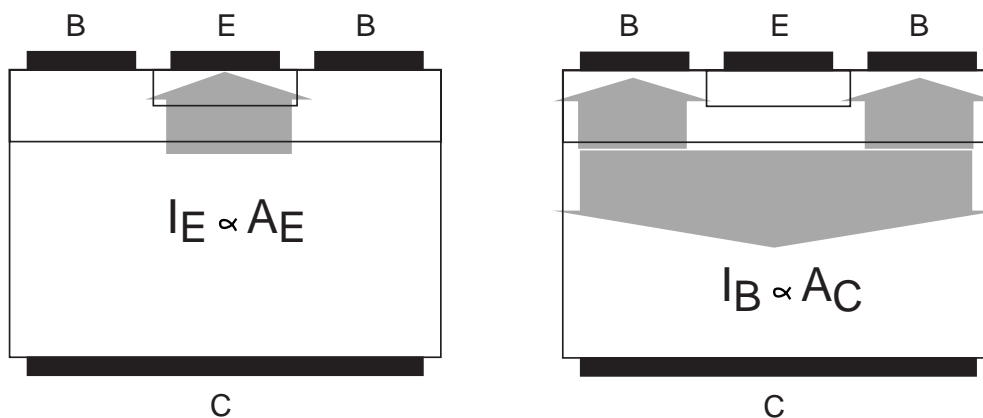
- Base injects holes into collector, recombine at collector contact and buried layer:

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

- Collector current:

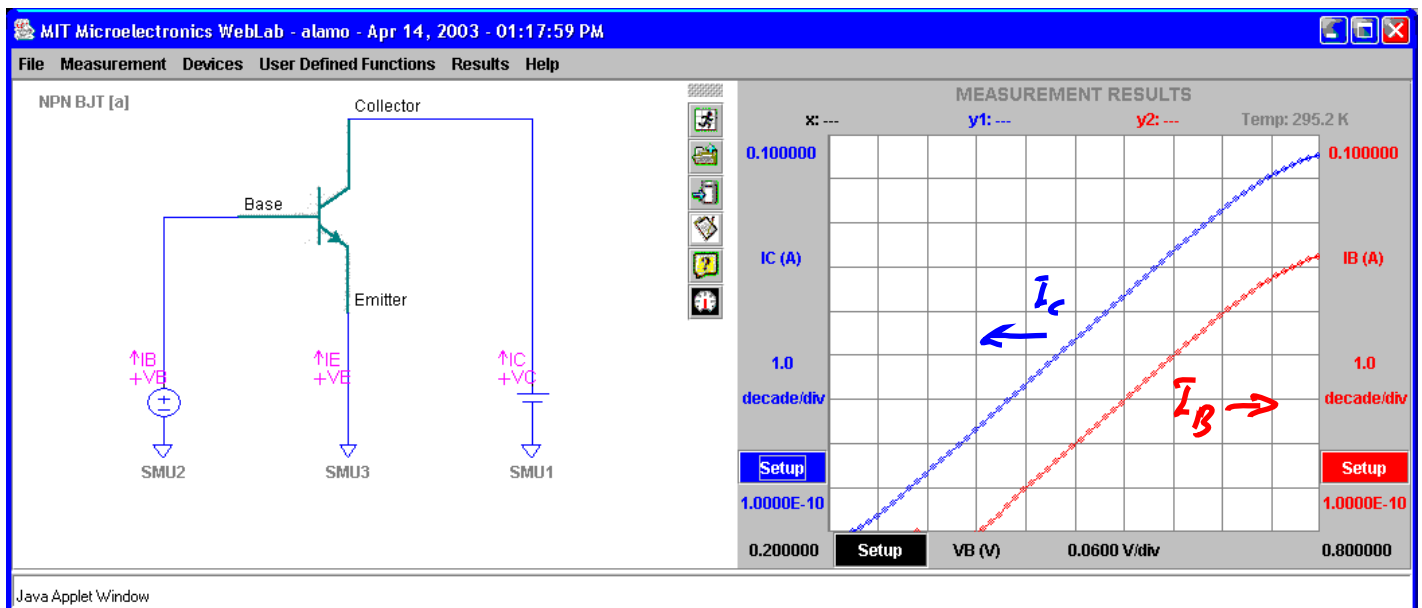
$$I_C = -I_E - I_B = -I_S \exp \frac{qV_{BC}}{kT} - \frac{I_S}{\beta_R} \left( \exp \frac{qV_{BC}}{kT} - 1 \right)$$

