Lecture 16

The Bipolar Junction Transistor (I)

Forward Active Regime

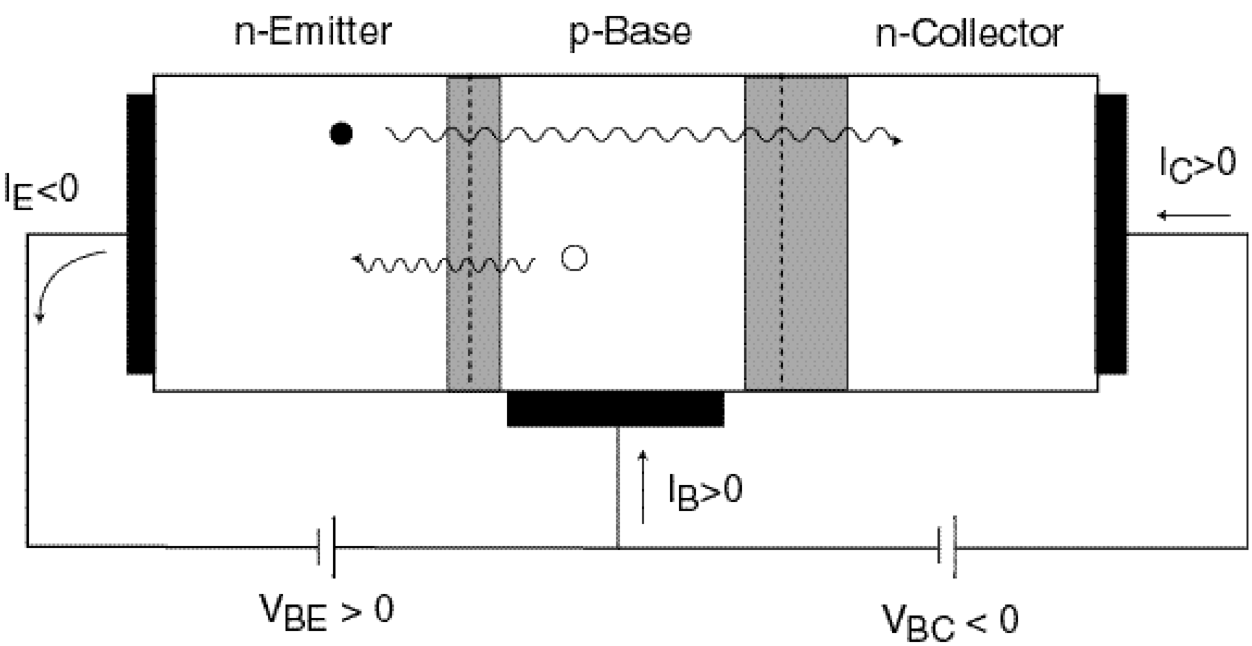
Outline

- 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

Summary of Key Concepts

npn BJT in forward active regime:



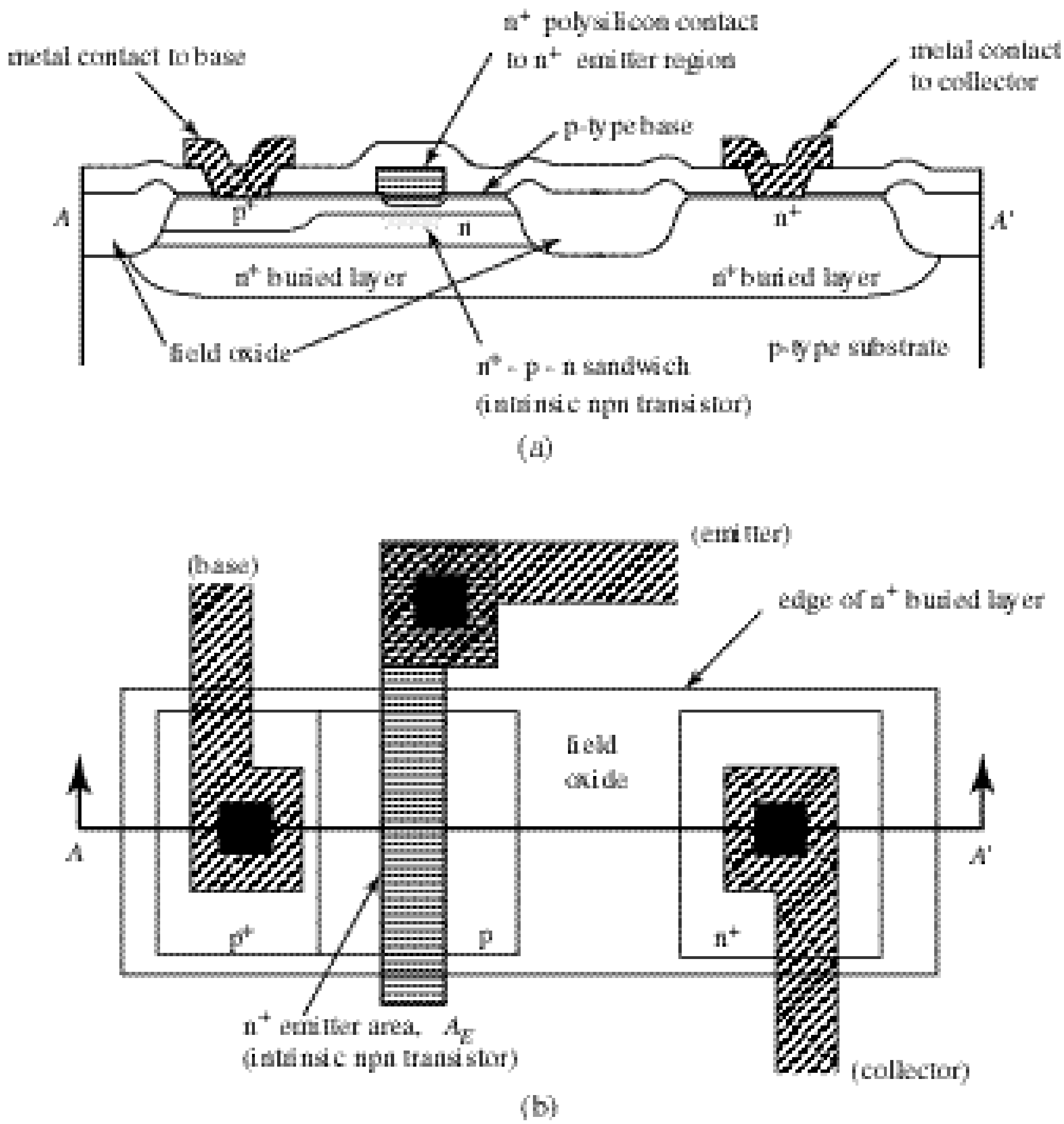
- ***Emitter*** "injects" electrons into ***Base***, Collector "collects" electrons from ***Base***
  - I_C controlled by V_{BE}, independent of V_{BC} (***transistor effect***)

