Lecture 17

The Bipolar Junction Transistor (I)

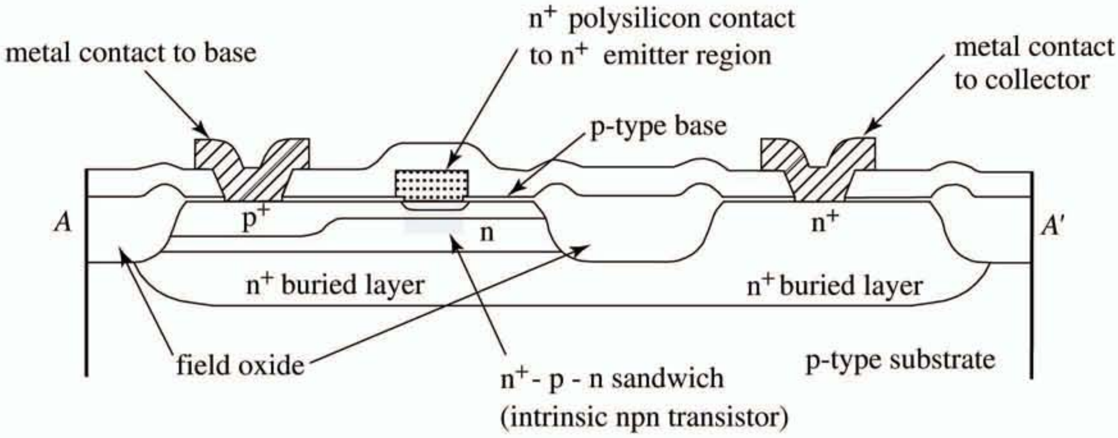
Forward Active Regime

Outline

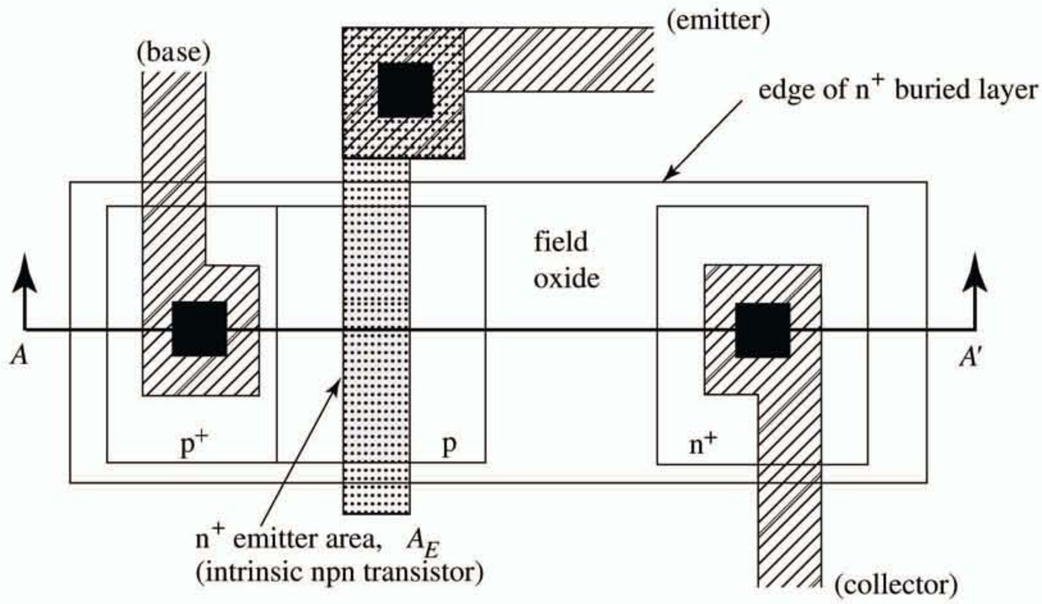
- The Bipolar Junction Transistor (BJT):
  - – structure and basic operation
- I-V characteristics in forward active regime

Reading Assignment:
Howe and Sodini; Chapter 7, Sections 7.1, 7.2

1. BJT: structure and basic operation



(a)

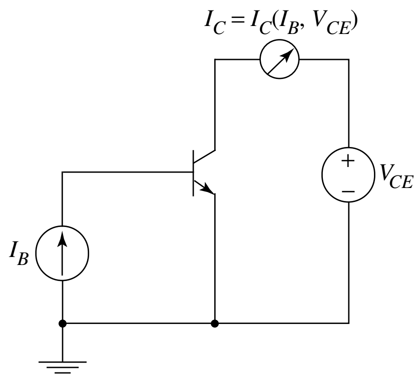


(b)