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

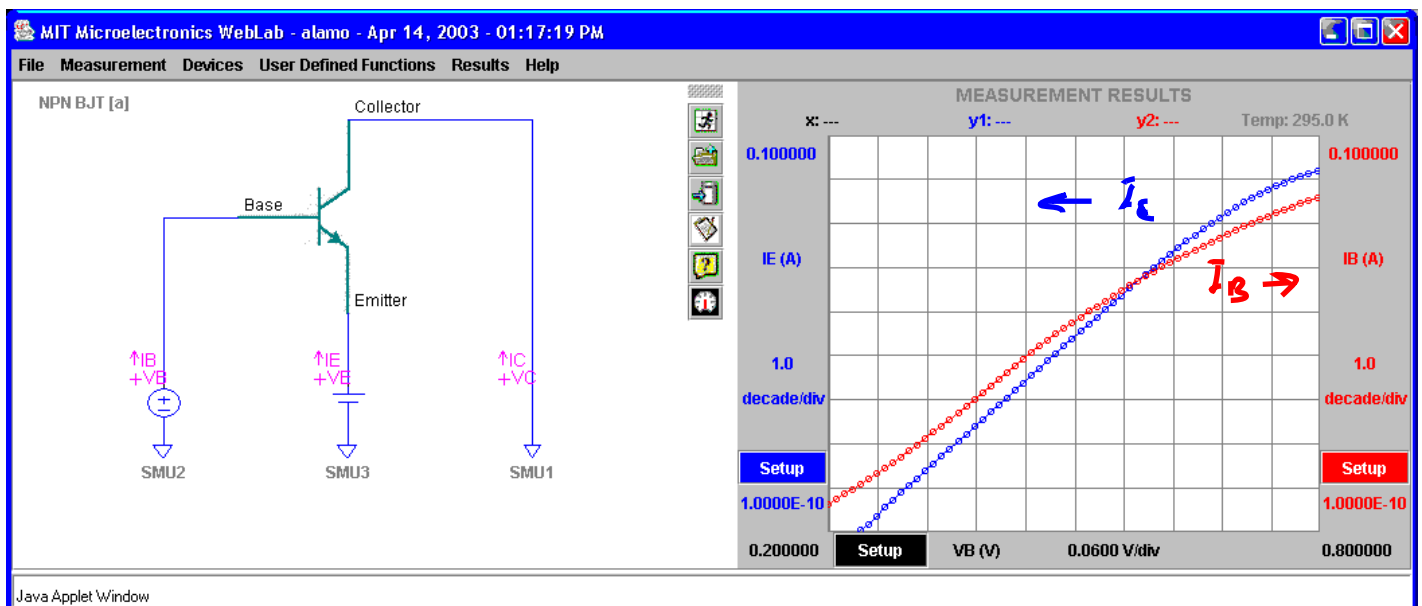




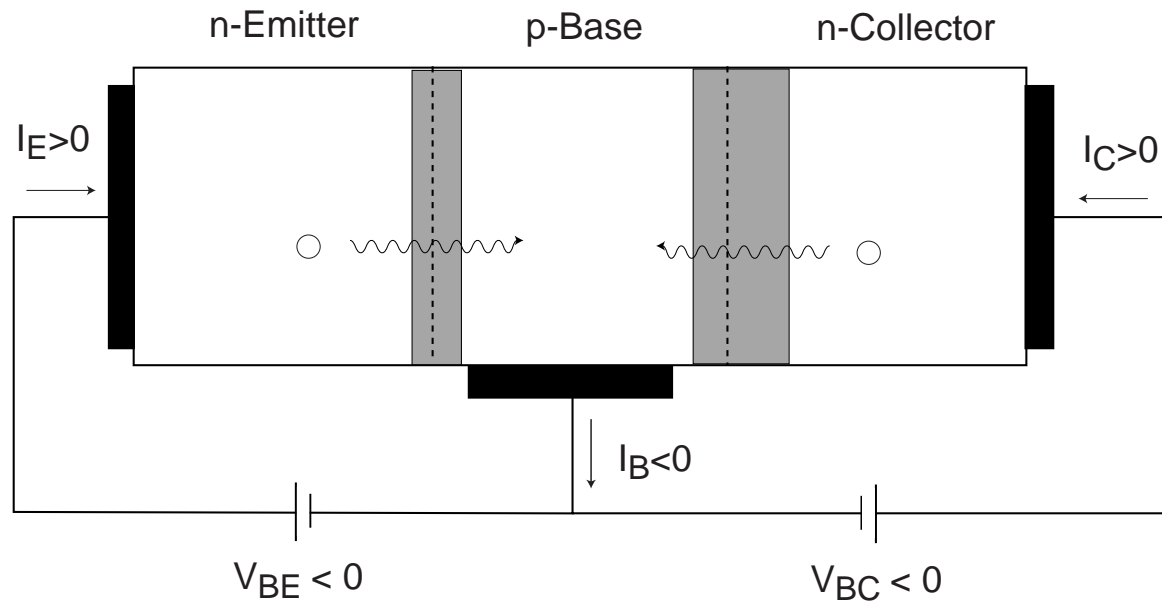
Forward-active Gummel plot ( $V_{CE} = 3\text{ V}$ ):



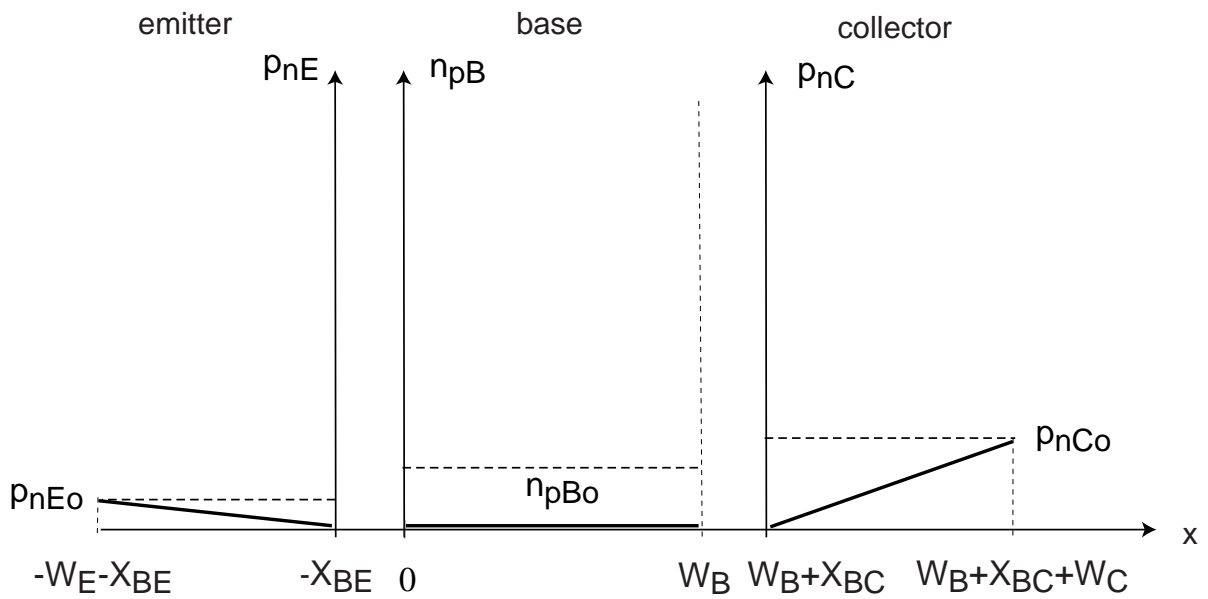
Reverse Gummel ( $V_{EC} = 3\text{ V}$ ):