$$I_C \quad \exp\left[\frac{qV_{BE}}{kT}\right]$$

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

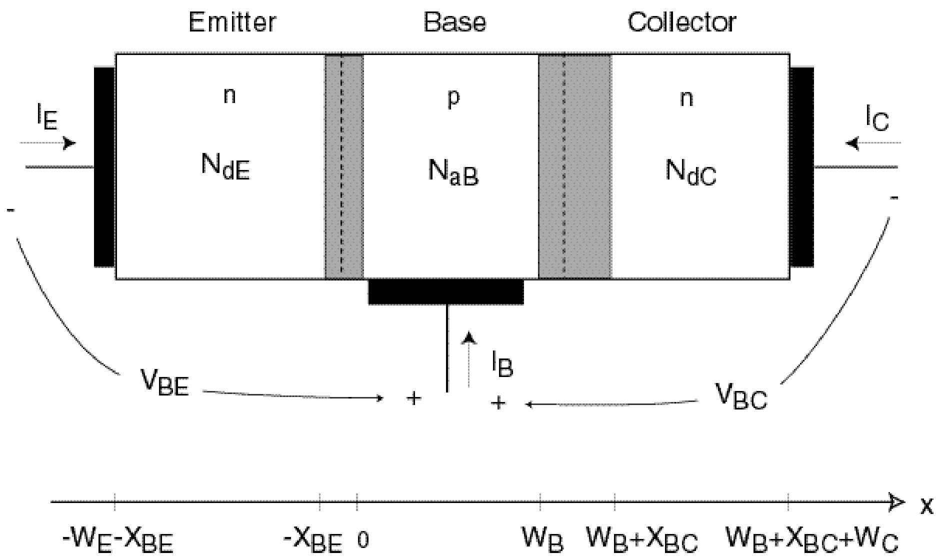
$$I_B \quad I_C$$

1. BJT: structure and basic operation



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

Simplified one-dimensional model of intrinsic device:



BJT=two neighbouring pn junctions back-to-back

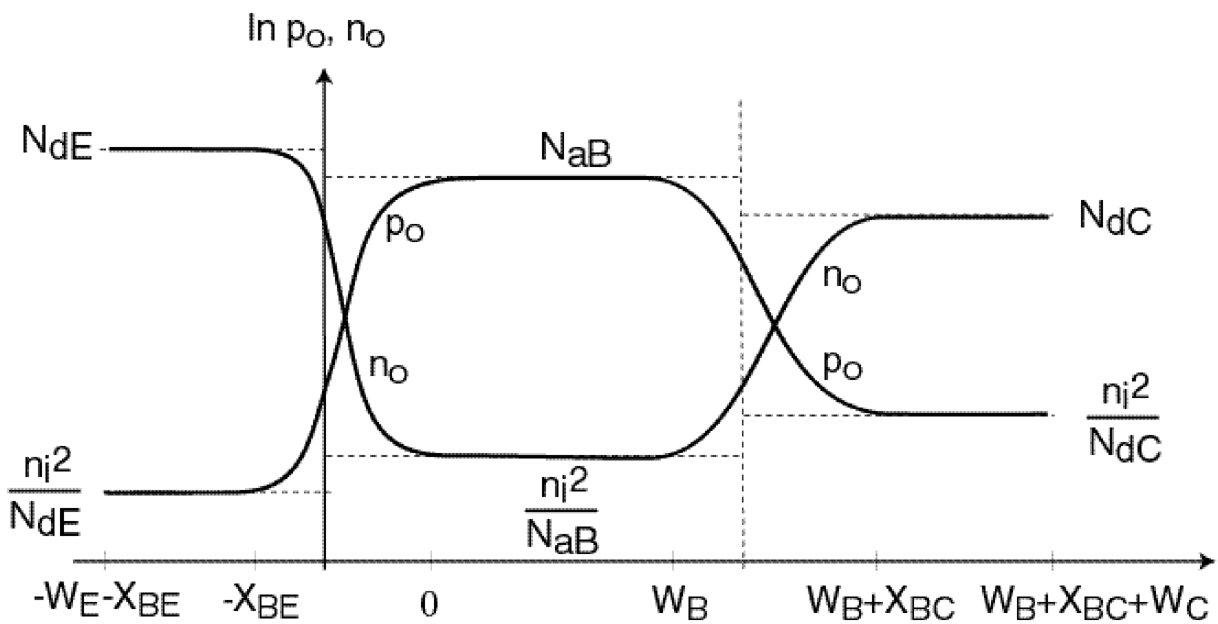
- Close enough for minority carriers to interact
  - can diffuse quickly through the base
- Far apart enough for depletion regions not to interact
  - prevent "punchthrough"