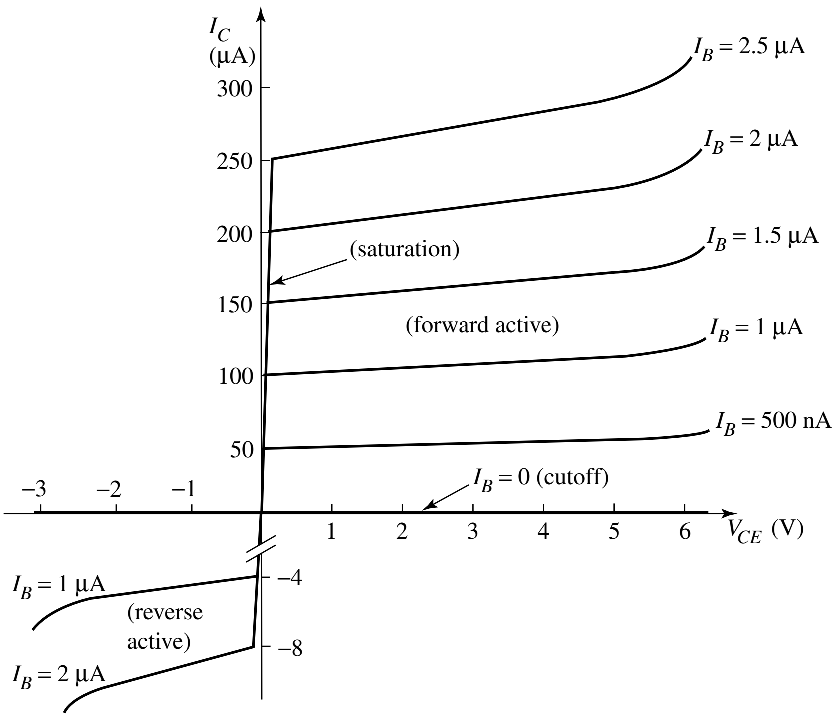
Bipolar Junction Transistor: excellent for analog and front-end communications applications.

NPN BJT Collector Characteristics

Similar to test circuit as for an n-channel MOSFET
…except I_B is the control variable rather than V_{BE}

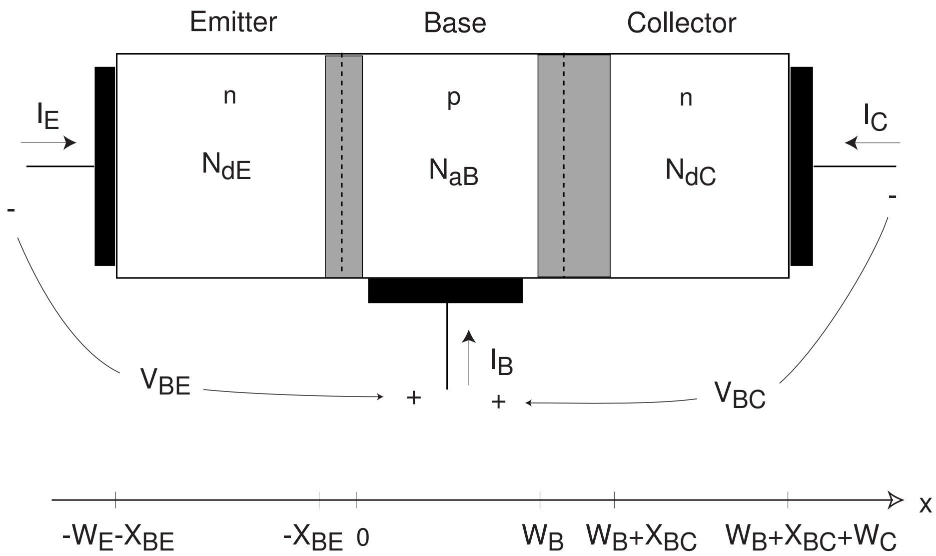


(a)



(b)

Simplified one-dimensional model of intrinsic device:

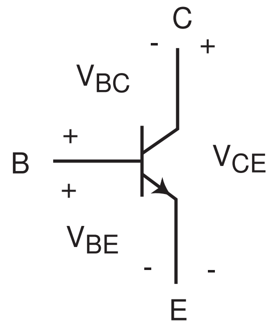


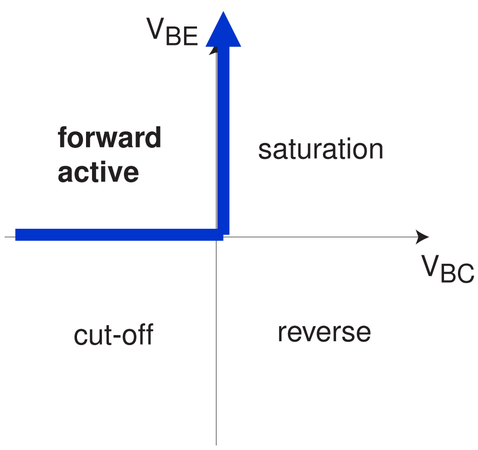
BJT=two neighboring pn junctions back-to-back

- Close enough for minority carriers to interact
  - ⇒ can diffuse quickly through the base
- Far apart enough for depletion regions not to interact
  - ⇒ prevent "punchthrough"