□ CUT-OFF:  $V_{BE} < 0$ ,  $V_{BC} < 0$



Minority carrier profiles:



- Base extracts holes from emitter:

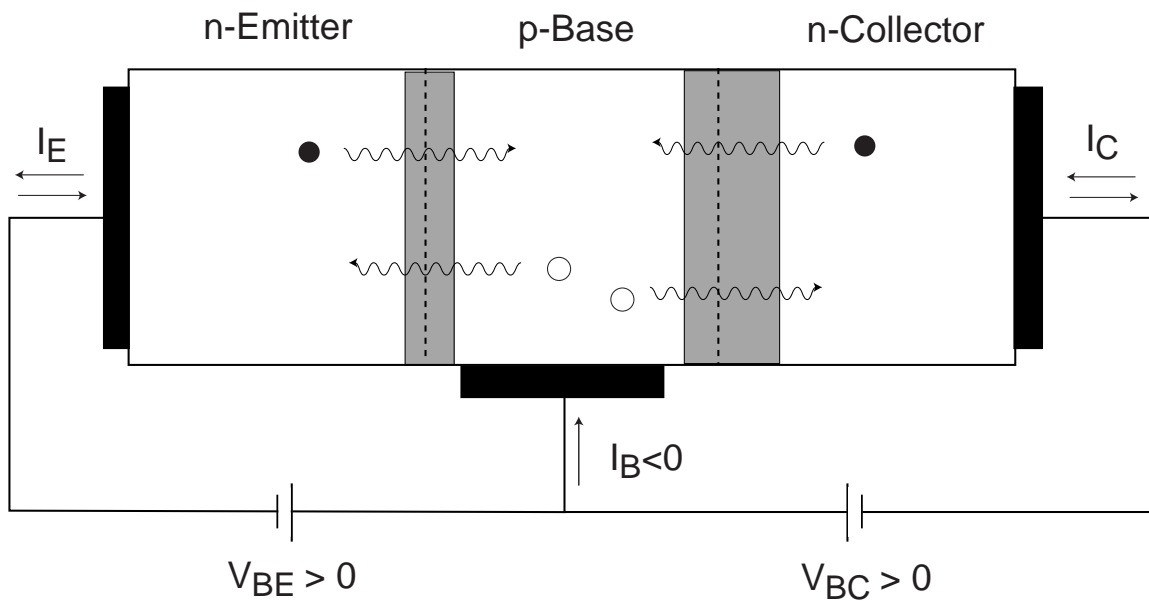
$$I_{B1} = -\frac{I_S}{\beta_F} = -I_E$$

- Base extracts holes from collector:

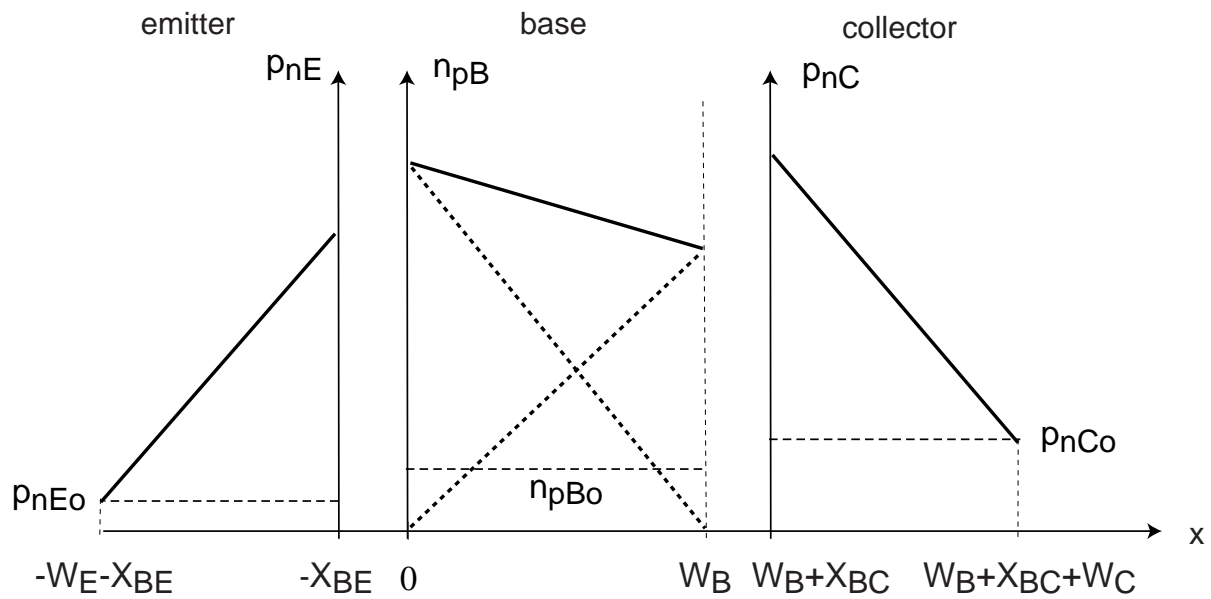
$$I_{B2} = -\frac{I_S}{\beta_R} = -I_C$$