Basic Operation: forward-active regime

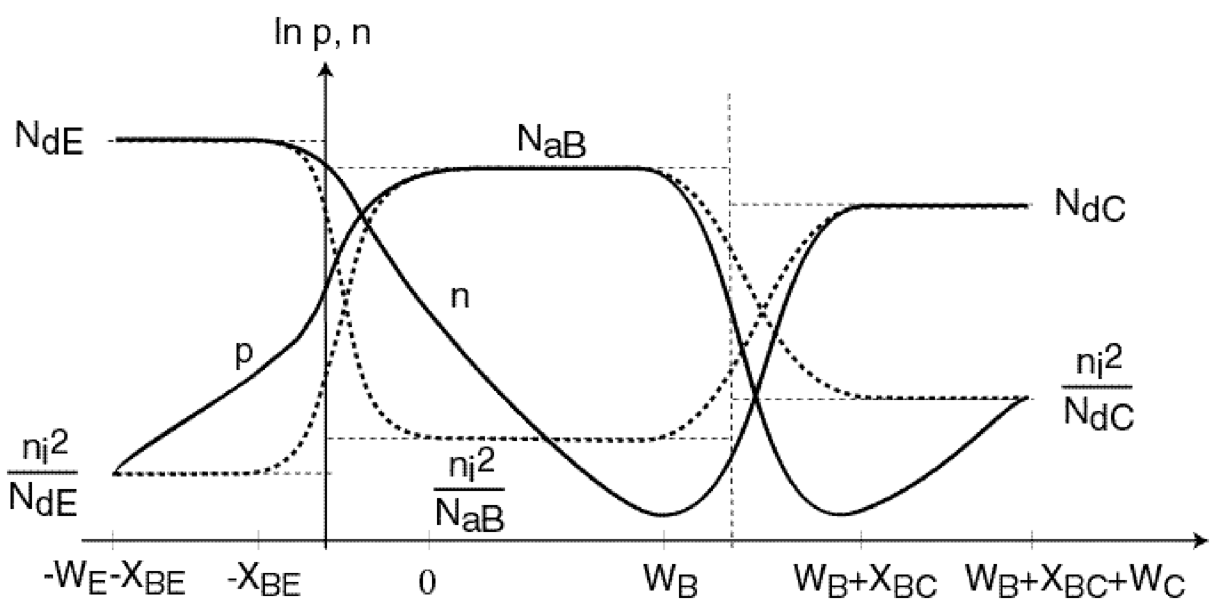
Transistor Effect : electrons injected from the ***Emitter*** to the ***Base***, extracted by the ***Collector***