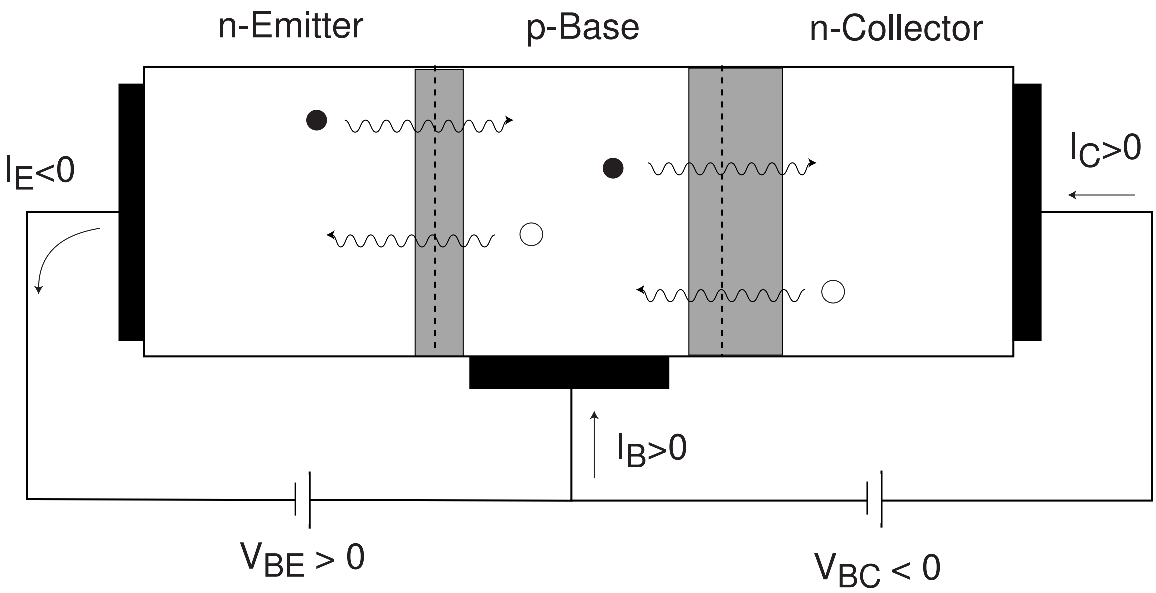
Regions of operation:

$$V_{CE} = V_{BE} - V_{BC}$$





Basic Operation: forward-active regime



$V_{BE}>0 \Rightarrow$ injection of electrons from the ***Emitter*** to the ***Base***

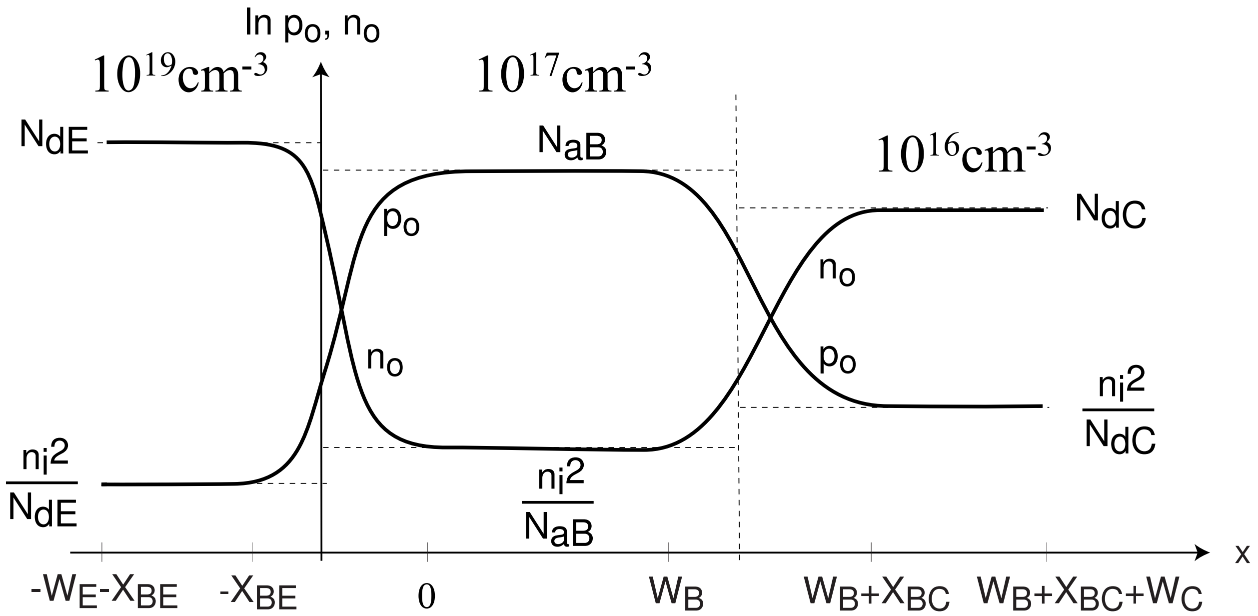
injection of holes from the ***Base*** to the ***Emitter***

$V_{BC}<0 \Rightarrow$ extraction of electrons from the ***Base*** to the ***Collector***

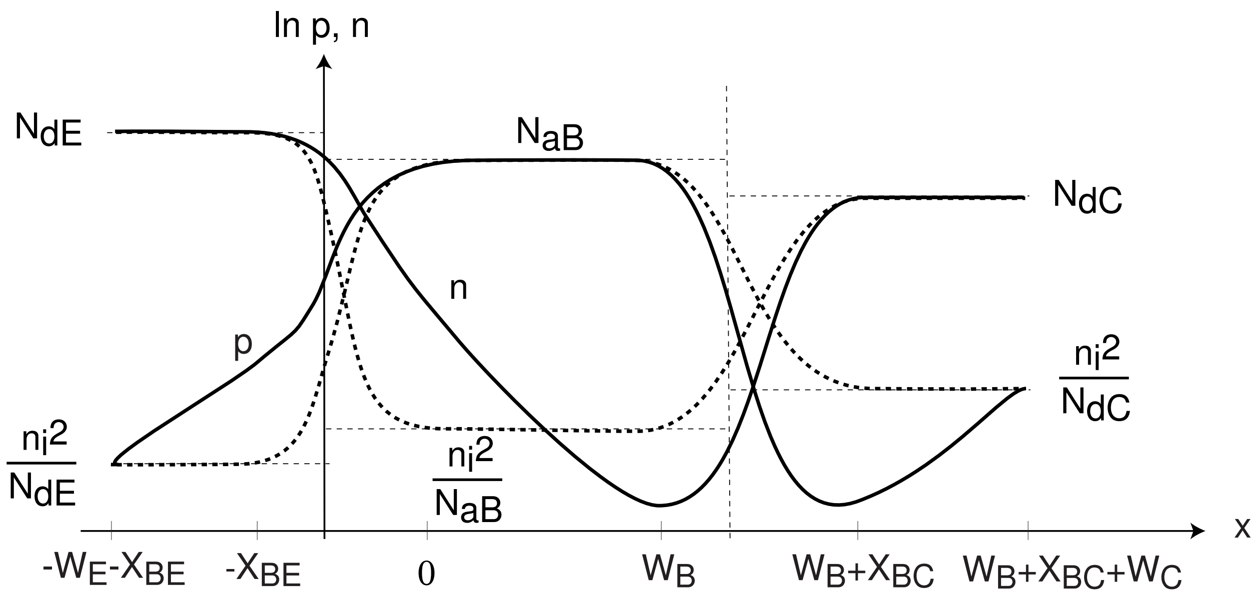
extraction of holes from the ***Collector*** to the ***Base***