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

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



Minority carrier profiles:



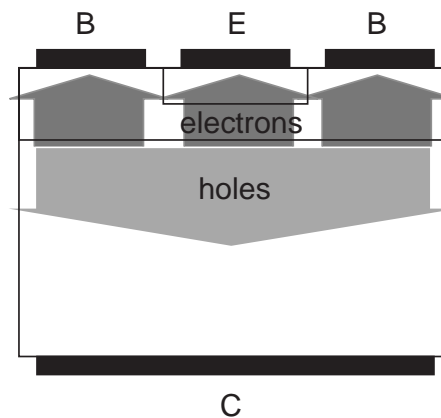
Saturation is superposition of forward active + reverse:

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

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

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

- $I_C$  and  $I_E$  can have either sign, depending on relative magnitude of  $V_{BE}$  and  $V_{BC}$ , and  $\beta_F$  and  $\beta_R$ .
- In saturation, collector and base flooded with excess minority carriers  $\Rightarrow$  takes lots of time to get transistor out of saturation.



## 2. Large-signal equivalent circuit model

System of equations that describes BJT operation:

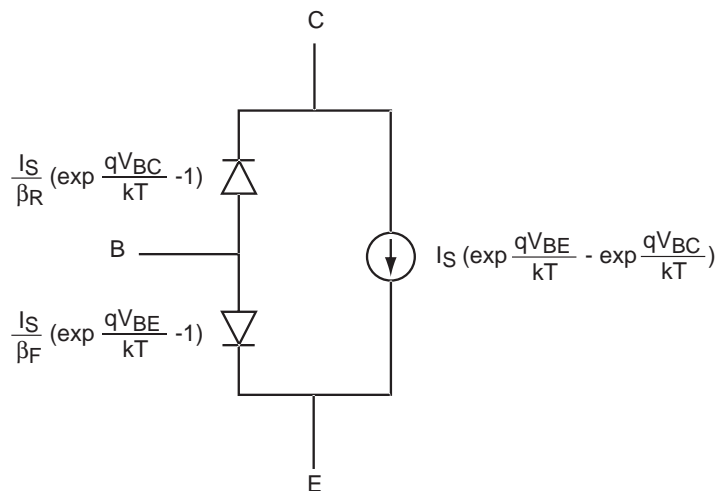
$$I_C = I_S \left( \exp \frac{qV_{BE}}{kT} - \exp \frac{qV_{BC}}{kT} \right) - \frac{I_S}{\beta_R} \left( \exp \frac{qV_{BC}}{kT} - 1 \right)$$

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

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

Equivalent-circuit model representation:

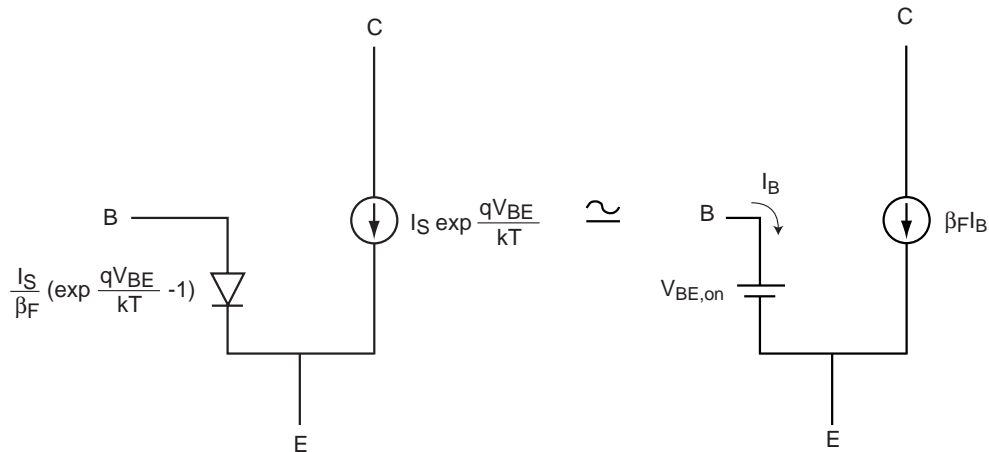
### *Non-Linear Hybrid- $\pi$ Model*



Three parameters in this model:  $I_S$ ,  $\beta_F$ , and  $\beta_R$ .  
Model equivalent to Ebers-Moll model in text.

Simplifications of equivalent-circuit model:

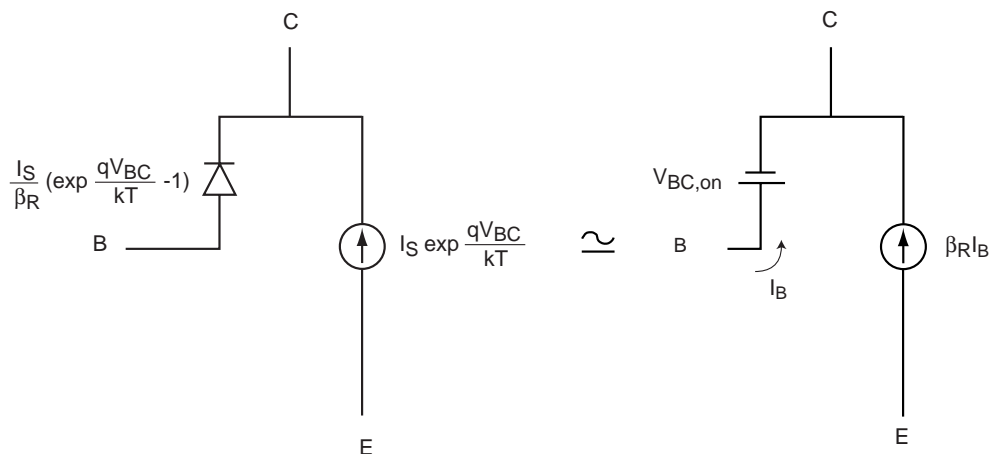
- Forward-active regime:  $V_{BE} > 0$ ,  $V_{BC} < 0$



For today's technology:  $V_{BE,on} \simeq 0.7 \text{ V}$ .

