Lecture 17 - The Bipolar Junction Transistor (I)

FORWARD ACTIVE REGIME

November 8, 2005

Contents:

1. BJT: structure and basic operation

2. I-V characteristics in forward active regime

Reading assignment:

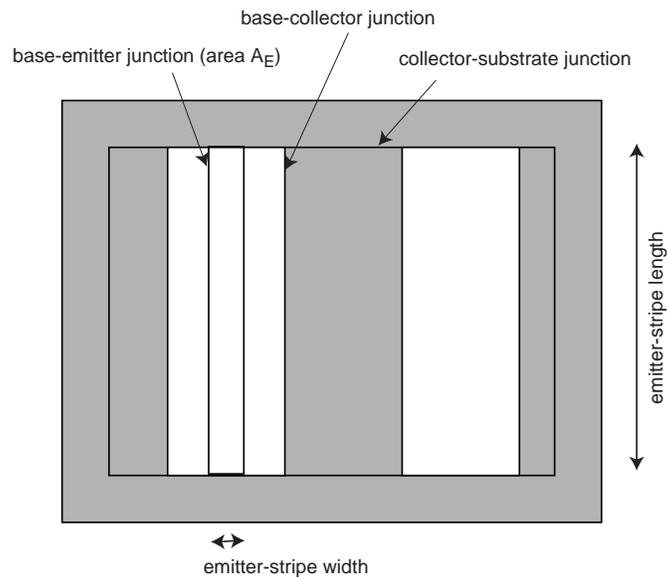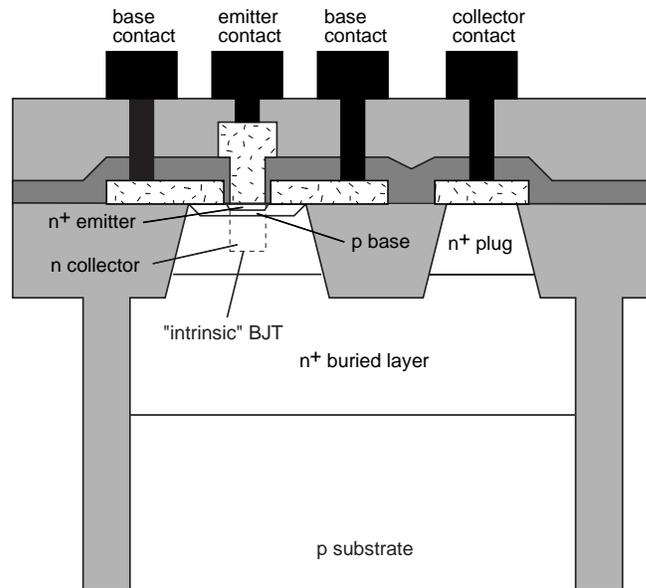Howe and Sodini, Ch. 7, §§7.1, 7.2

Announcements:

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

Key questions

- What does a bipolar junction transistor look like?

- How does a bipolar junction transistor operate?

- What are the leading dependencies of the terminal currents of a BJT in the forward active regime?

1. BJT: structure and basic operation

base contact | emitter contact | base contact | collector contact

n^+ emitter

n collector

p base

n^+ plug

"intrinsic" BJT

n^+ buried layer

p substrate

base-collector junction

base-emitter junction (area A_E)