Basic Operation: forward-active regime

• **Carrier profiles in thermal equilibrium:**

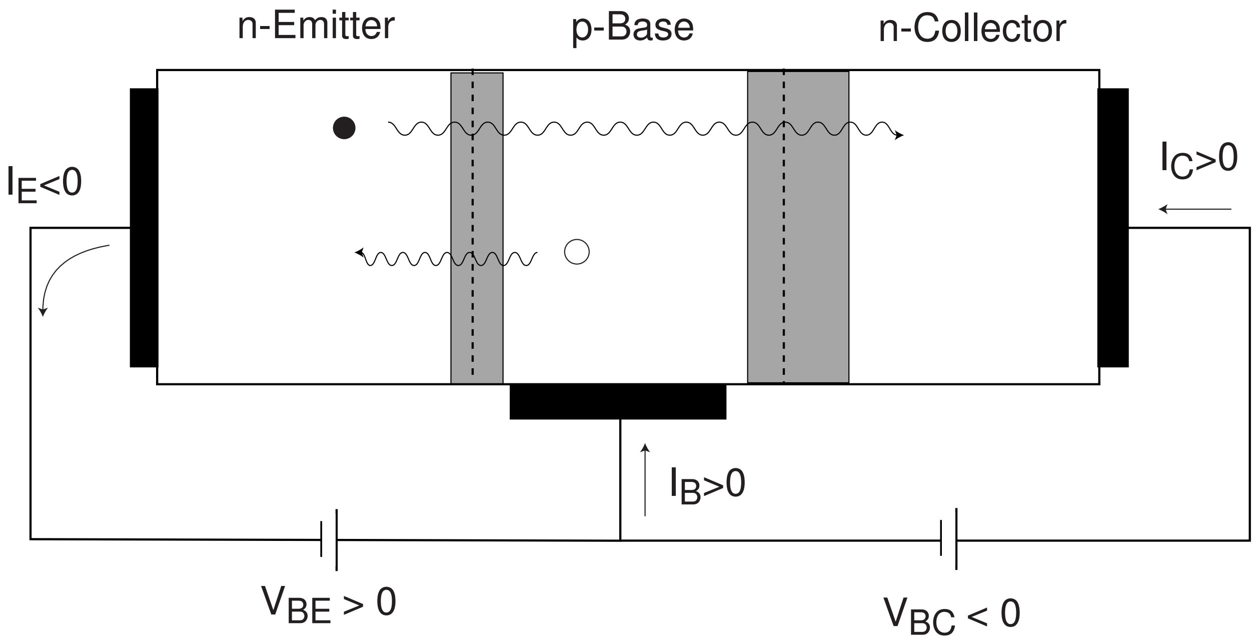


• **Carrier profiles in forward-active regime:**



Basic Operation: forward-active regime

Dominant current paths in forward active regime:



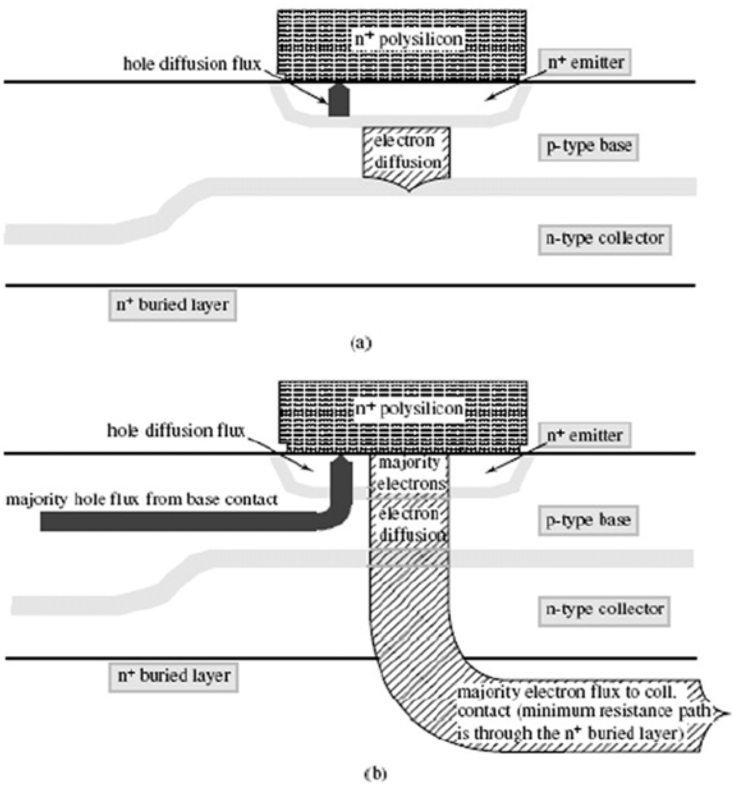
I_C: electron injection from ***Emitter*** to ***Base*** and collection by ***Collector***