$I_B$  depends on outside circuit.

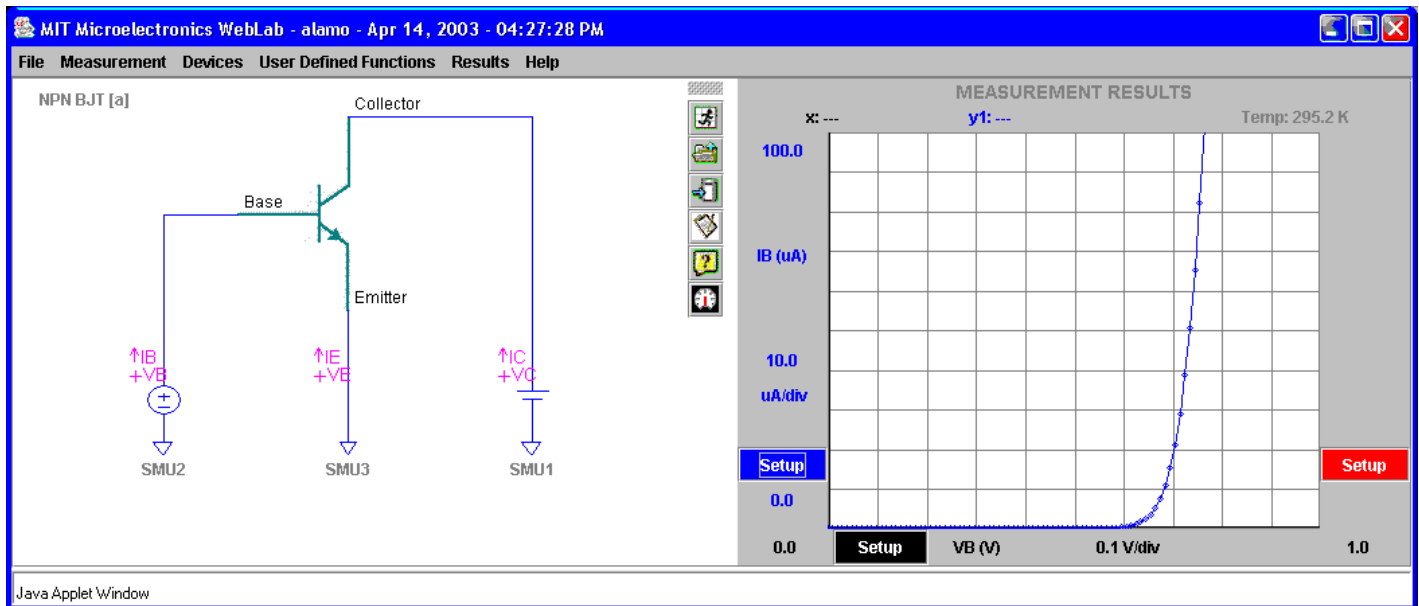
- Reverse:  $V_{BE} < 0$ ,  $V_{BC} > 0$



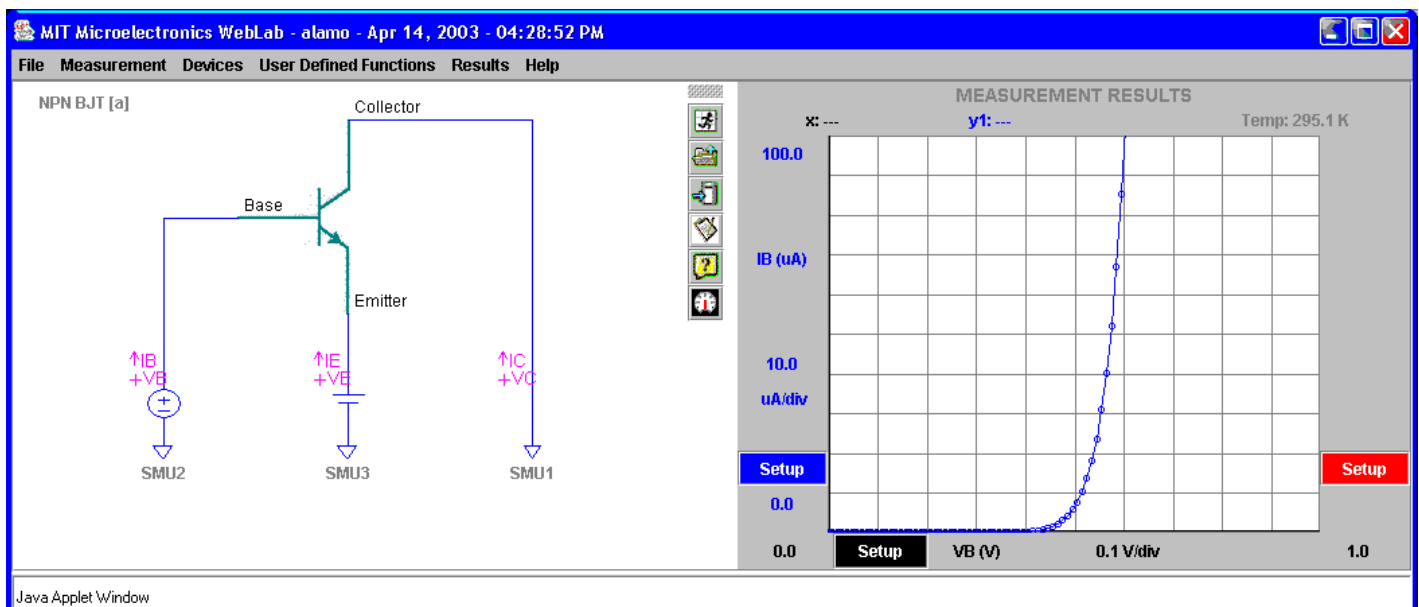
For today's technology:  $V_{BC,on} \simeq 0.5 \text{ V}$ .