collector-substrate junction

emitter-stripe length

emitter-stripe width

Uniqueness of BJT: high-current drivability per input capacitance $\Rightarrow$ fast $\Rightarrow$ excellent for analog and front-end communications applications.
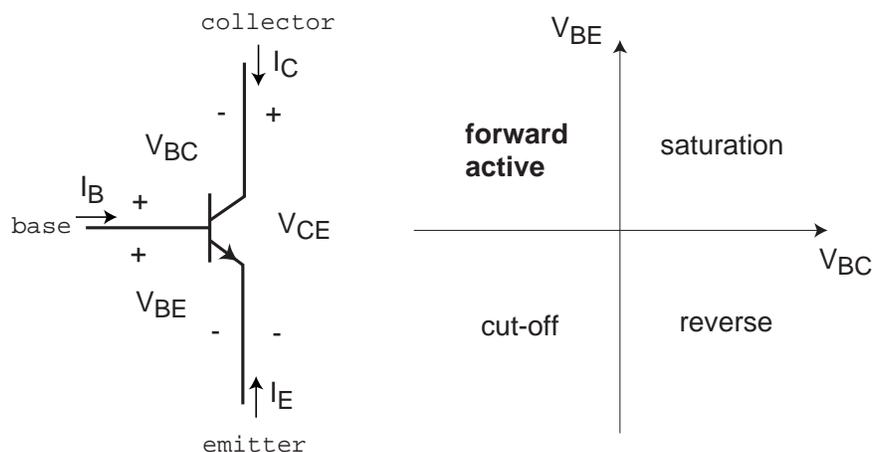
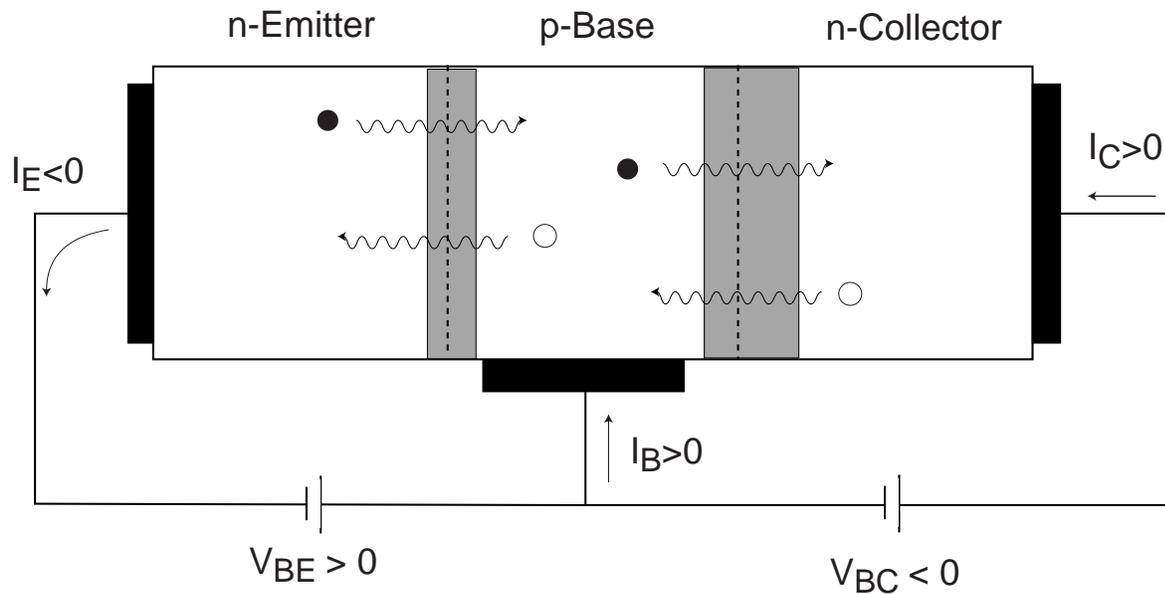# Simplified one-dimensional model of intrinsic device:
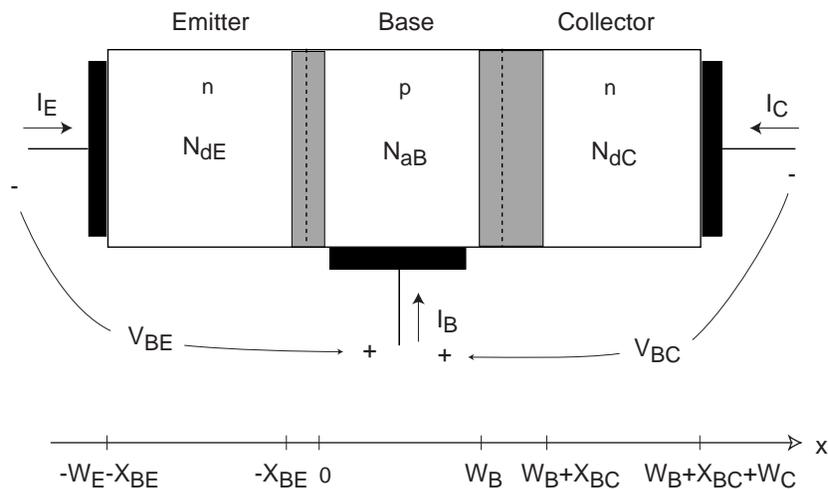
BJT = two neighbouring pn junctions back-to-back:

- close enough for minority carriers to interact (can diffuse quickly through base)

- far apart enough for depletion regions not to interact (prevent "punchthrough")