I_B: hole injection from ***Base*** to ***Emitter***

I_E: $I_E = -(I_C+I_B)$

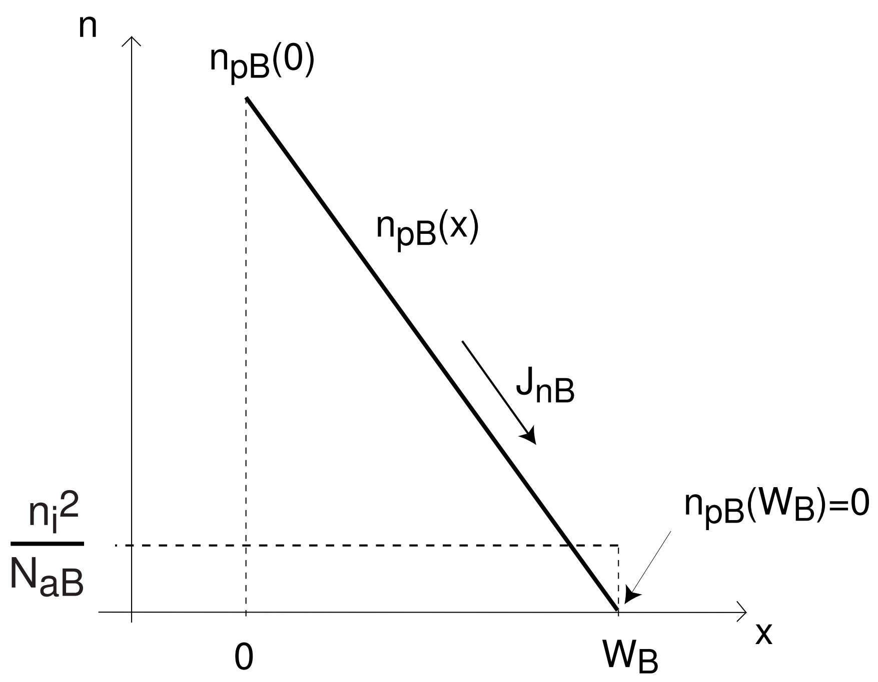
The Flux Picture - Forward Active Region

- The width of the electron flux "stream" is greater than the hole flux stream.
- The electrons are supplied by the emitter contact injected across the base-emitter SCR and diffuse across the base
- Electric field in the base-collector SCR extracts electrons into the collector.
- Holes are supplied by the base contact and diffuse across the emitter.
- The reverse injected holes recombine at the emitter ohmic contact.



2. I-V characteristics in forward-active regime

Collector current: focus on electron diffusion in base



Boundary conditions:

$$n_{pB}(0) = n_{pBo}e^{\left[\frac{V_{BE}}{V_{th}}\right]}, \qquad n_{pB}(W_B) = 0$$

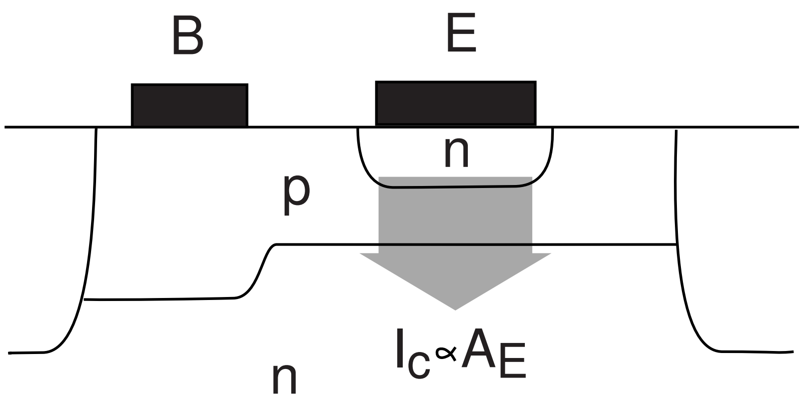
Electron profile:

$$n_{pB}(x) = n_{pB}(0)\left[1 - \frac{x}{W_B}\right]$$

Electron current density:

$$J_{nB} = qD_n \frac{dn_{pB}}{dx} = -qD_n \frac{n_{pB}(0)}{W_B}$$

Collector current scales with area of base-emitter junction A_E:



Collector terminal current:

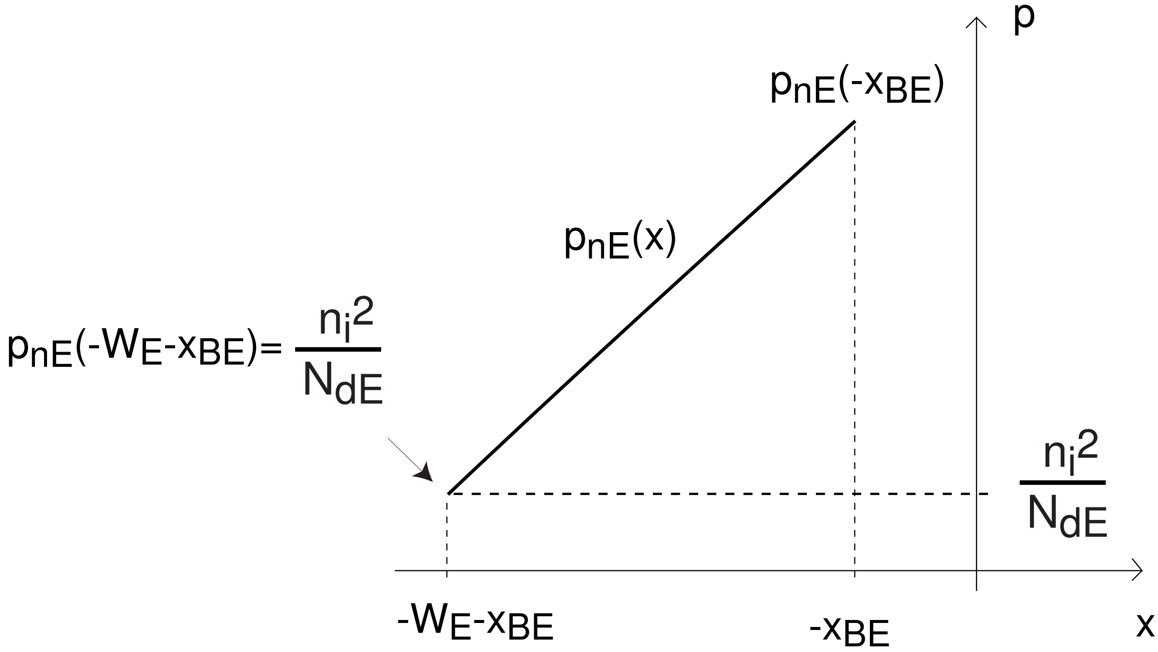
$$I_C = -J_{nB}A_E = qA_E \frac{D_n}{W_B} n_{pBo} \bullet e^{\left[\frac{V_{BE}}{V_{th}}\right]}$$

or

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

$I_S \equiv$ *transistor saturation current*

Base current: focus on hole injection and recombination at emitter contact.



Boundary conditions:

$$p_{nE}(-x_{BE}) = p_{nEo}\, e^{\left[\frac{V_{BE}}{V_{th}}\right]}; \qquad p_{nE}(-W_E - x_{BE}) = p_{nEo}$$

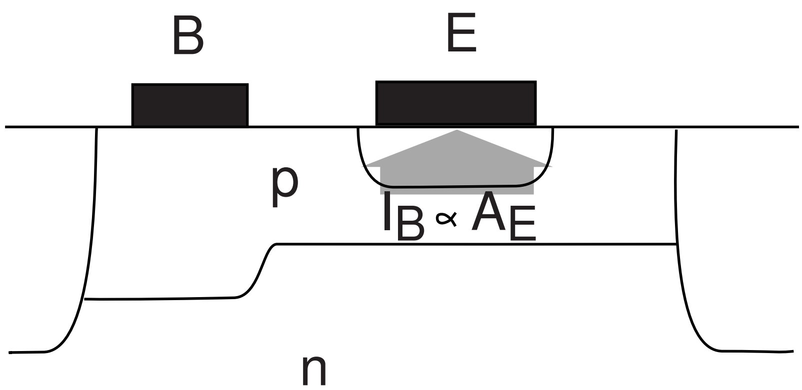
Hole profile:

$$p_{nE}(x) = \left[p_{nE}(-x_{BE}) - p_{nEo}\right] \bullet \left(1 + \frac{x + x_{BE}}{W_E}\right) + p_{nEo}$$

Hole current density:

$$J_{pE} = -qD_p \frac{dp_{nE}}{dx} = -qD_p \frac{p_{nE}(-x_{BE}) - p_{nEo}}{W_E}$$

Base current scales with area of base-emitter junction A_E:



Base terminal current:

$$I_B = -J_{pE} A_E = qA_E \frac{D_p}{W_E} p_{nEo} \bullet \left(e^{\left[\frac{V_{BE}}{V_{th}}\right]} - 1 \right)$$

$$I_B \approx qA_E \frac{D_p}{W_E} p_{nEo} \bullet e^{\left[\frac{V_{BE}}{V_{th}}\right]}$$

Emitter current: $-(I_B + I_C)$

$$I_E = -\left[\left(qA_E \frac{D_p}{W_E} p_{nEo} \right) + \left(qA_E \frac{D_n}{W_B} n_{pBo} \right) \right] \bullet e^{\left[\frac{V_{BE}}{V_{th}}\right]}$$

Forward Active Region: Current gain

$$\alpha_F = \frac{I_C}{|I_E|} = \frac{1}{1 + \dfrac{N_{aB} D_p W_B}{N_{dE} D_n W_E}}$$

Want α_F close to unity---> typically $\alpha_F = 0.99$

$$I_B = -I_E - I_C = \frac{I_C}{\alpha_F} - I_C = I_C \left(\frac{1 - \alpha_F}{\alpha_F} \right)$$

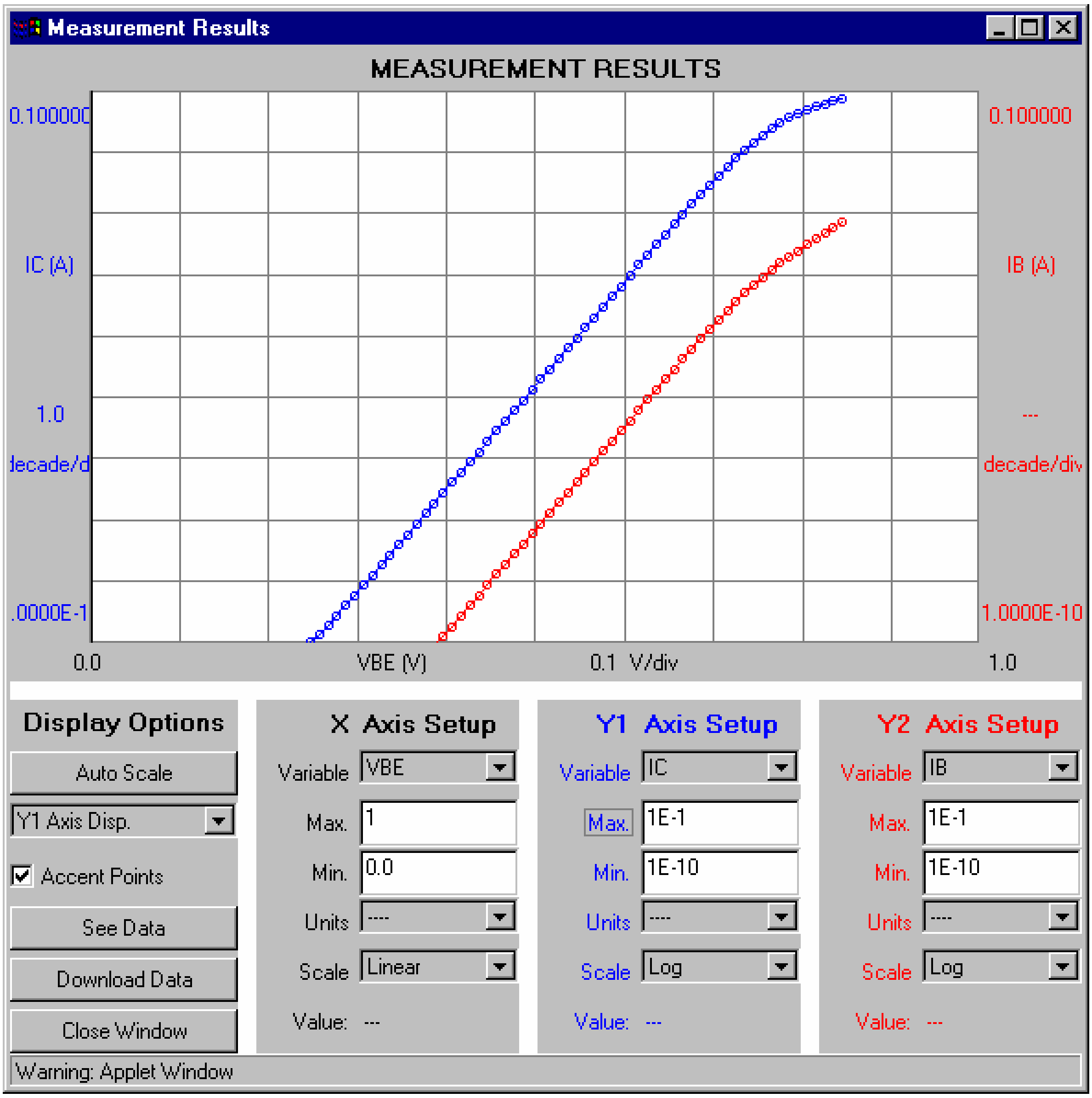
$$\beta_F = \frac{I_C}{I_B} = \left(\frac{\alpha_F}{1 - \alpha_F} \right)$$