$I_B$  also depends on outside circuit.

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

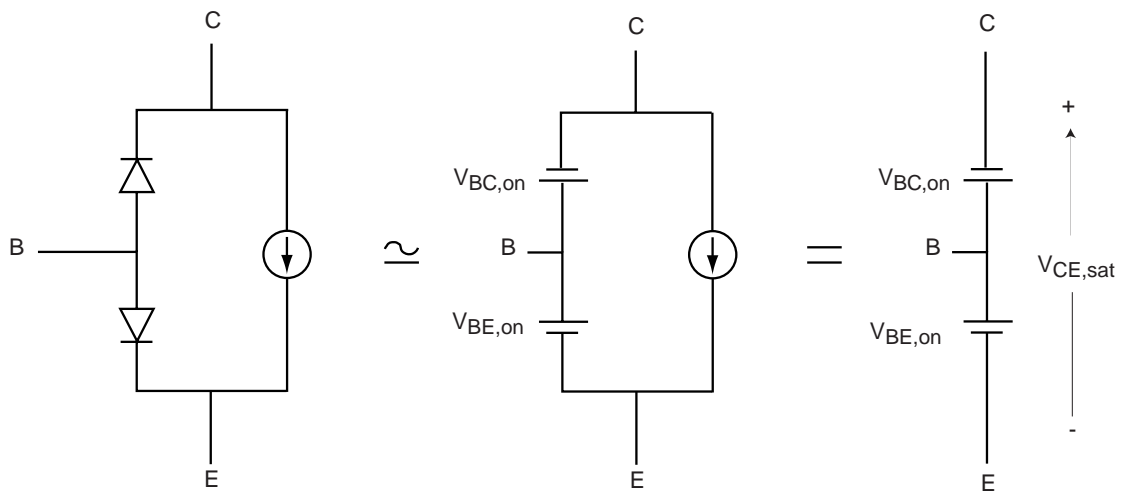


$I_B$  vs.  $V_{BC}$  for  $V_{EC} = 3\text{ V}$ :



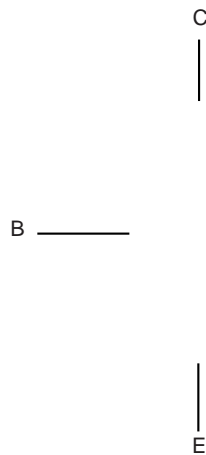


- Saturation:  $V_{BE} > 0$ ,  $V_{BC} > 0$



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.

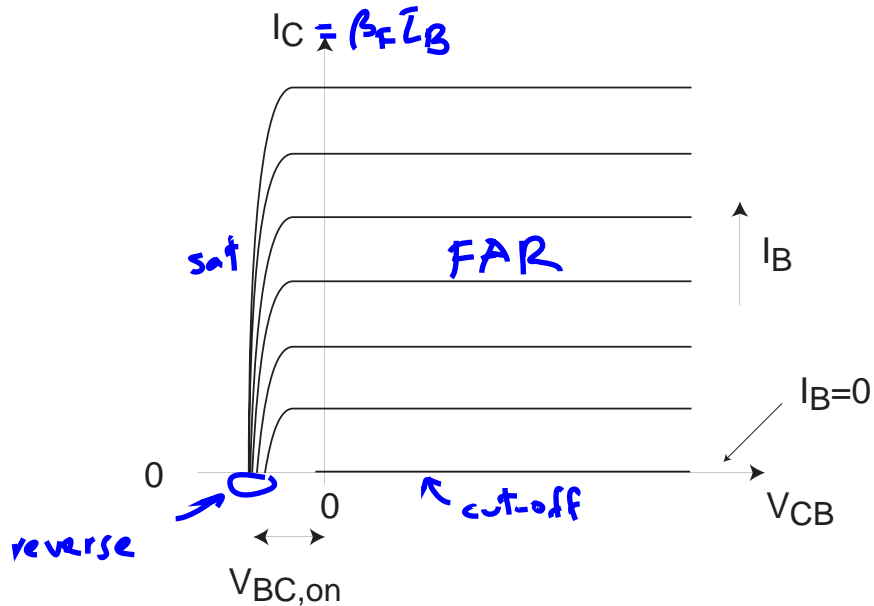
- Cut-off:  $V_{BE} < 0$ ,  $V_{BC} < 0$