Regimes of operation:
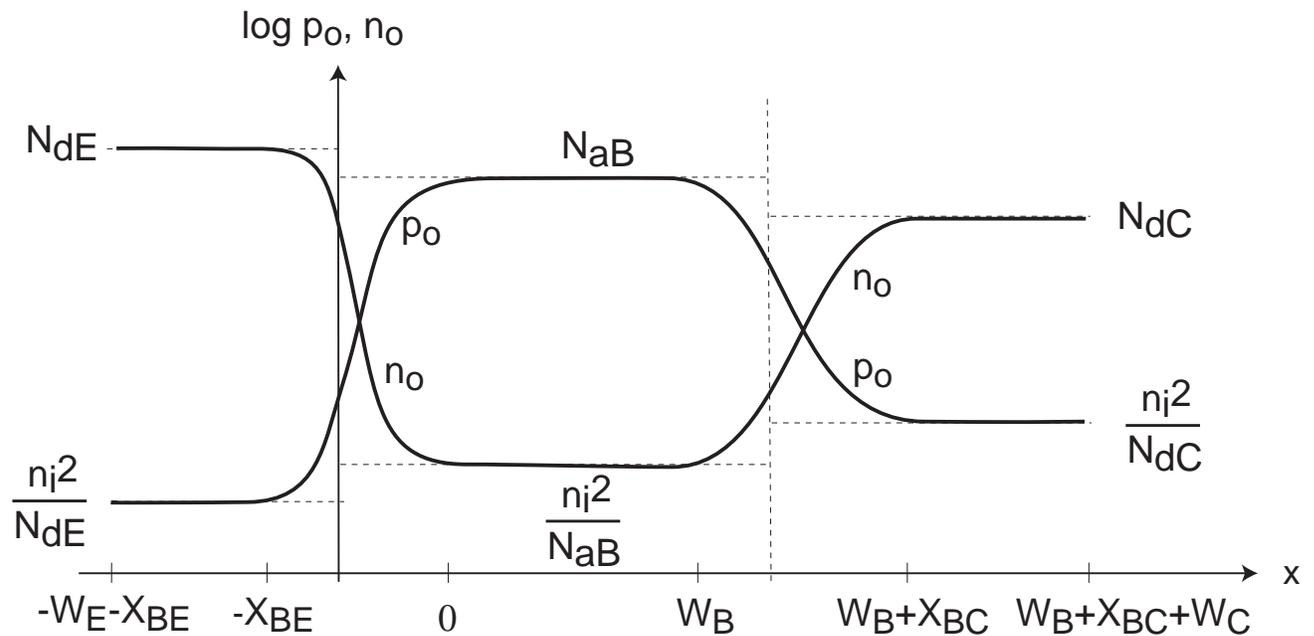
Basic operation in *forward-active regime*:

$V_{BE} > 0 \Rightarrow$ injection of electrons from E to B
injection of holes from B to E

$V_{BC} < 0 \Rightarrow$ extraction of electrons from B to C
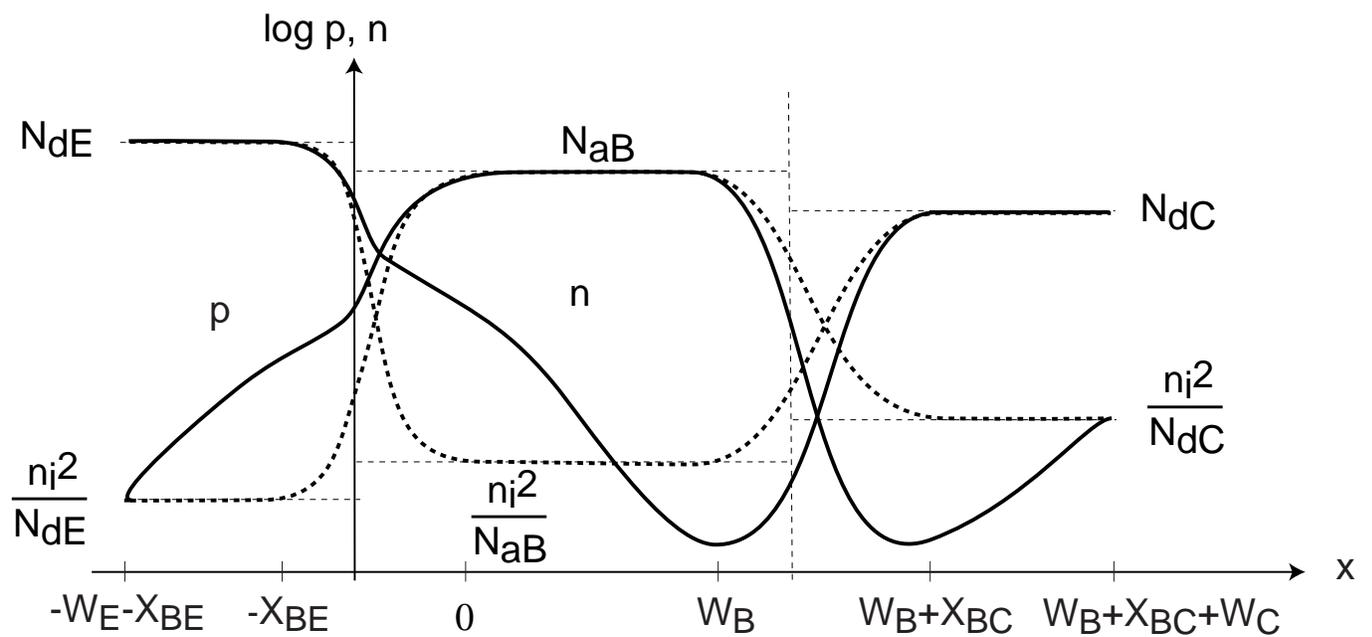extraction of holes from C to B