Basic Operation: forward-active regime

- **Carrier profiles in thermal equilibrium:**

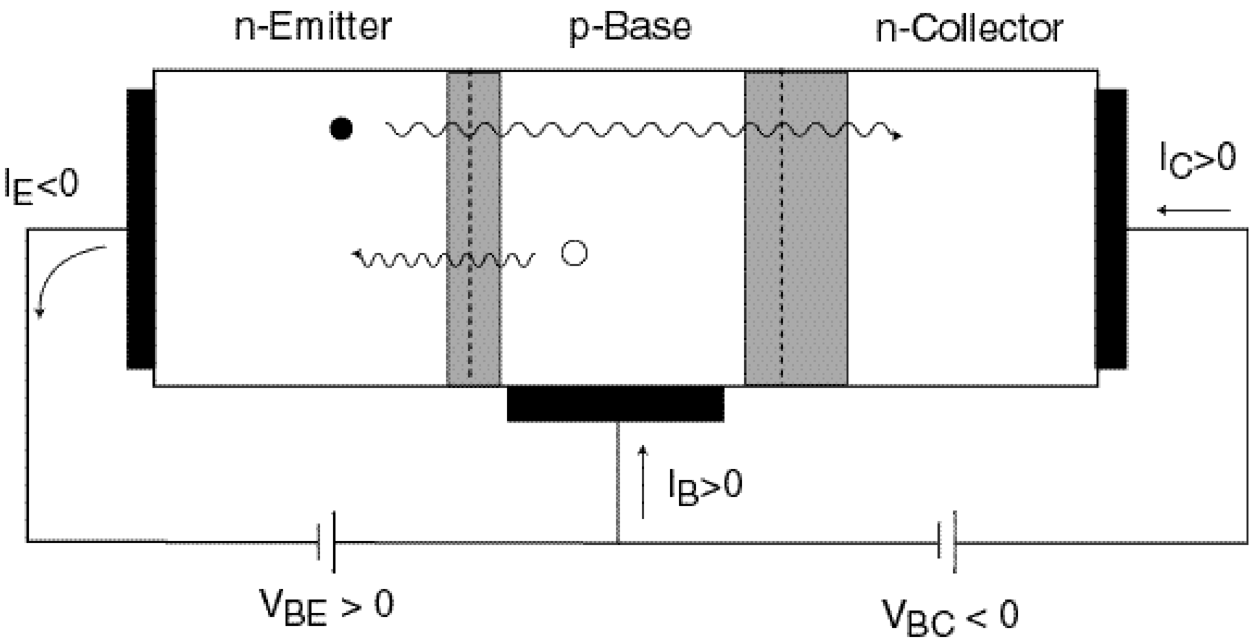


- **Carrier profiles in forward-active regime:**



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: $I_E = -(I_C+I_B)$

Key dependencies (choose one):

I_C on V_{BE} : $\exp\left[\frac{qV_{BE}}{kT}\right]$, $\frac{1}{\sqrt{V_{BE}}}$, **no dep., other**

I_C on V_{BC} : $\exp\left[\frac{qV_{BC}}{kT}\right]$, $\frac{1}{\sqrt{V_{BC}}}$, **no dep., other**

I_B on V_{BE} : $\exp\left[\frac{qV_{BE}}{kT}\right]$, $\frac{1}{\sqrt{V_{BE}}}$, **no dep., other**

I_B on V_{BC} : $\exp\left[\frac{qV_{BC}}{kT}\right]$, $\frac{1}{\sqrt{V_{BC}}}$, **no dep., other**

I_C on I_B : exp**onential, quadratic, no dep., other**

Basic Operation: forward-active regime

- V_{BE} controls I_C ("**transistor effect**")
- I_C independent of V_{BC} ("**isolation**")
- Price to pay for control: I_B (**base current**)

Comparison with MOSFET:

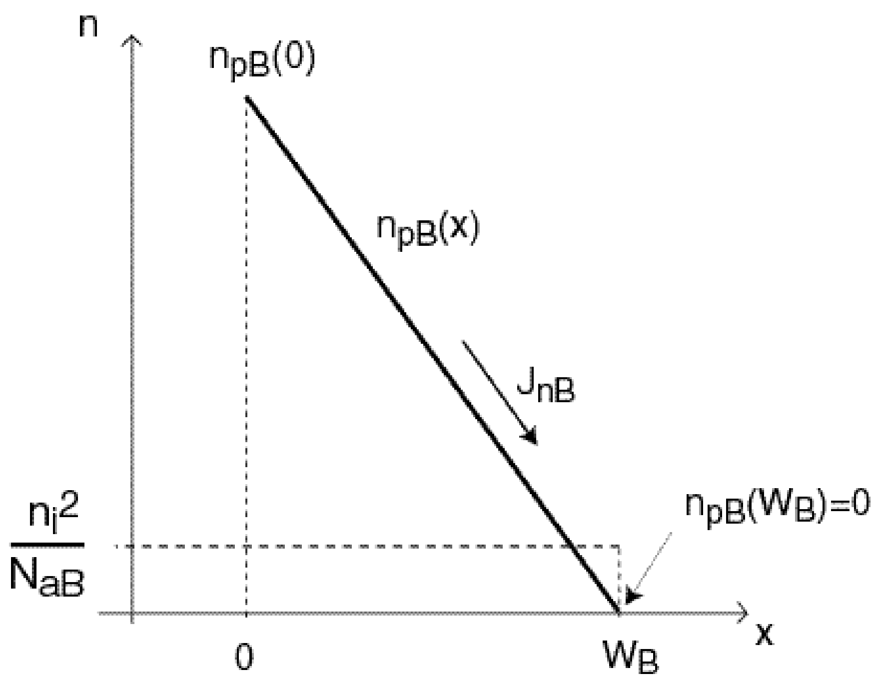
Feature	MOSFET in saturation	BJT in FAR
Controlling terminal	Gate	Base
Common terminal	Source	Emitter
Controlled terminal	Drain	Collector
Functional dependence of controlled current	Quadratic	Exponential
DC current in controlling terminal	0	Exponential

Figure of Merit for BJT:

- Common-emitter current gain: $\beta_F = \frac{I_C}{I_B}$
  - Want it as large as possible
- Common-base current gain: $\alpha_F = \frac{I_C}{I_E}$
  - Want it close to 1

2. I-V characteristics in forward-active regime

Collector current: focus on electron diffusion in base



Boundary conditions:

$$n_{pB}(0) = n_{pBo} \exp\left[\frac{qV_{BE}}{kT}\right] \qquad n_{pB}(W_B) = 0$$

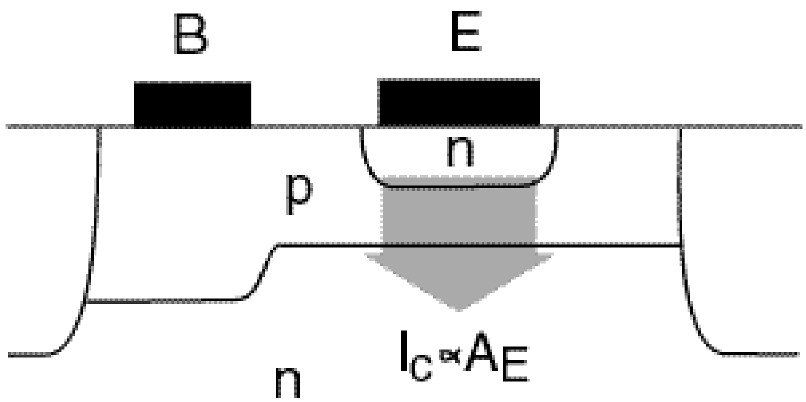
Electron profile:

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

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:

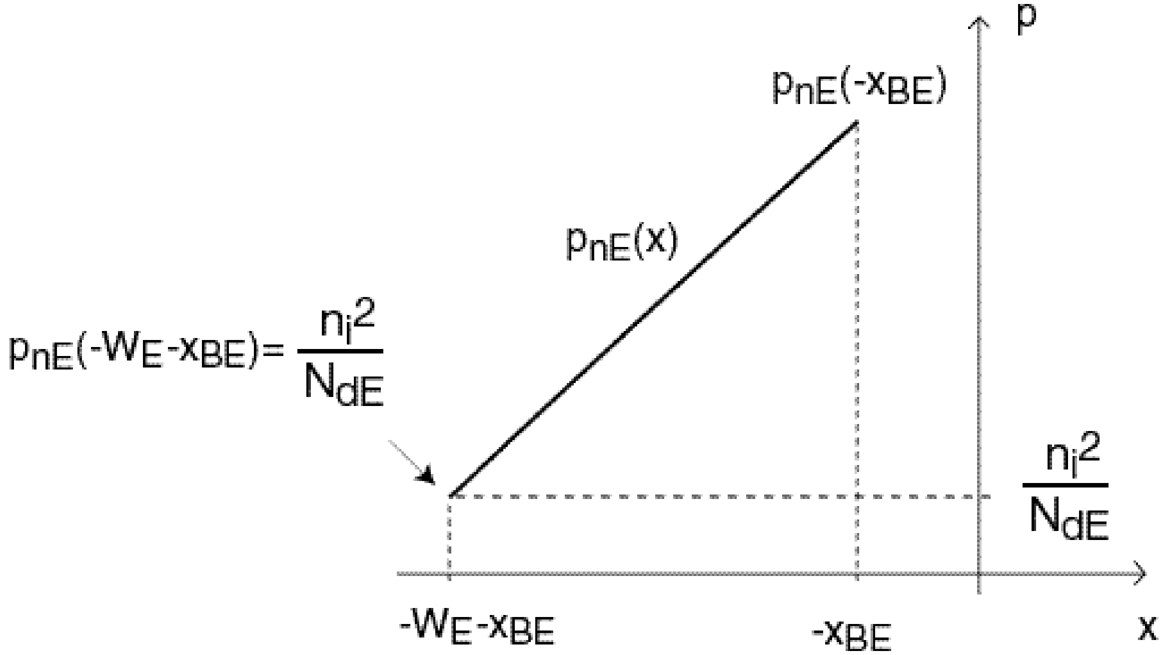
$$\mathbf{I_C = -J_{nB}A_E = -qA_E \frac{D_n}{W_B} n_{pBo} \cdot \exp\left[\frac{qV_{BE}}{kT}\right]}$$

or

$$I_C = I_S \exp\left[\frac{qV_{BE}}{kT}\right]$$

$I_S \equiv$ *transistor saturation current*

Base current: focus on hole injection and recombination in emitter



Boundary conditions:

$$\mathbf{p_{nE}}(-\mathbf{x_{BE}}) = \mathbf{p_{nEo}} \exp\left[\frac{\mathbf{qV_{BE}}}{\mathbf{kT}}\right] \qquad \mathbf{p_{nE}}(-\mathbf{W_E} - \mathbf{x_{BE}}) = \mathbf{p_{nEo}}$$

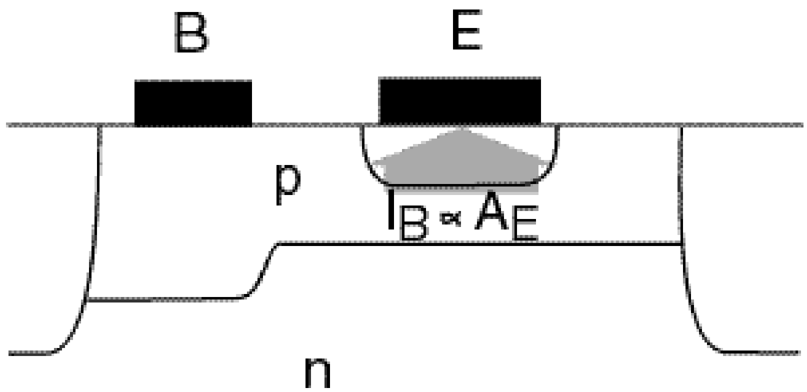
Hole profile:

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

Hole current density:

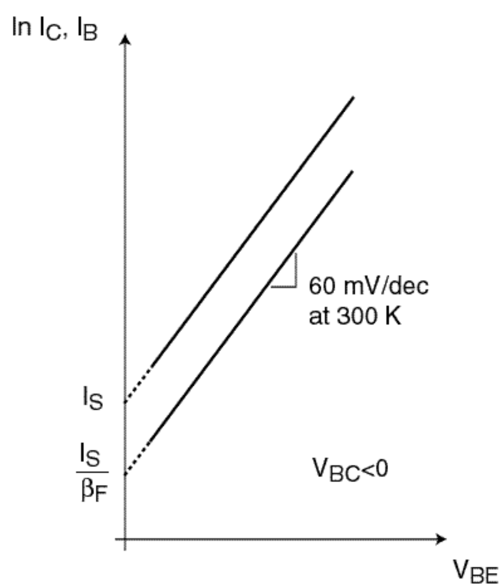
$$J_{pE} = -qD_p \frac{dp_{nE}}{dx} = -qD_p \frac{p_{nE}(-x_{BE}) - p_{nEo}}{W_E}$$

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



Base terminal current:

$$I_B = -J_{pE} A_E = -qA_E \frac{D_p}{W_E} p_{nEo} \cdot \exp\left[\frac{qV_{BE}}{kT} - 1\right]$$