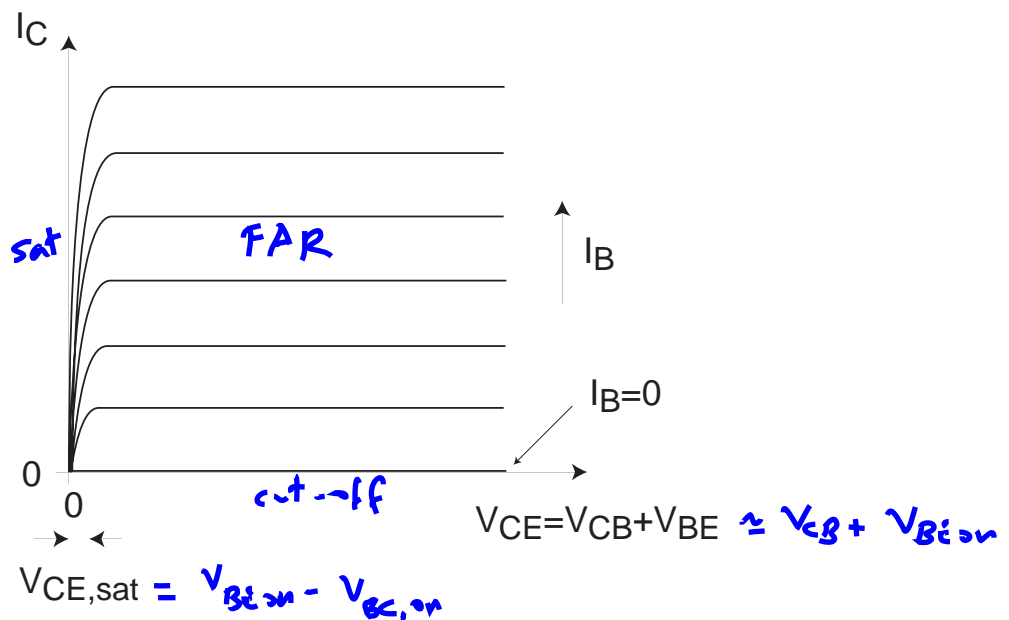
Only negligible leakage currents.

### 3. Output characteristics

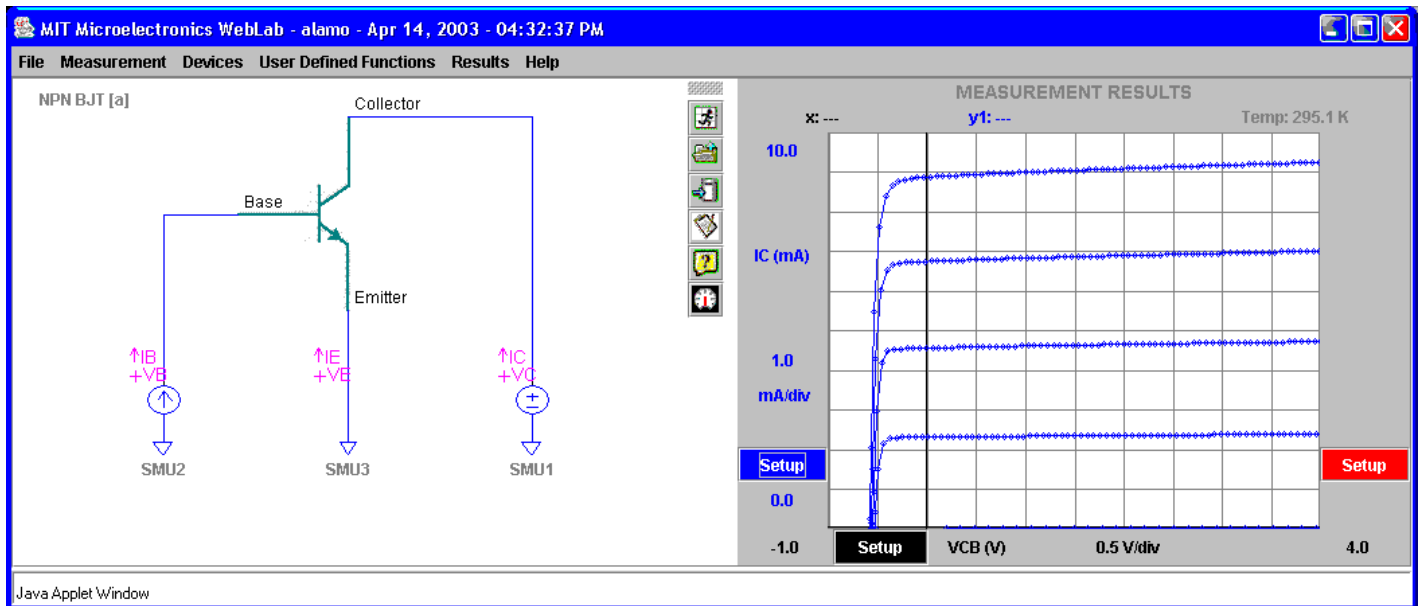
First,  $I_C$  vs.  $V_{CB}$  with  $I_B$  as parameter:



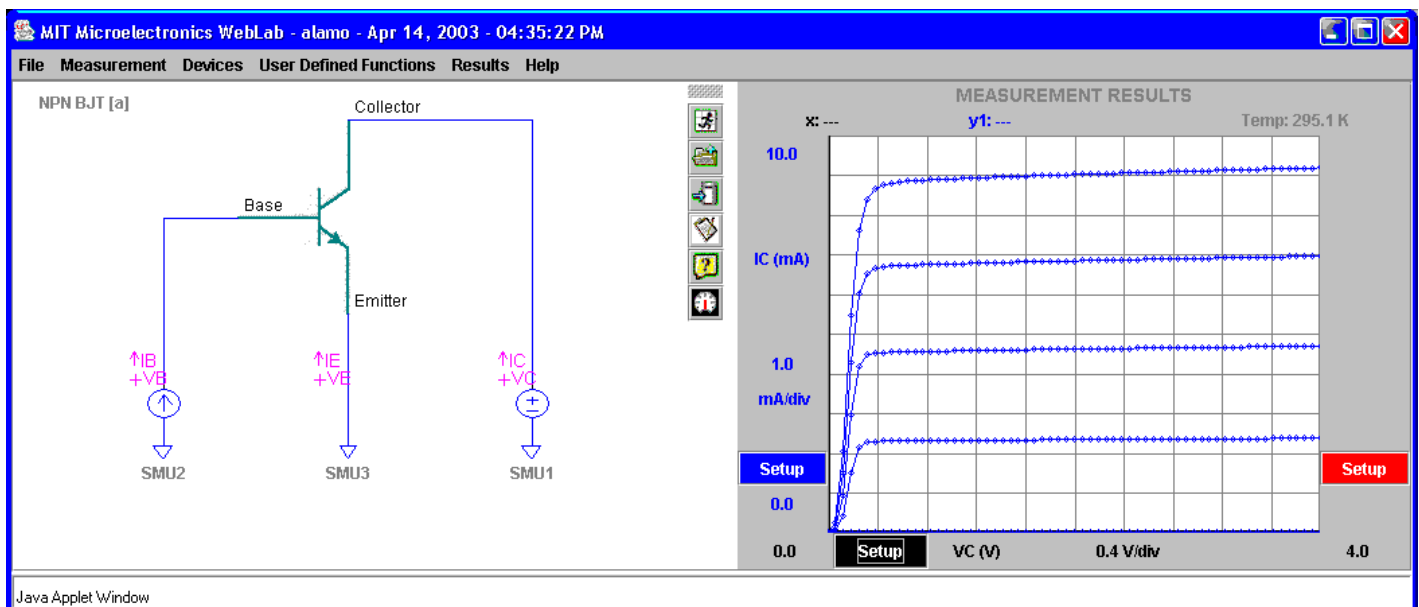
Next, *common-emitter output characteristics* ( $I_C$  vs.  $V_{CE}$  with  $I_B$  as parameter):



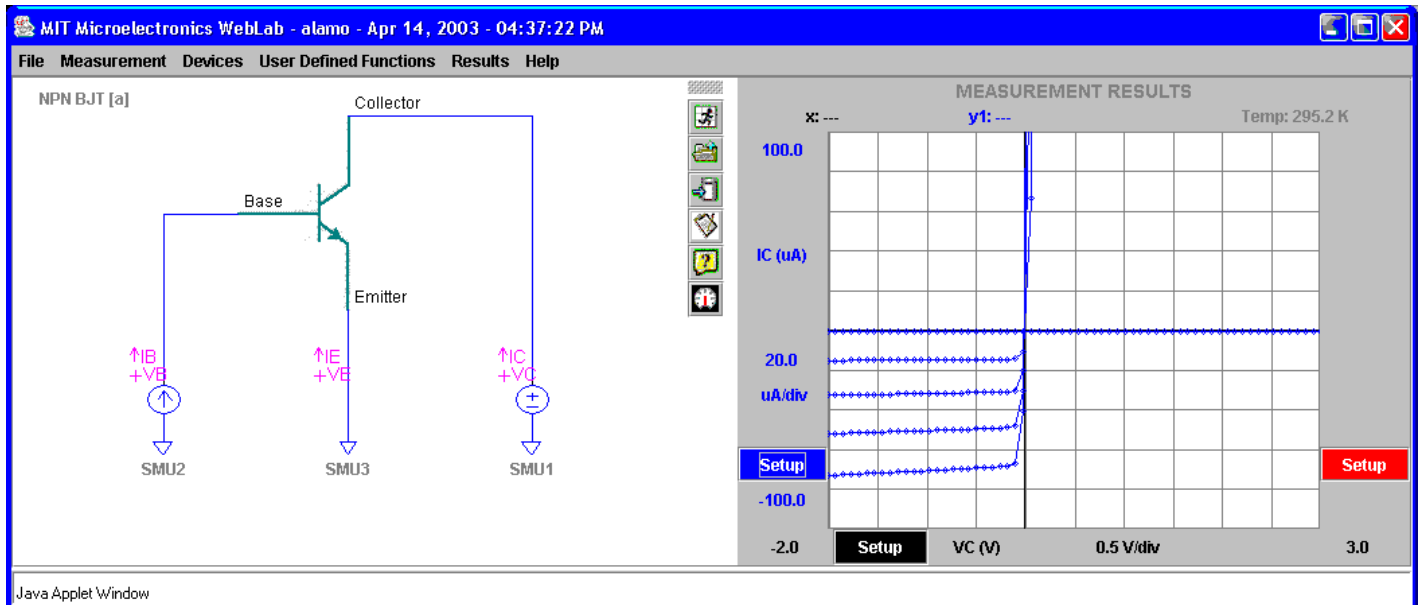
$I_C$  vs.  $V_{CB}$  for  $0 \leq I_B \leq 100 \mu A$ :



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

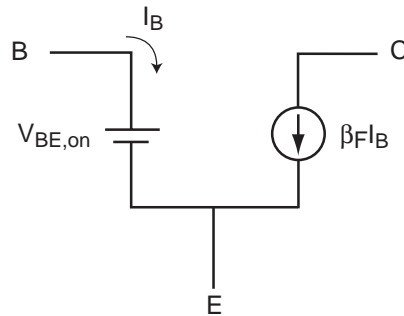


$I_C$  vs.  $V_{CE}$  for  $0 \leq I_B \leq 100 \mu A$ :

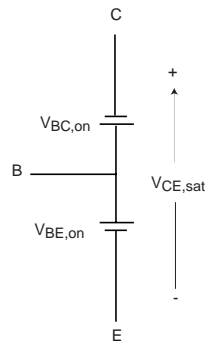


## Key conclusions

- 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:

