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

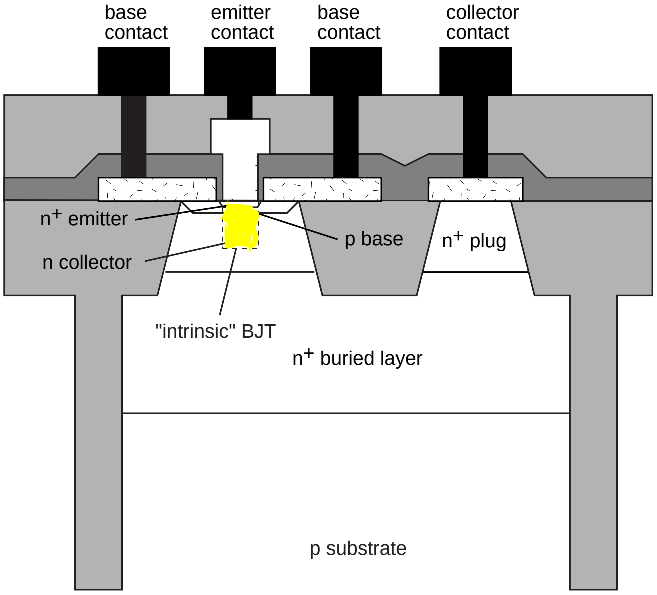
Announcements:

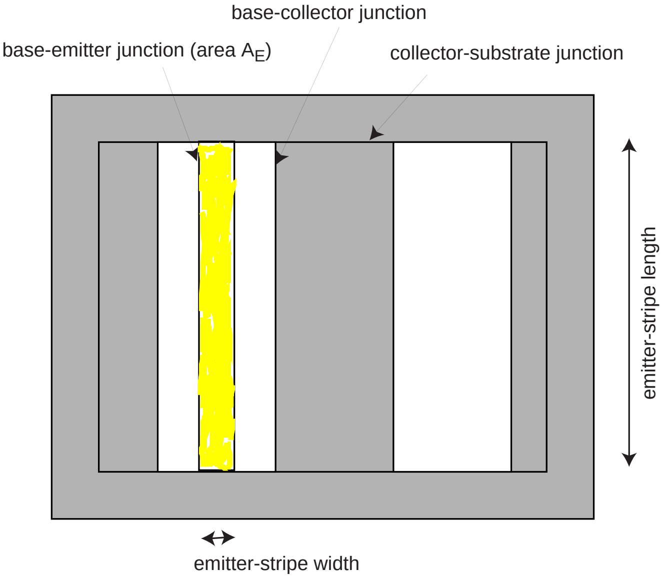
Quiz 2: 11/16, 7:30-9:30 PM,
open book, <u>must</u> bring calculator; lectures #10-18.

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?

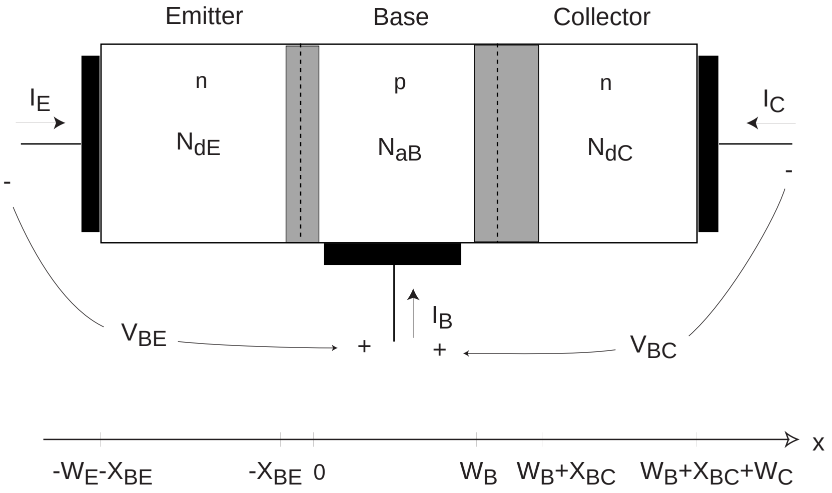
1. BJT: structure and basic operation





Uniqueness of BJT: high-current drivability per input capacitance ⇒ fast ⇒ excellent for analog and front-end communications applications.

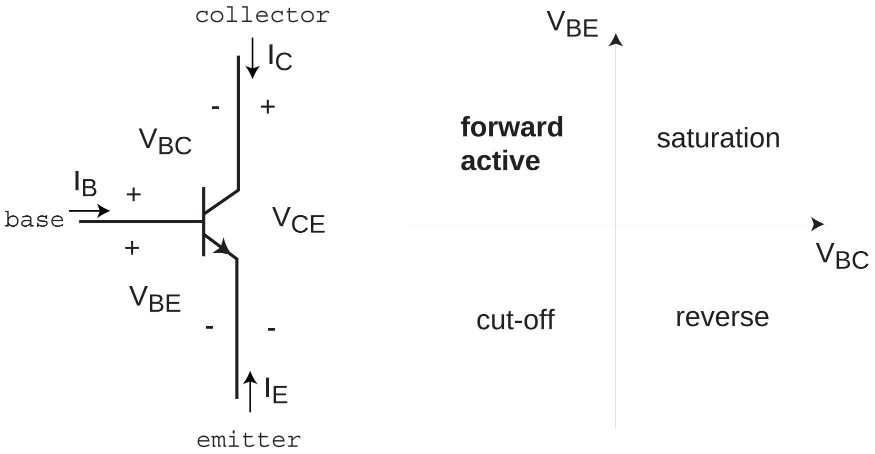
Simplified one-dimensional model of intrinsic device:



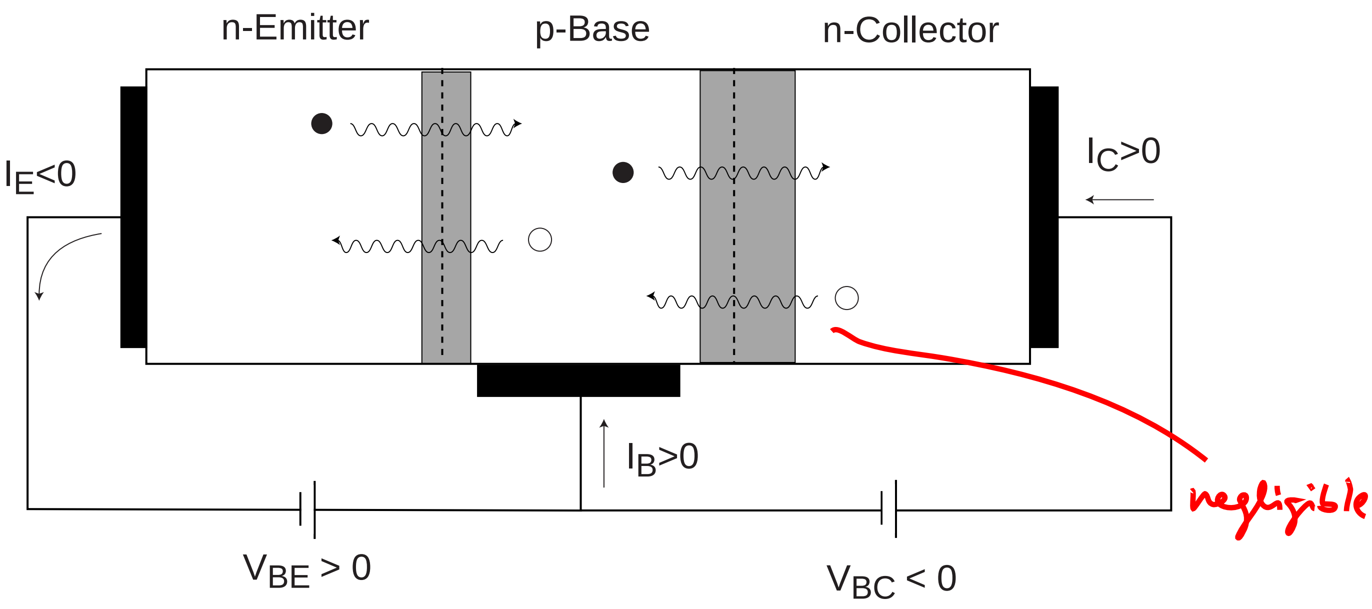
BJT = two neighbouring pn junctions back-to-back:

- 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*:

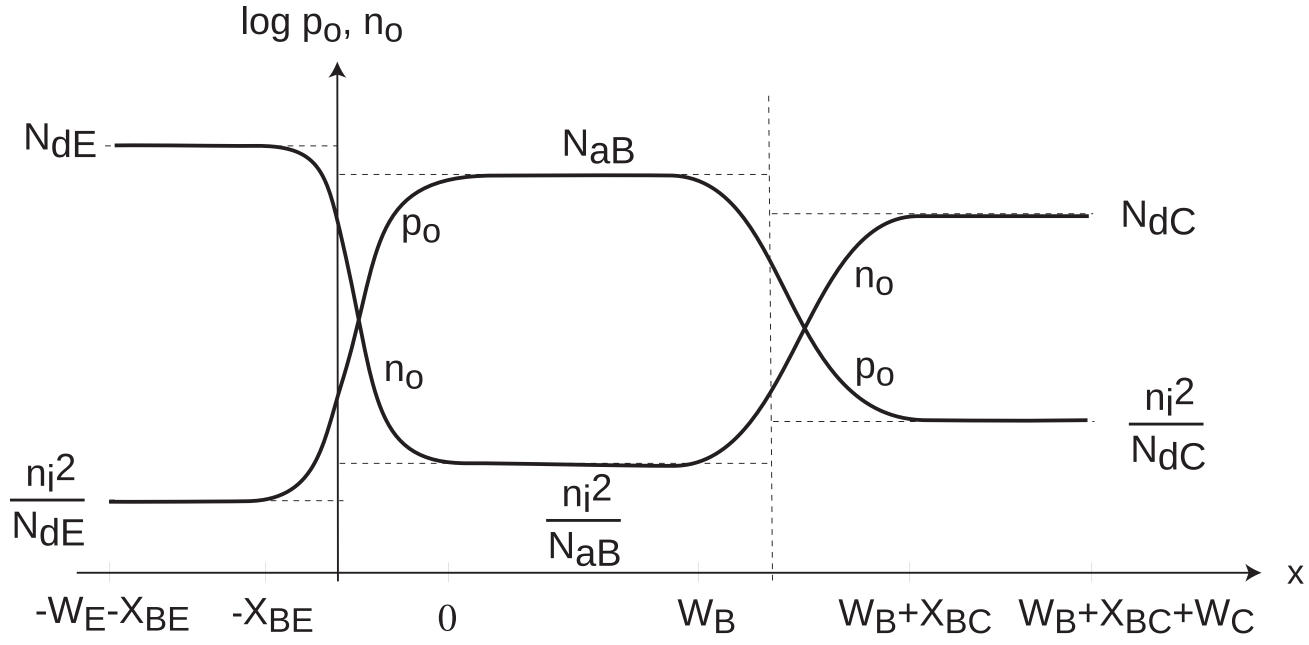


$V_{BE} > 0 \;\Rightarrow$ injection of electrons from E to B
injection of holes from B to E

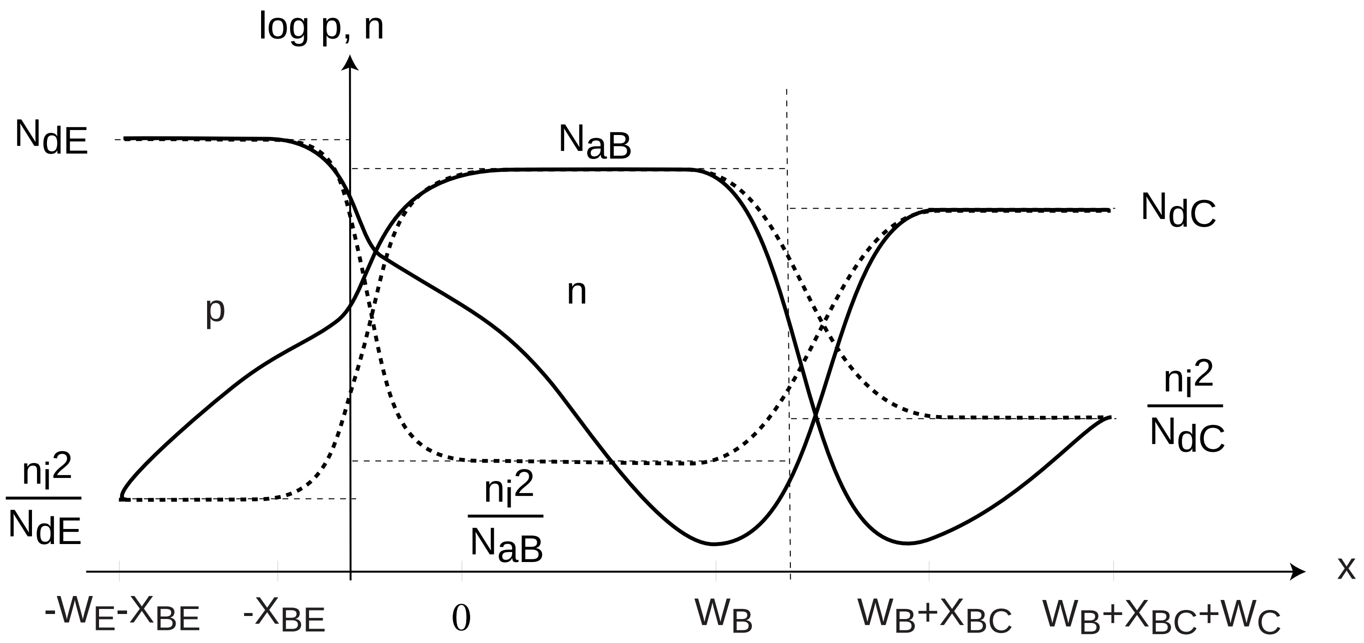
$V_{BC} < 0 \;\Rightarrow$ extraction of electrons from B to C
extraction of holes from C to B

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

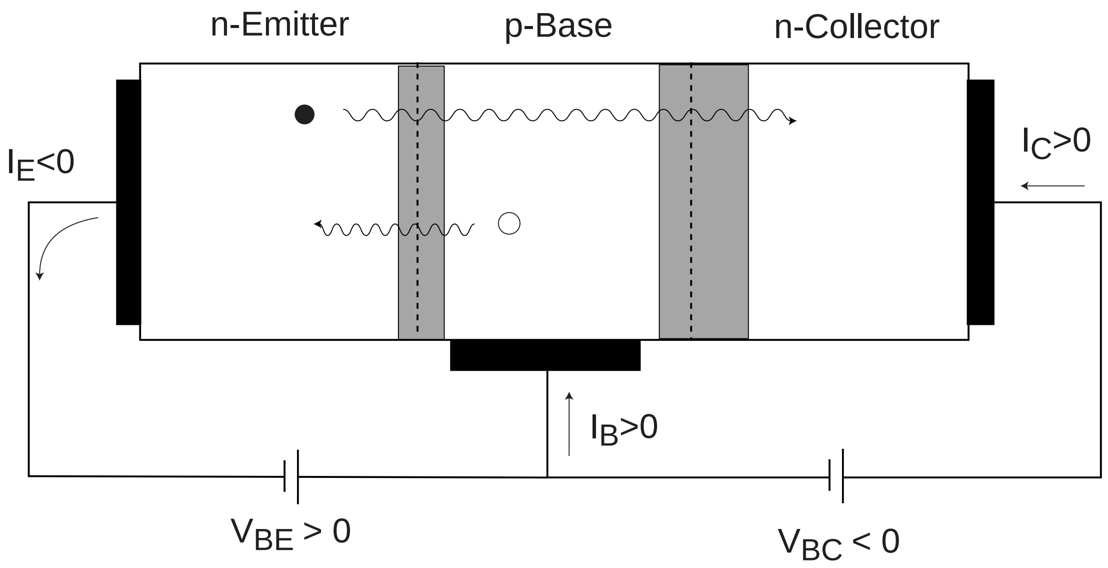
- Carrier profiles in thermal equilibrium:



- 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*] → linear

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

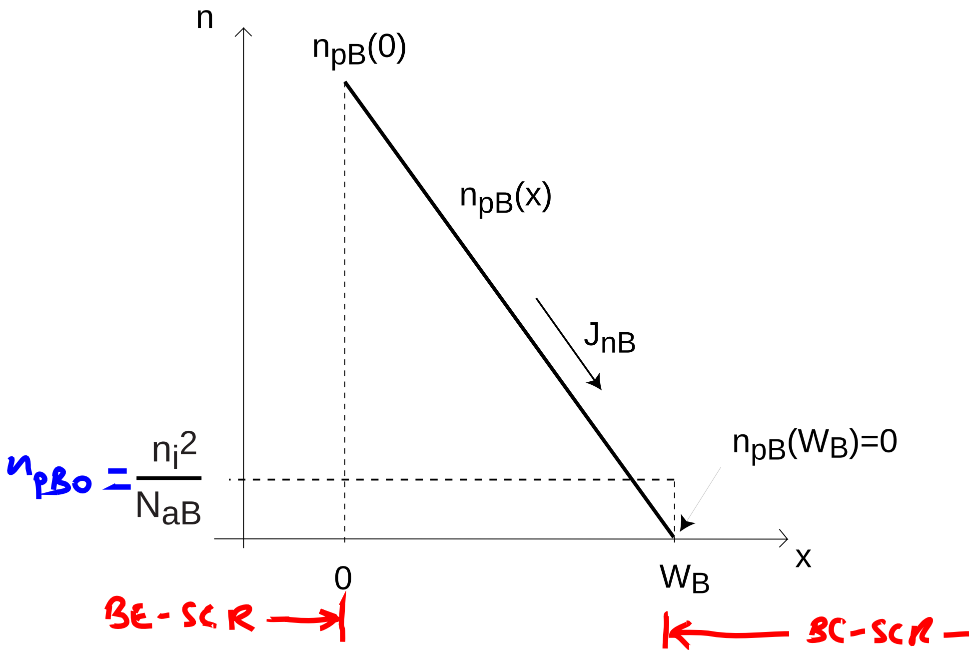
Figure of merit for BJT:

-common-emitter current gain:

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

2. I-V characteristics in forward active regime

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



Boundary conditions:

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

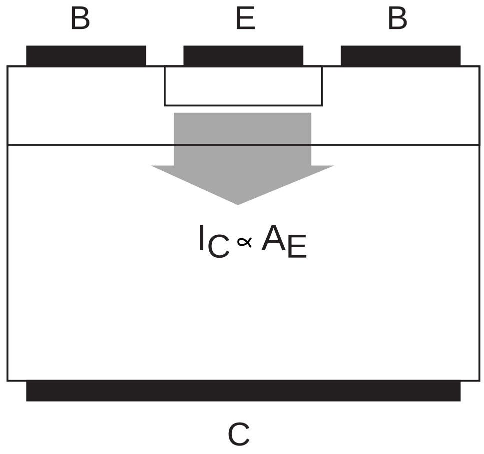
Electron profile:

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

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:

to force terminal current to be positive

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

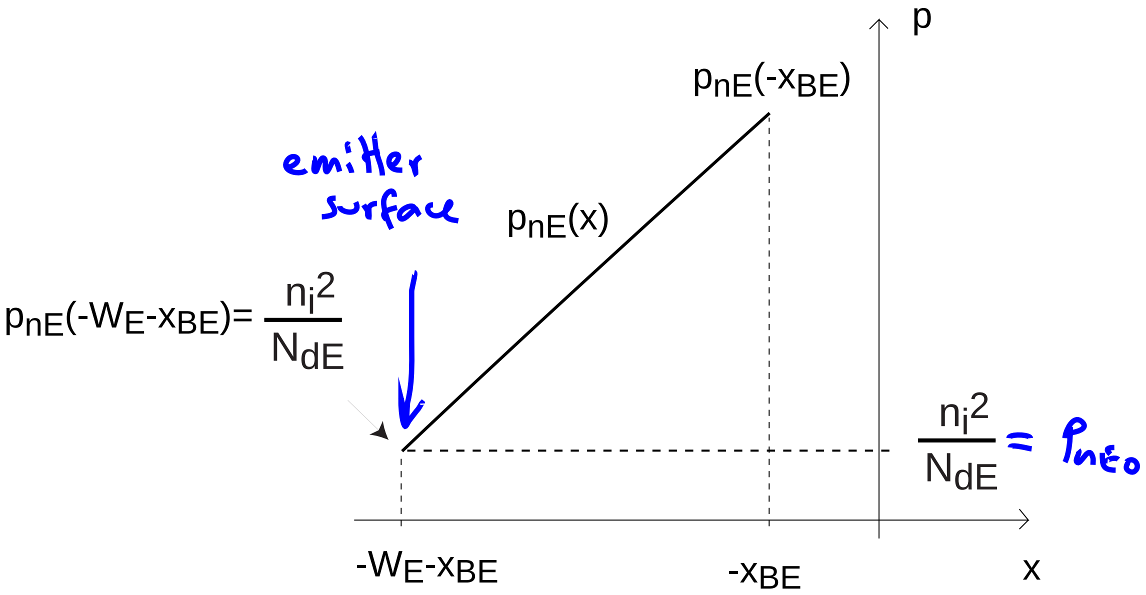
or

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

***

$$I_S \equiv \textit{ collector saturation current [A]}$$

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



Boundary conditions:

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

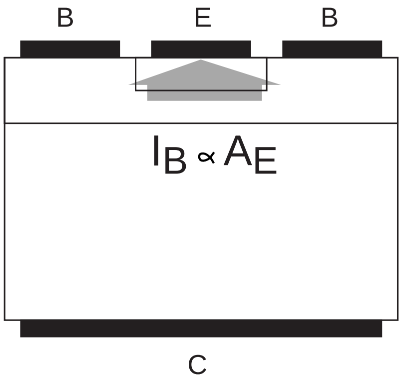
Hole profile:

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

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:

to force terminal current to be positive

$$I_B = \overset{\downarrow}{-}J_{pE}A_E = \overset{=\frac{I_S}{\beta_F}}{\boxed{qA_E \frac{D_p}{W_E} p_{nEo}}}(\exp \frac{qV_{BE}}{kT} - 1)$$

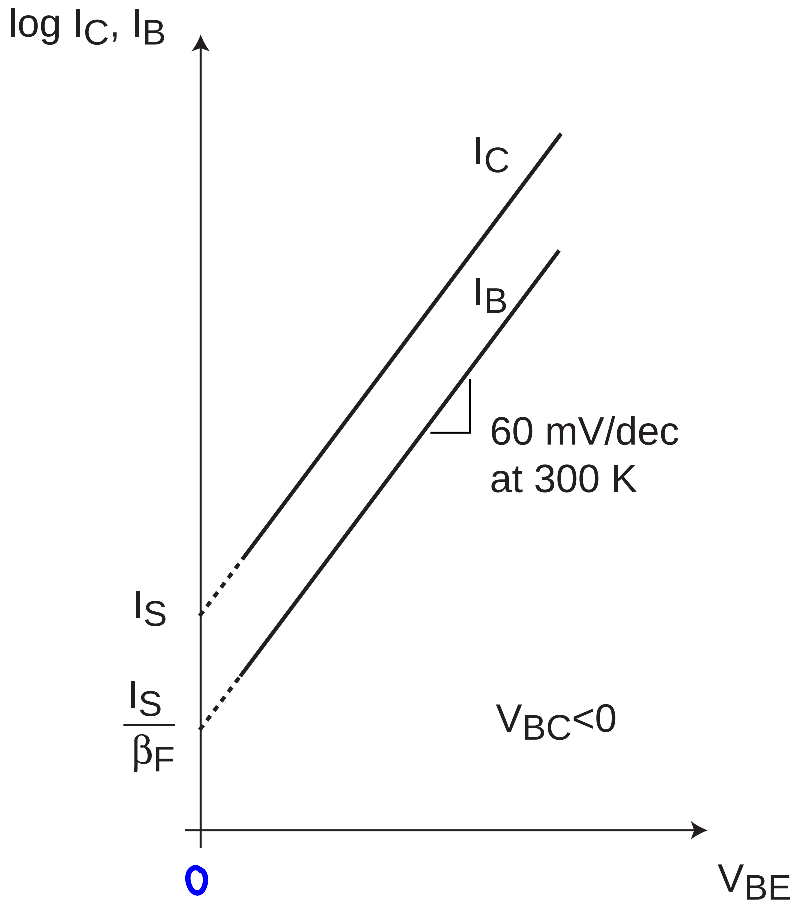
Then:

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

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

$$\boxed{I_B \simeq \frac{I_C}{\beta_F}} \quad ***$$

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



☐ *Current gain*:

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

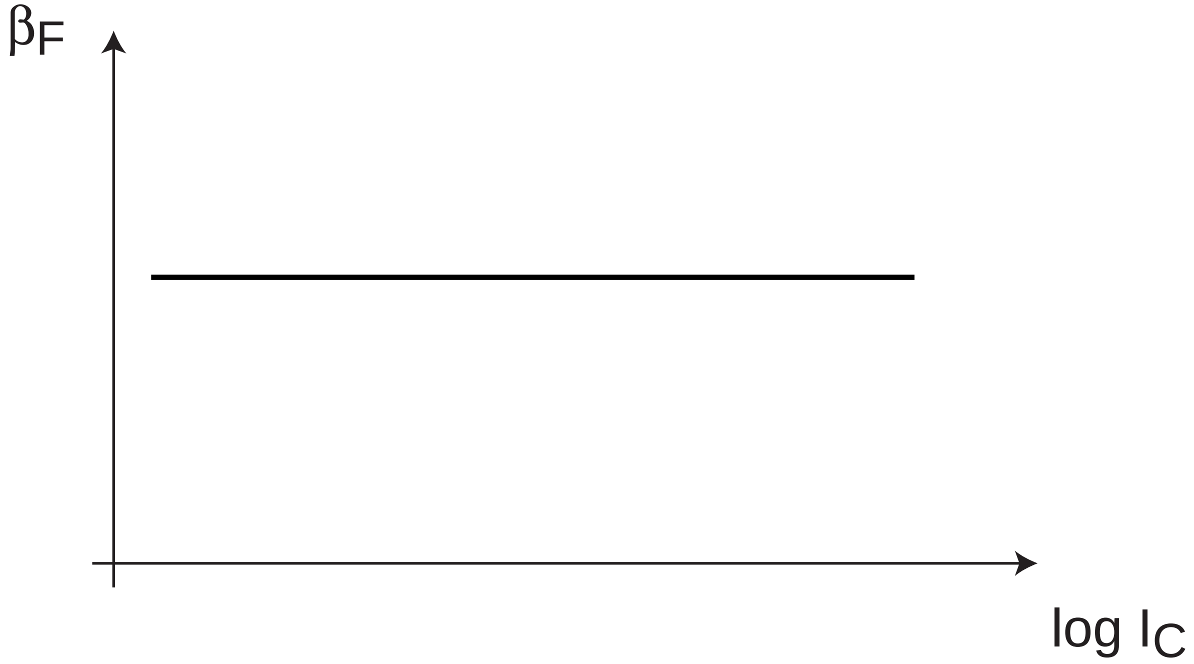
To maximize β_F:

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

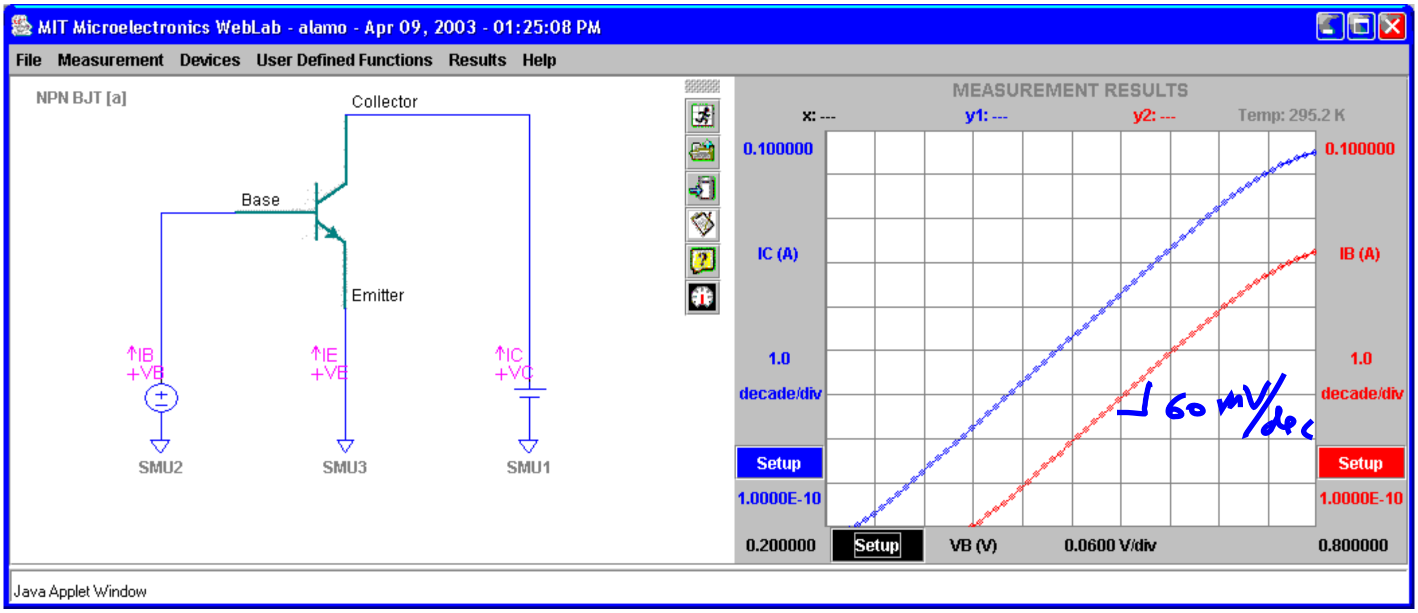
State-of-the-art IC BJT's today: $I_C \sim 0.1 - 1\ mA$, $\beta_F \sim 50 - 300$