Transistor effect:
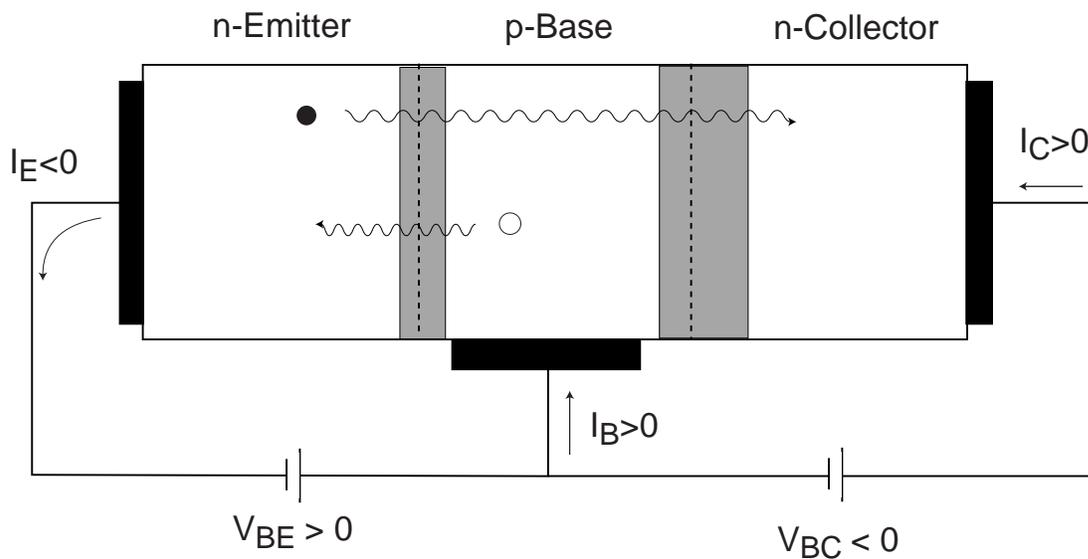electrons injected from E to B, extracted by C!

- Carrier profiles in thermal equilibrium:

- Carrier profiles in forward-active regime:

Dominant current paths in forward active regime:

I_C: electron injection from E to B and collection into C

I_B: hole injection from B to E

$I_E = -I_C - I_B$

Key dependencies (choose one):

I_C on V_{BE}: $e^{qV_{BE}/kT}$, $1/\sqrt{V_{BE}}$, *none, other*

I_C on V_{BC}: $e^{qV_{BC}/kT}$, $1/\sqrt{V_{BC}}$, *none, other*

I_B on V_{BE}: $e^{qV_{BE}/kT}$, $1/\sqrt{V_{BE}}$, *none, other*

I_B on V_{BC}: $e^{qV_{BC}/kT}$, $1/\sqrt{V_{BC}}$, *none, other*

I_C on I_B: *exponential, quadratic, none, other*

In forward-active regime:

- V_{BE} controls I_C ("transistor effect")

- I_C independent of V_{BC} ("isolation")

