Lecture 34 - Bipolar Junction Transistor

May 2, 2007

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1. The ideal BJT
2. Current-voltage characteristics of ideal BJT

Reading material:

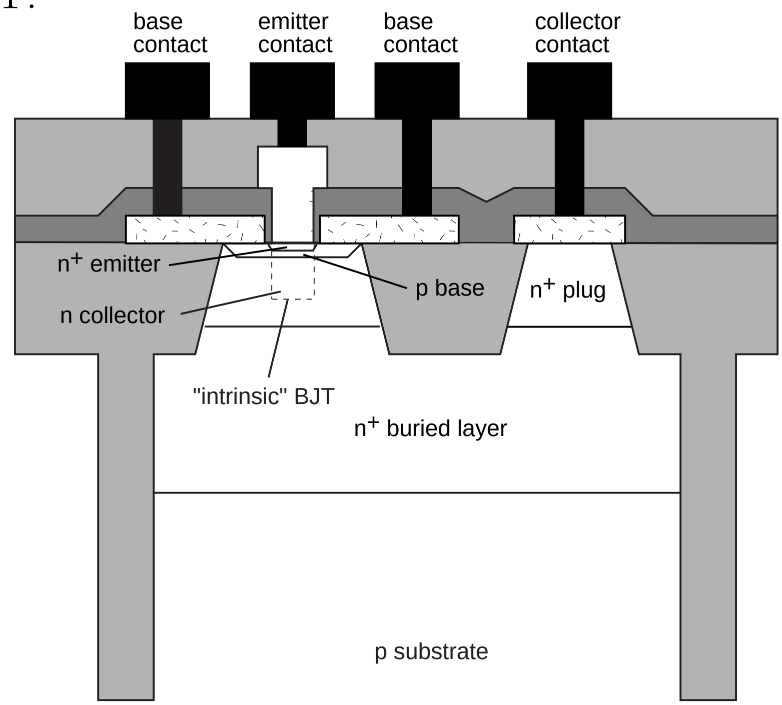
del Alamo, Ch. 11, §§11.1, 11.2 (11.2.1)

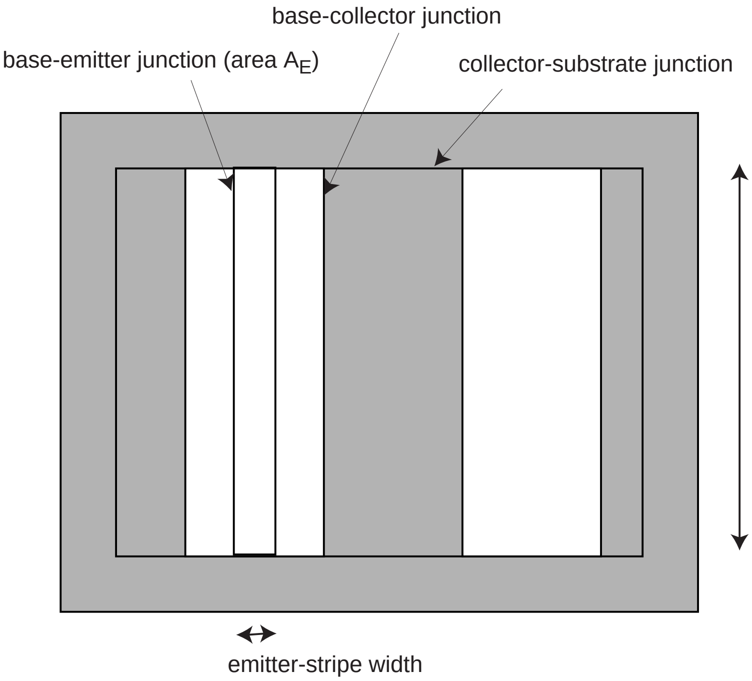
Key questions

- How does a bipolar junction transistor look like?
- How does a BJT basically work?
- Can we derive a first order model for I_C and I_B in forward-active regime?