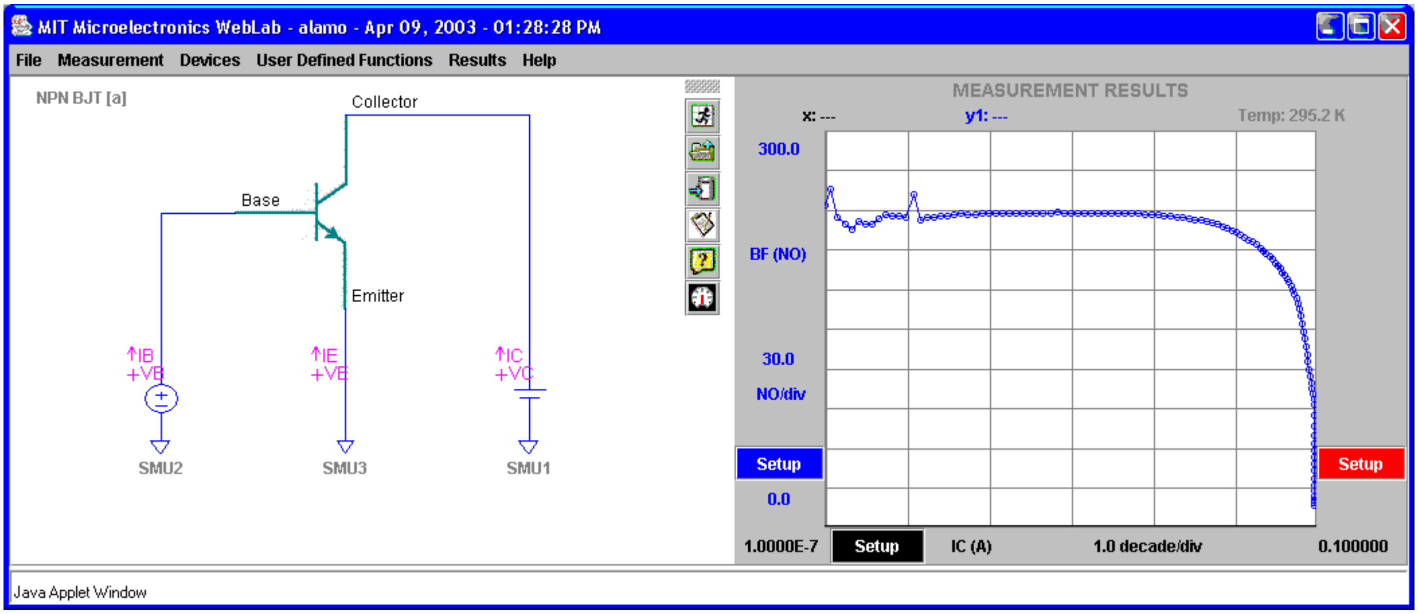
β_F hard to control in manufacturing environment ⇒ need circuit techniques that are insensitive to variations in β_F

β_F dependence on I_C:



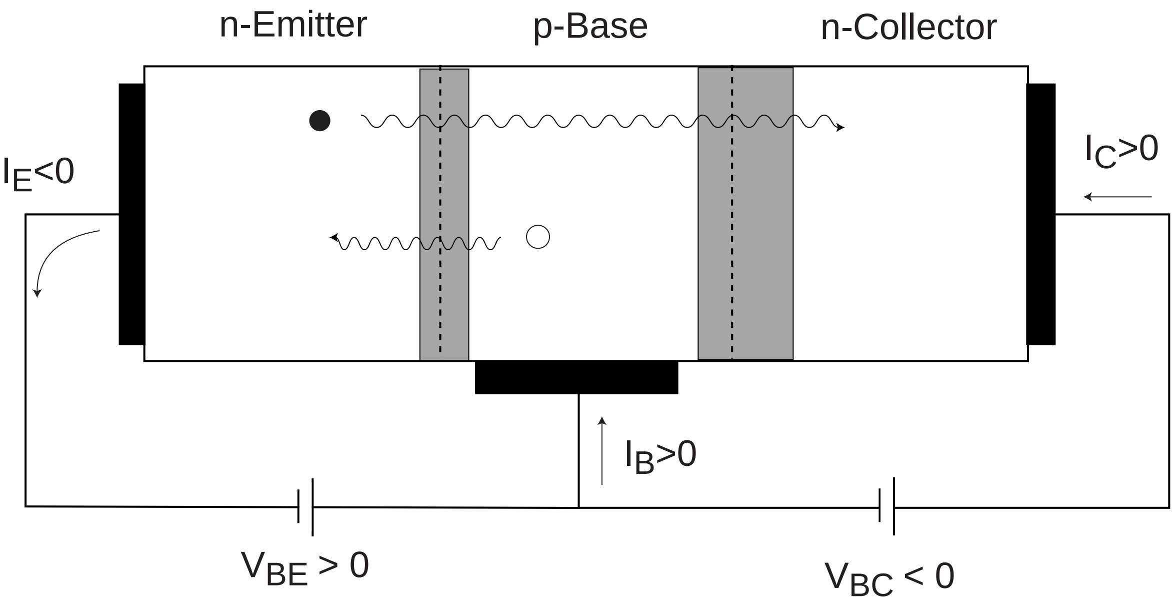
Gummel plot of BJT ($V_{CE} = 3\ V$):





Key conclusions

npn BJT in forward active regime:



- Emitter "injects" electrons into Base,
  Collector "collects" electrons from Base.
  ⇒ 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 ⇒ I_B

$$I_B \propto I_C$$