- price to pay for control: I_B

Comparison with MOSFET:

| feature	ideal MOSFET in saturation	ideal BJT in FAR
controlling terminal	gate	base
common terminal	source	emitter
controlled terminal	drain	collector
functional dependence of controlled current	quadratic	exponential
DC current in controlling terminal	0	exponential

Figure of merit for BJT:

-common-emitter current gain:

$$\beta_F = \frac{I_C}{I_B} \qquad \text{(want big enough, } \simeq 100\text{)}$$

2. I-V characteristics in forward active regime

☐ *Collector current*: focus on electron diffusion in base
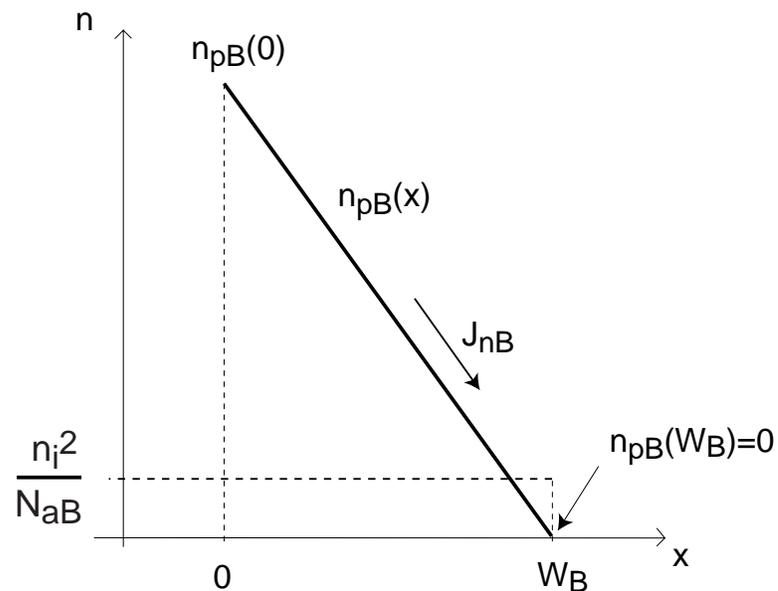
Boundary conditions:

$$n_{pB}(0) = n_{pBo} \exp \frac{qV_{BE}}{kT}, \qquad n_{pB}(W_B) = 0$$
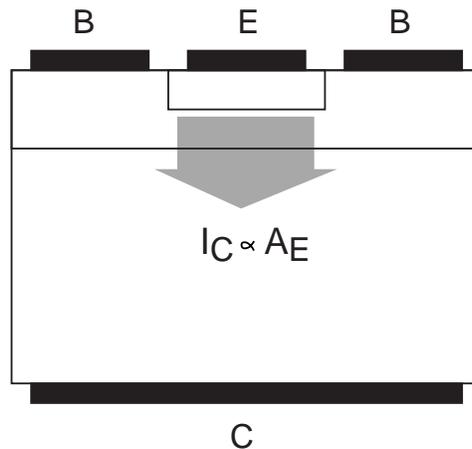
Electron profile:

$$n_{pB}(x) = n_{pB}(0)(1 - \frac{x}{W_B})$$

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:
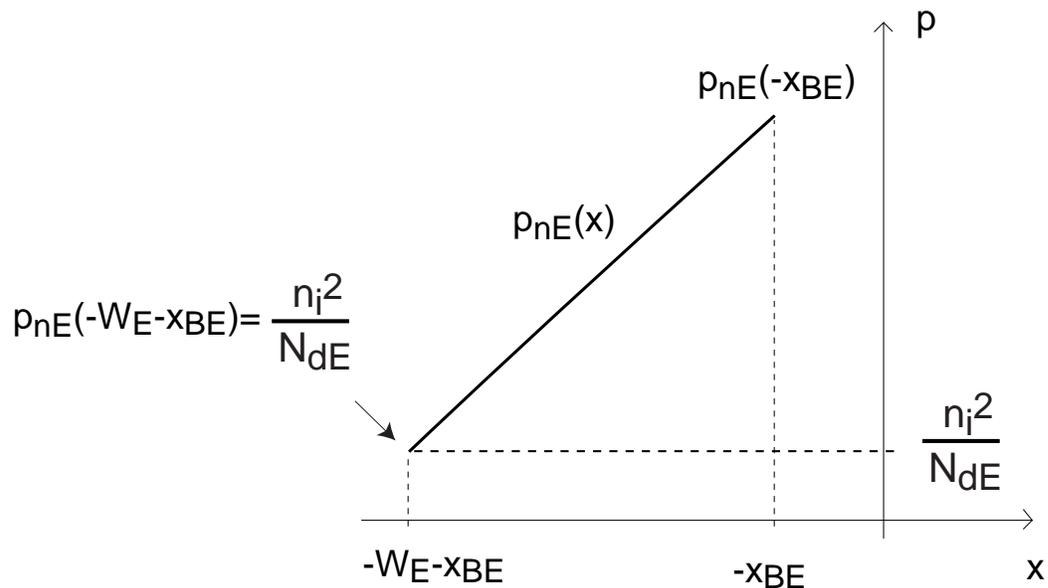