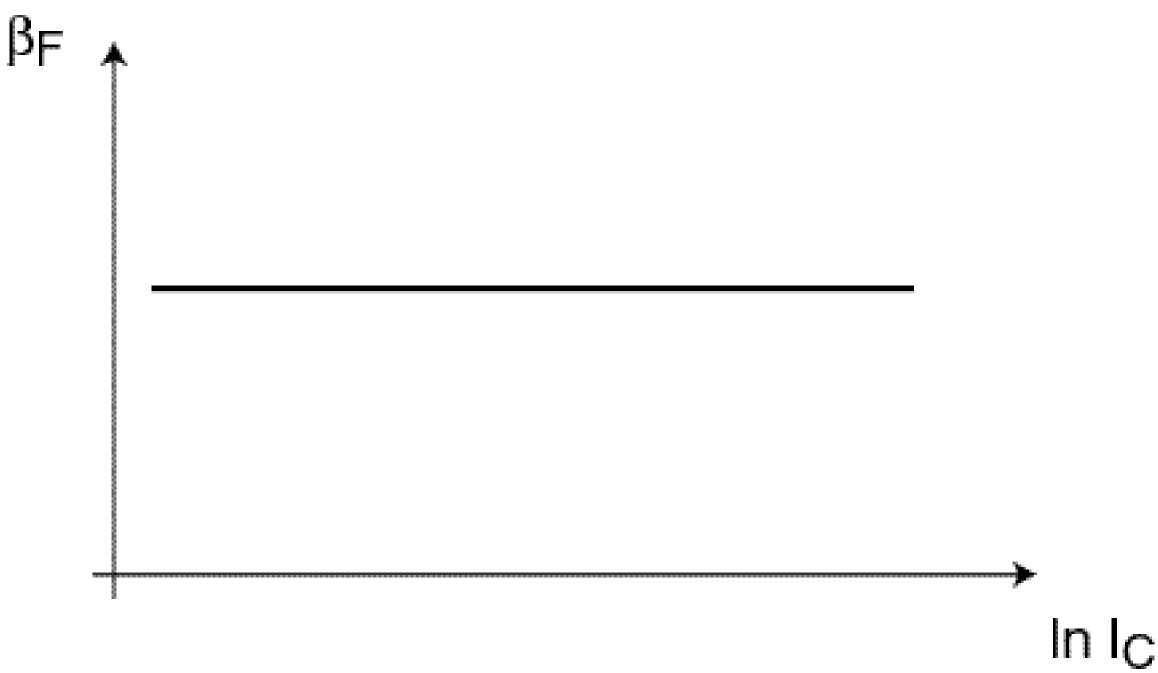


Forward Active Region: Current gain

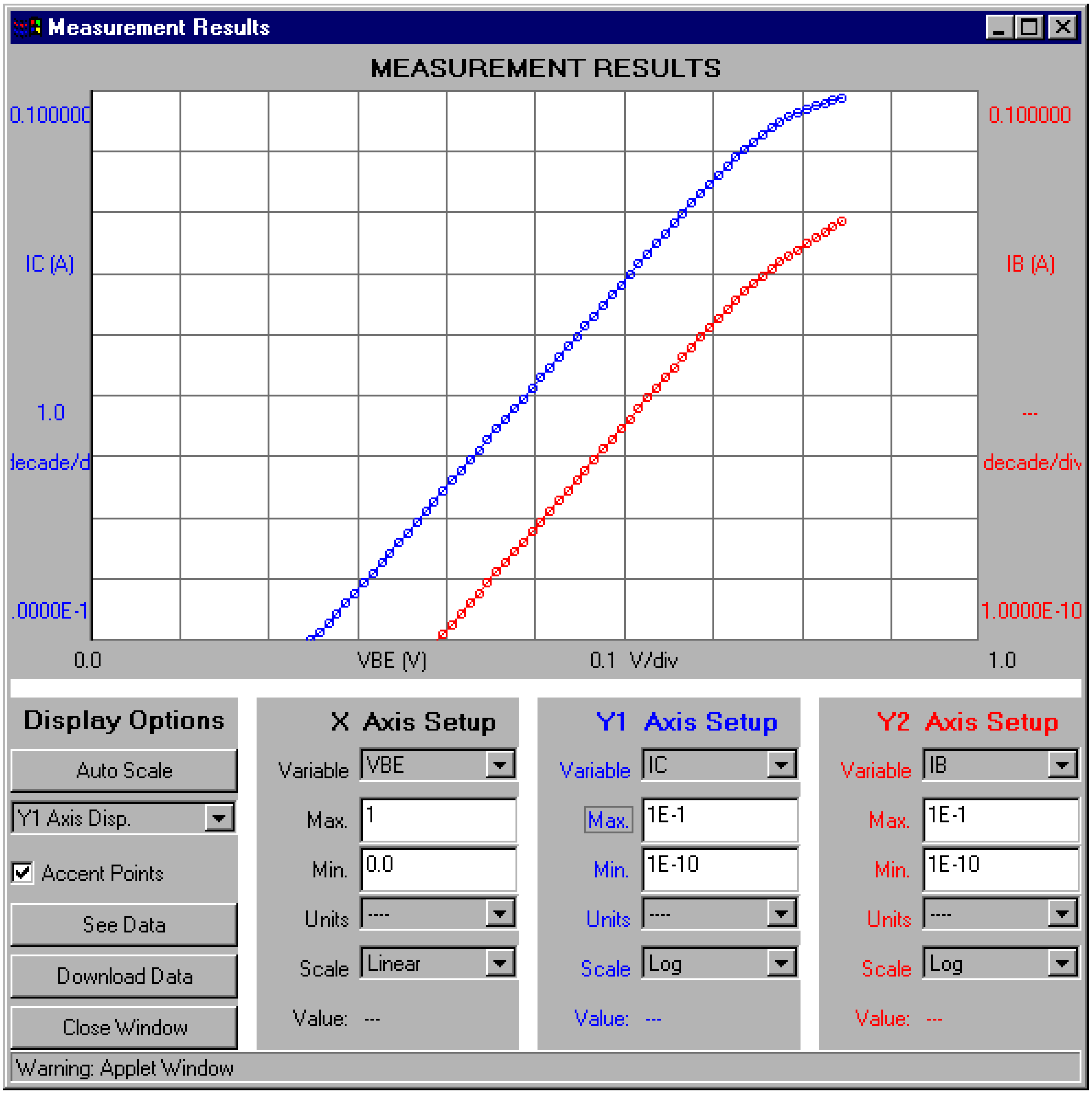
$$\beta_F = \frac{I_C}{I_B} = \frac{n_{pBo} \cdot \frac{D_n}{W_B}}{p_{nEo} \cdot \frac{D_p}{W_E}} = \frac{N_{dE} D_n W_E}{N_{aB} D_p W_B}$$

To maximize β_F:

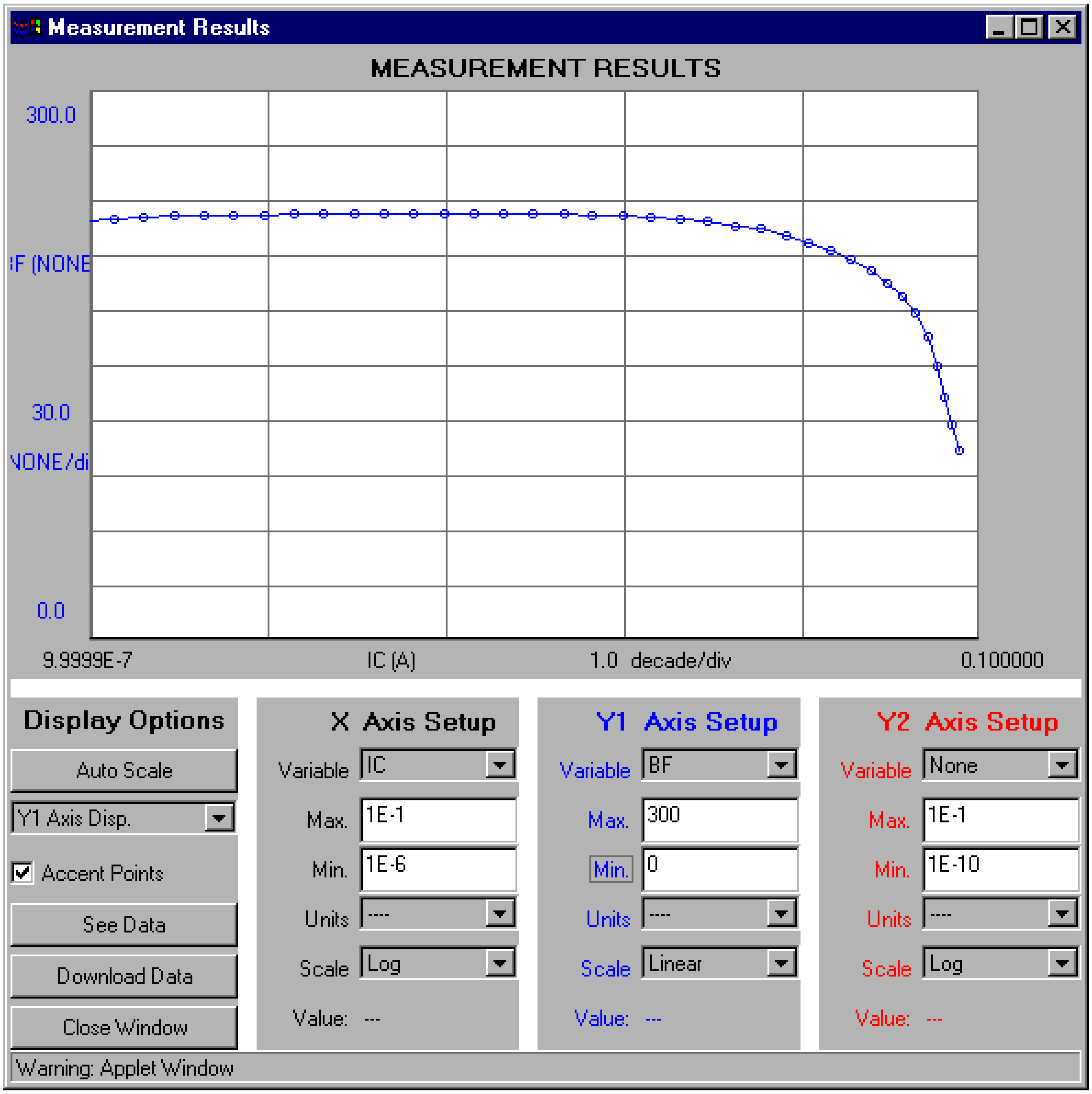
- $N_{dE} >> N_{aB}$
- $W_E >> W_B$
- want npn, rather than pnp design because $D_n > D_p$



Plot of I_C and I_B



Current Gain



What did we learn today?

Summary of Key Concepts

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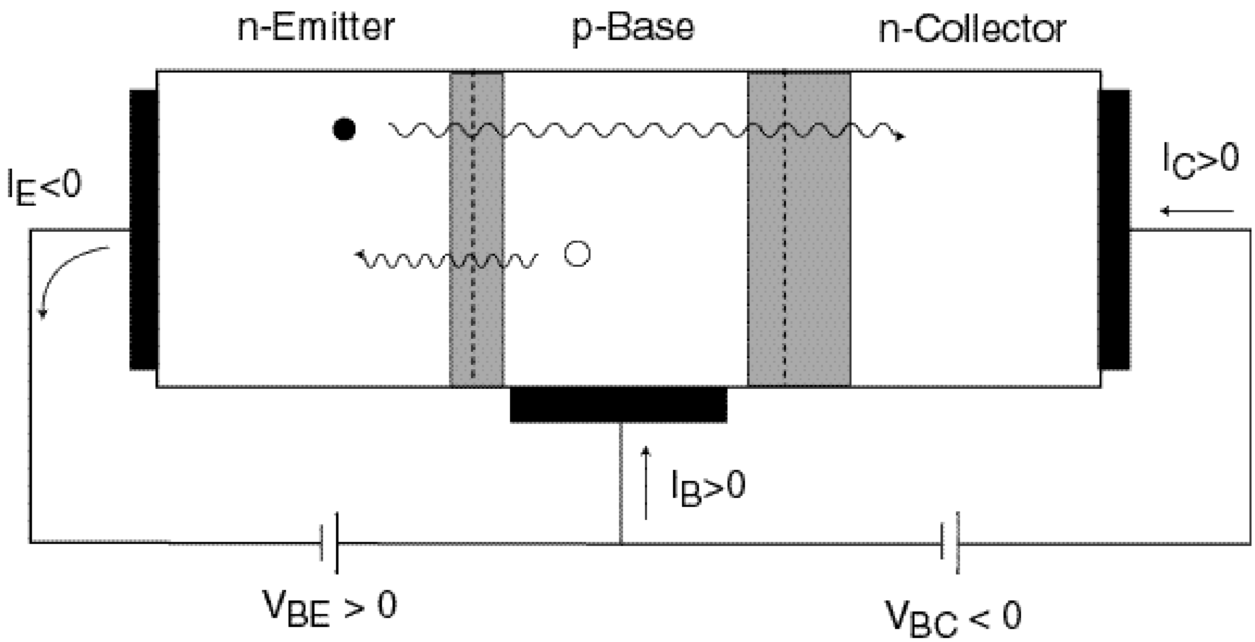

- ***Emitter*** "injects" electrons into ***Base***, ***Collector*** "collects" electrons from ***Base***
  - IC controlled by V_{BE}, independent of V_{BC}
  - (***transistor effect***)

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

$$I_B \quad I_C$$