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

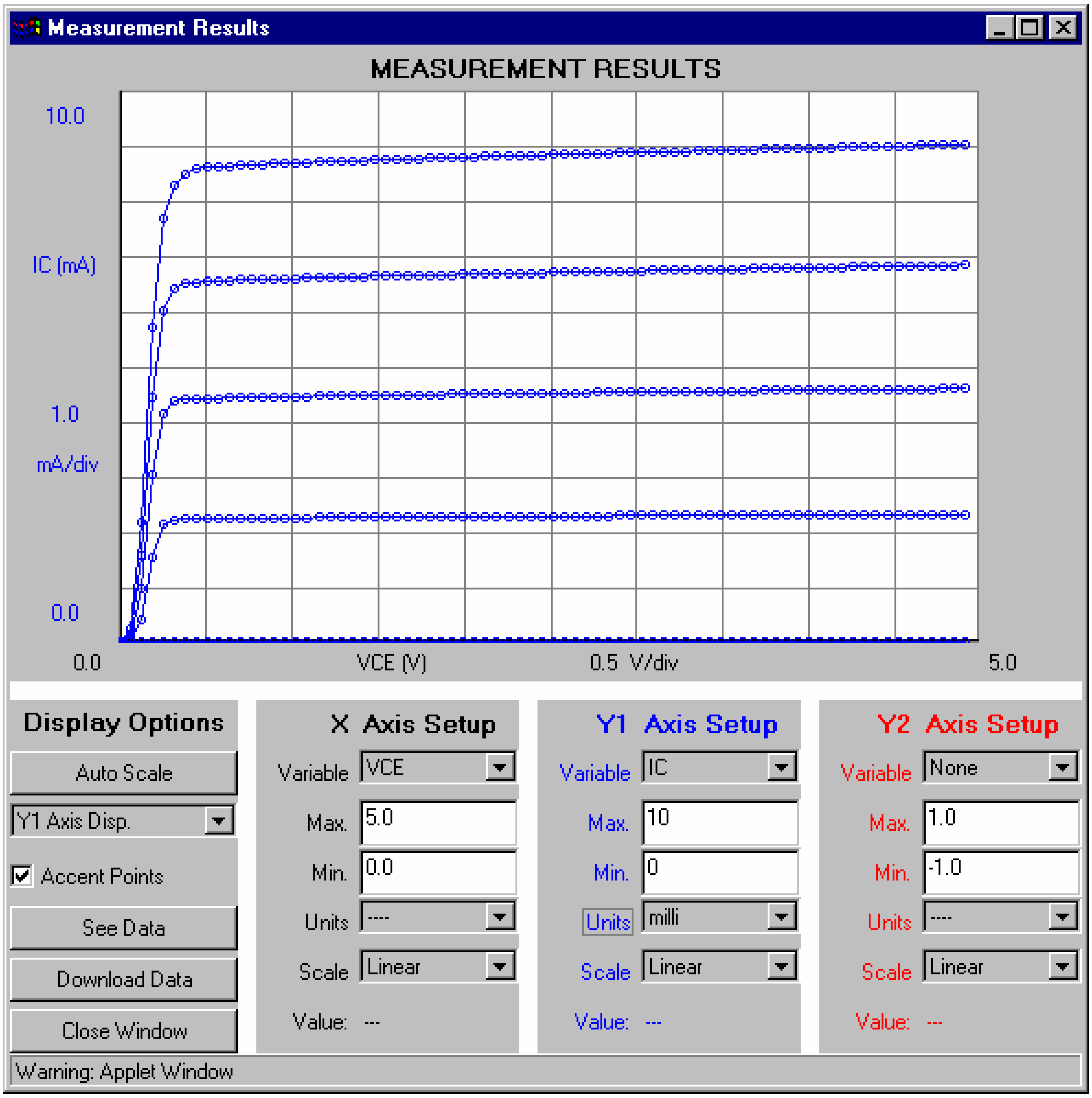
To maximize β_F:

- $N_{dE} >> N_{aB}$
- $W_E >> W_B$
- want npn, rather than pnp design because $D_n > D_p$

Plot of log I_C and log I_B vs V_{BE}



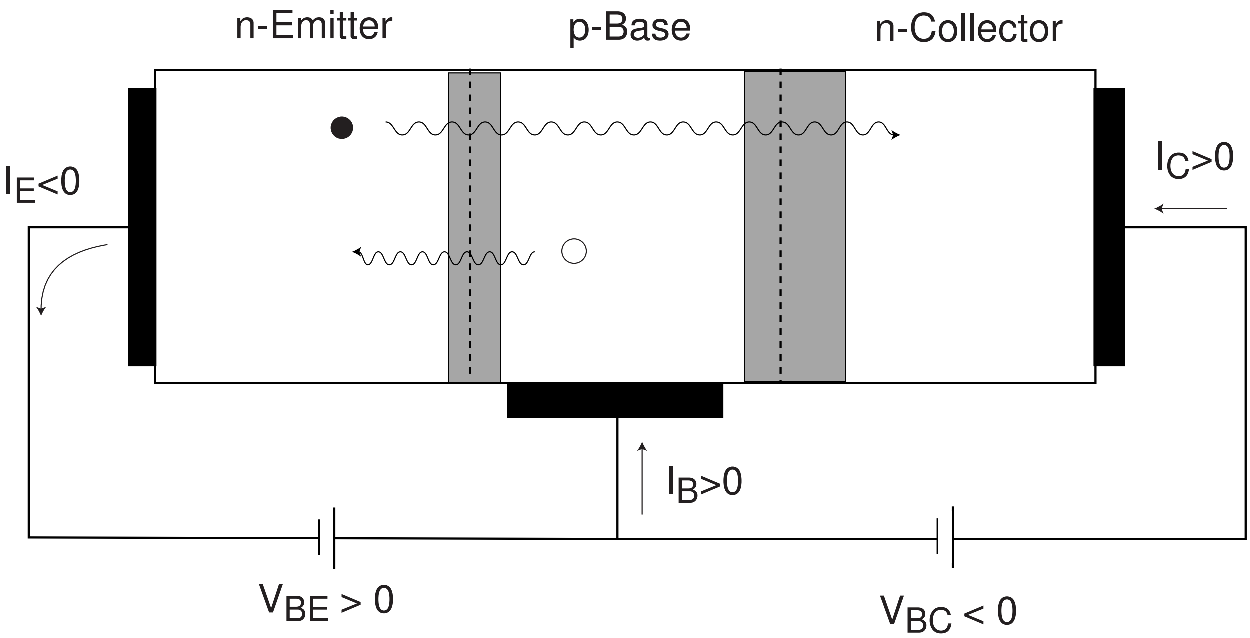
Common-Emitter Output Characteristics



What did we learn today?

Summary of Key Concepts

npn BJT in forward active regime:



- ***Emitter*** "injects" electrons into ***Base***, ***Collector*** "collects" electrons from ***Base***
  - I_C controlled by V_{BE}, independent of V_{BC}
  - (***transistor effect***)

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

- ***Base***: injects holes into ***Emitter*** $\Rightarrow$ I_B

$$I_C \propto I_B$$