Collector terminal current:

$$I_C = -J_{nB}A_E = qA_E\frac{D_n}{W_B}n_{pBo}\exp\frac{qV_{BE}}{kT}$$

or

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

$$I_S \equiv \ collector\ saturation\ current\ [A]$$

□ *Base current*: focus on hole injection and recombination in emitter

Boundary conditions:

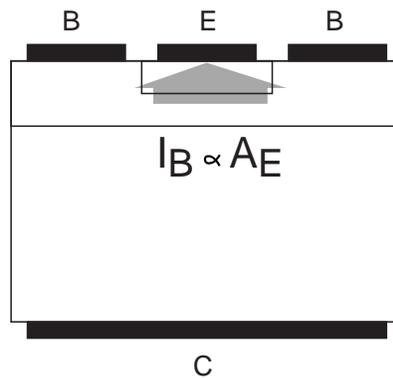$$p_{nE}(-x_{BE}) = p_{nEo} \exp \frac{qV_{BE}}{kT}, \quad p_{nE}(-W_E - x_{BE}) = p_{nEo}$$

Hole profile:

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

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:

$$I_B = -J_{pE}A_E = qA_E \frac{D_p}{W_E} p_{nEo} (\exp \frac{qV_{BE}}{kT} - 1)$$
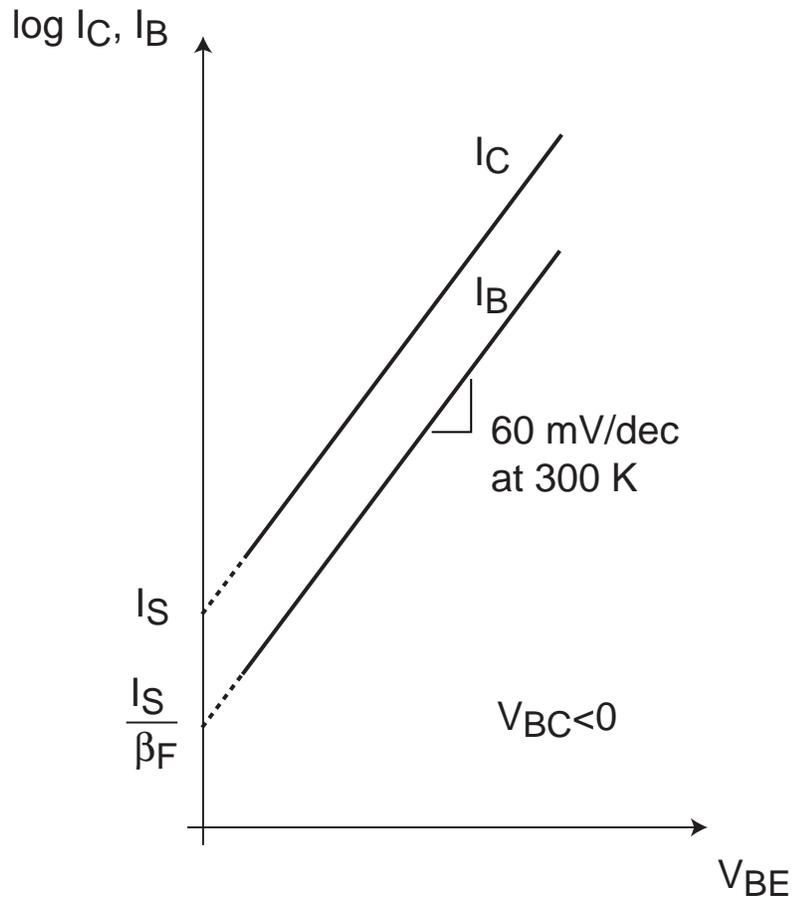
Then:

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

For $V_{BE} \gg \frac{kT}{q}$:

$$I_B \simeq \frac{I_C}{\beta_F}$$

Gummel plot: semilog plot of I_C and I_B vs. V_{BE}:

log I_C, I_B

I_C

I_B

60 mV/dec
at 300 K

I_S

$\dfrac{I_S}{\beta_F}$

$V_{BC} < 0$

V_{BE}

□ *Current gain*:

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

To maximize β_F:

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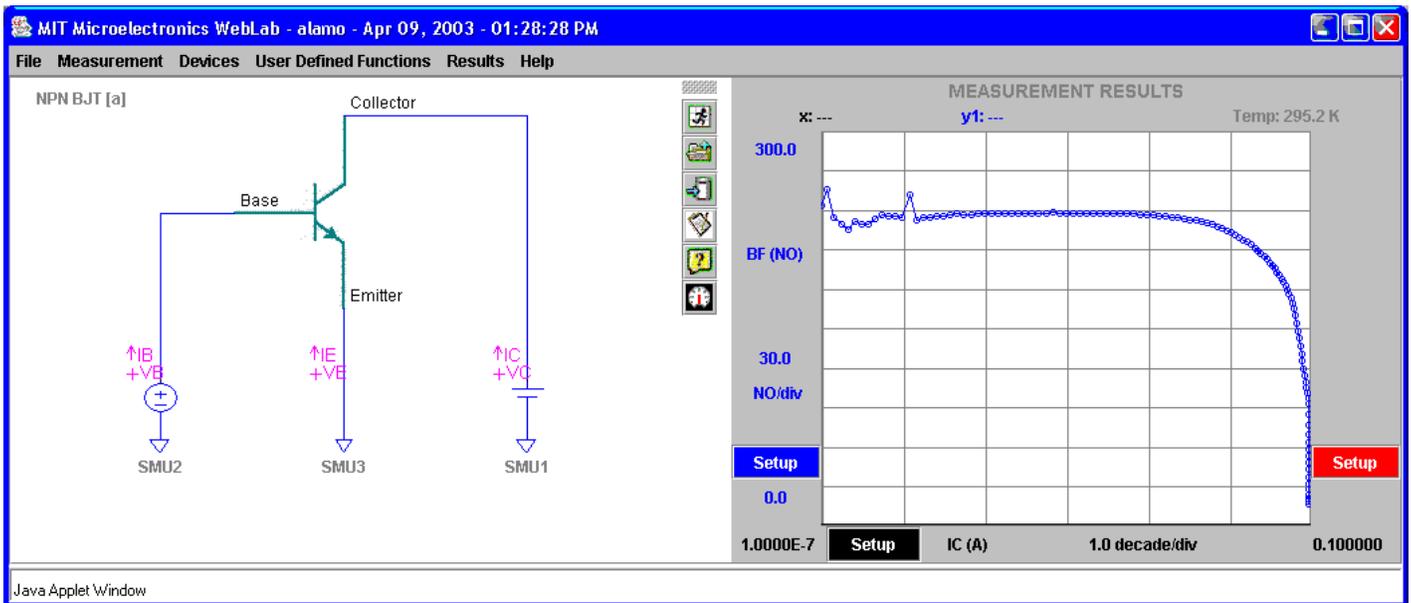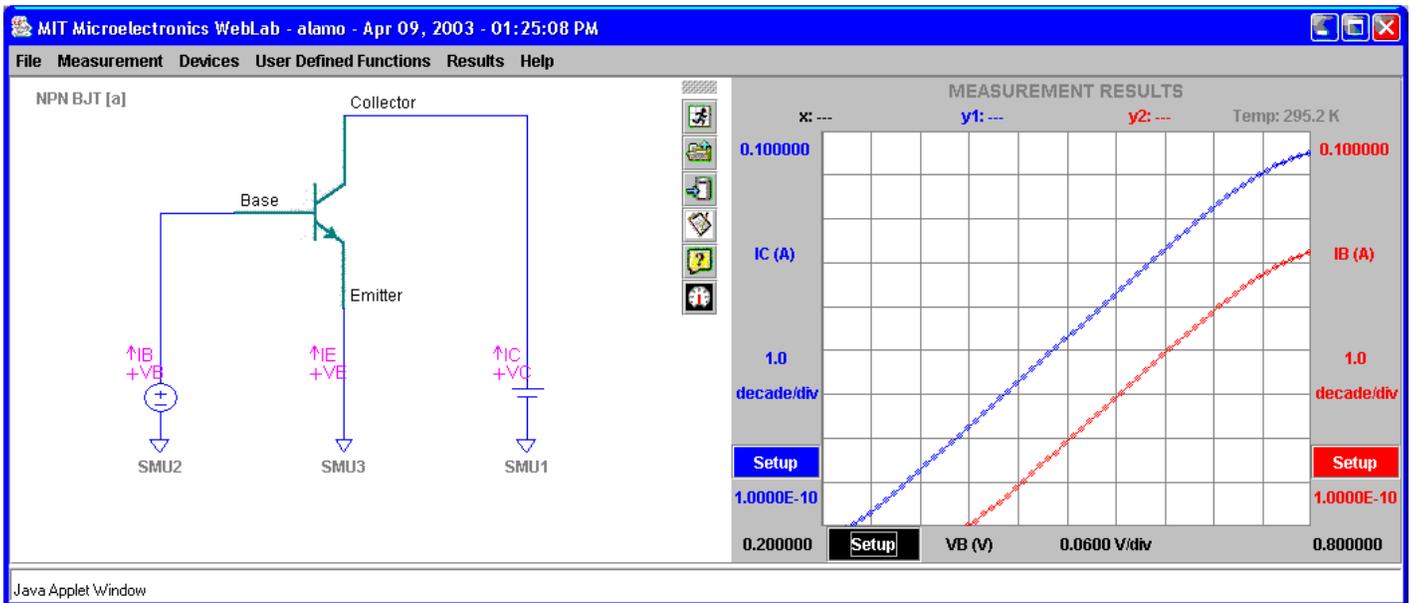- want *npn*, rather than *pnp* design because $D_n > D_p$

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

β_F hard to control in manufacturing environment $\Rightarrow$ need circuit techniques that are insensitive to variations in β_F
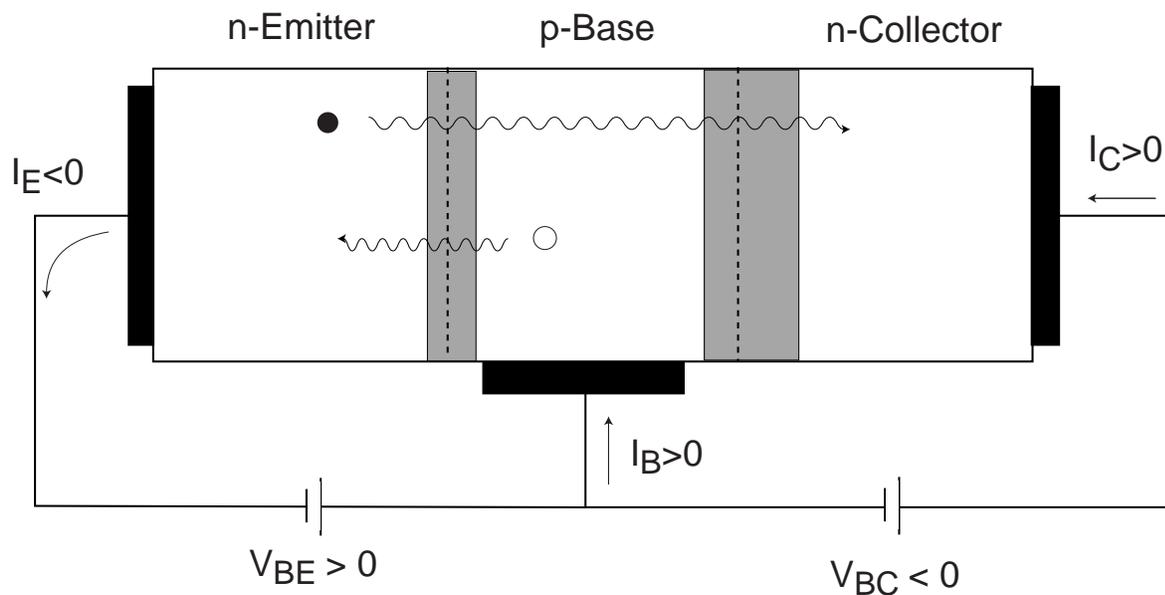
β_F dependence on I_C:

Gummel plot of BJT ($V_{CE} = 3\ V$):

Key conclusions

npn BJT in forward active regime:

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

$$I_C \propto \exp \frac{qV_{BE}}{kT}$$

- Base injects holes into Emitter $\Rightarrow I_B$

$$I_B \propto I_C$$