1. The ideal BJT

Modern BJT:





BJT basically consists of two neighbouring pn junctions back-to-back:

- close enough that minority carriers interact (negligible recombination in base)
- far apart enough that depletion regions don't interact (no "punchthrough")

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

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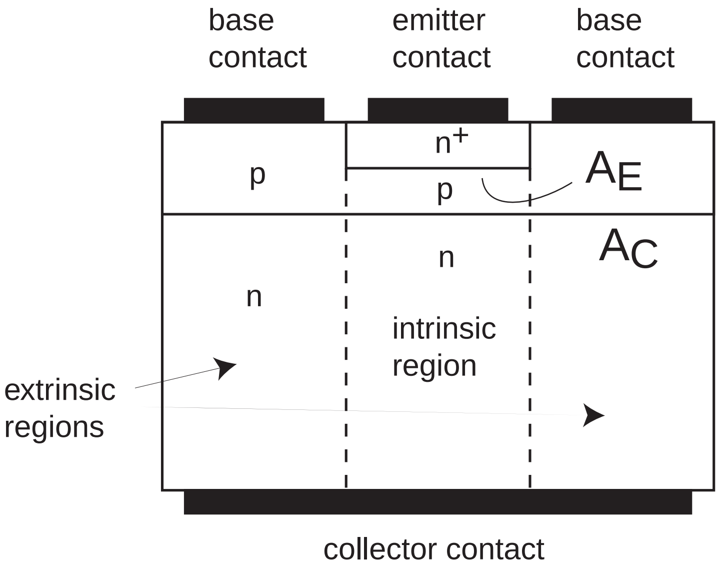
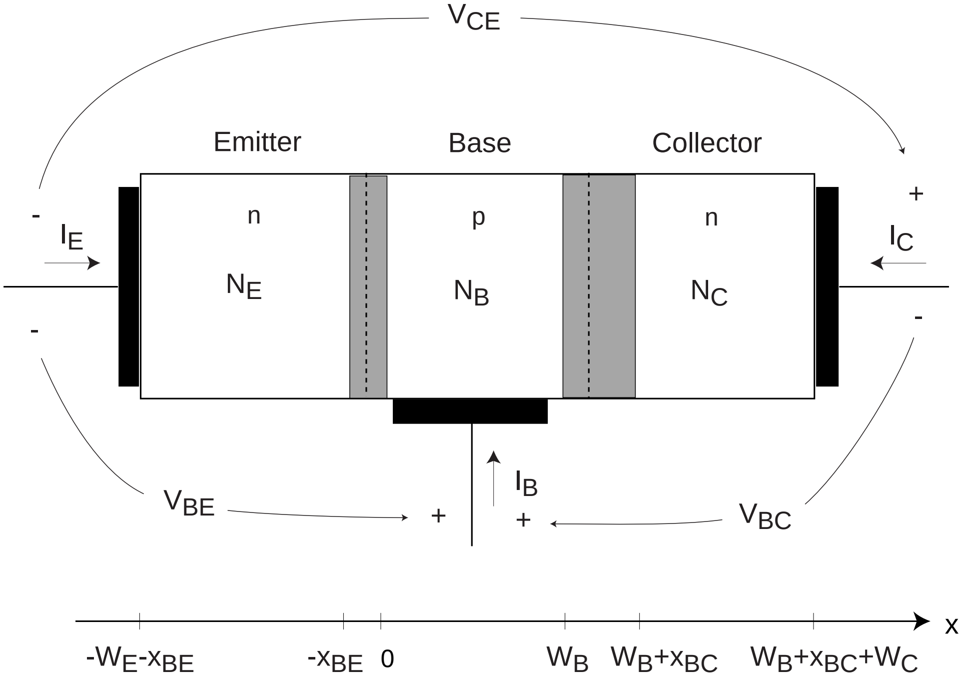
Ideal BJT:



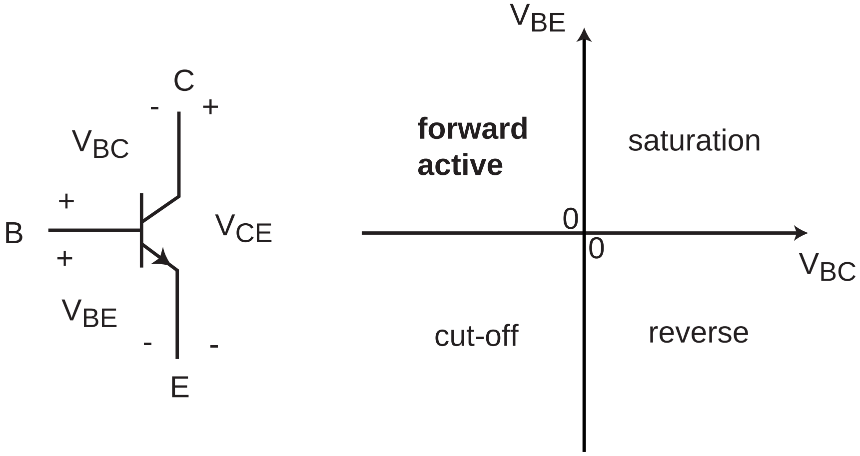
Ideal BJT simplifications:

- 1D.
- Uniform doping distributions.
- Minority carrier G&R in intrinsic base is negligible.
- Emitter, extrinsic base and collector also assumed "short" from minority carrier point of view.
- Low-level injection.
- QNR thicknesses independent of V_{BE} and V_{BC}.
- Ignore sidewall effects.
- No parasitic resistances.
- Ignore substrate.

Simplified 1D model of intrinsic device:



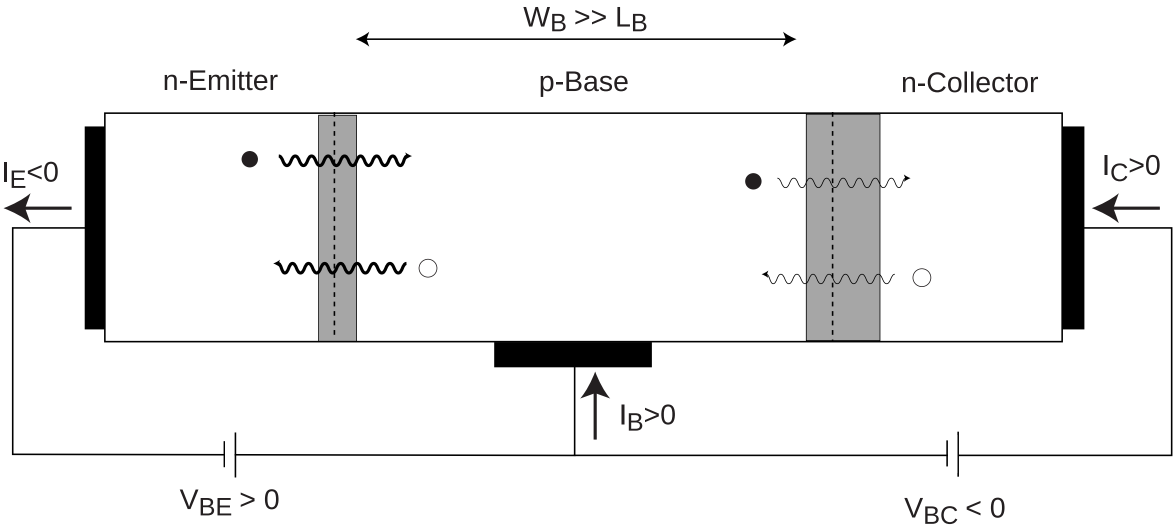
Regimes of operation:



2. Current-voltage characteristics of ideal BJT

☐ Basic operation in forward active regime:

- Two junctions back-to-back:

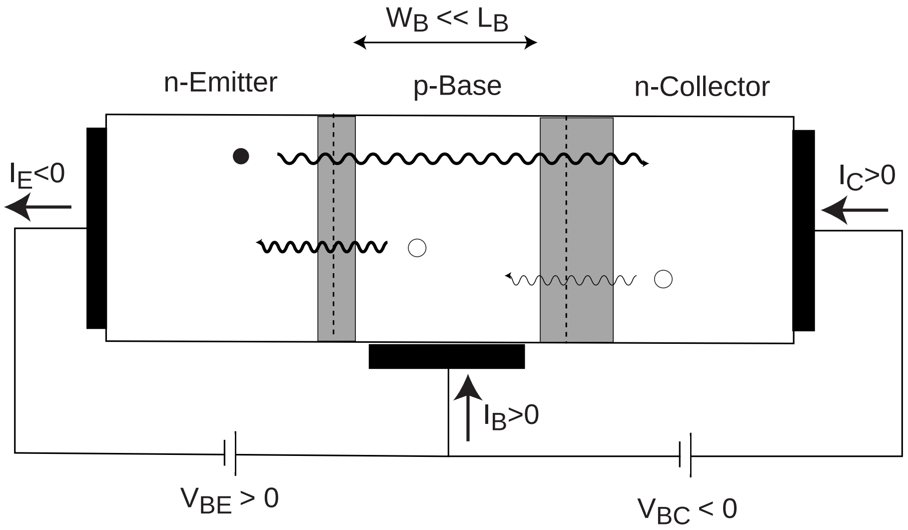


$V_{BE} > 0$ ⇒ injection of electrons from E to B
injection of holes from B to E

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

$$I_B \simeq -I_E \gg I_C$$

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

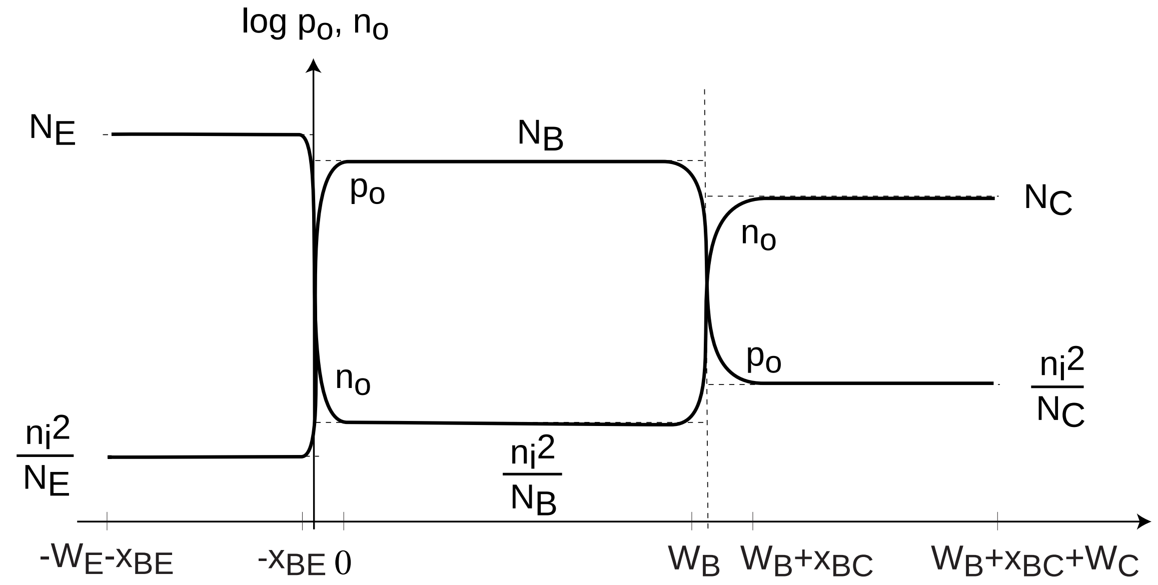


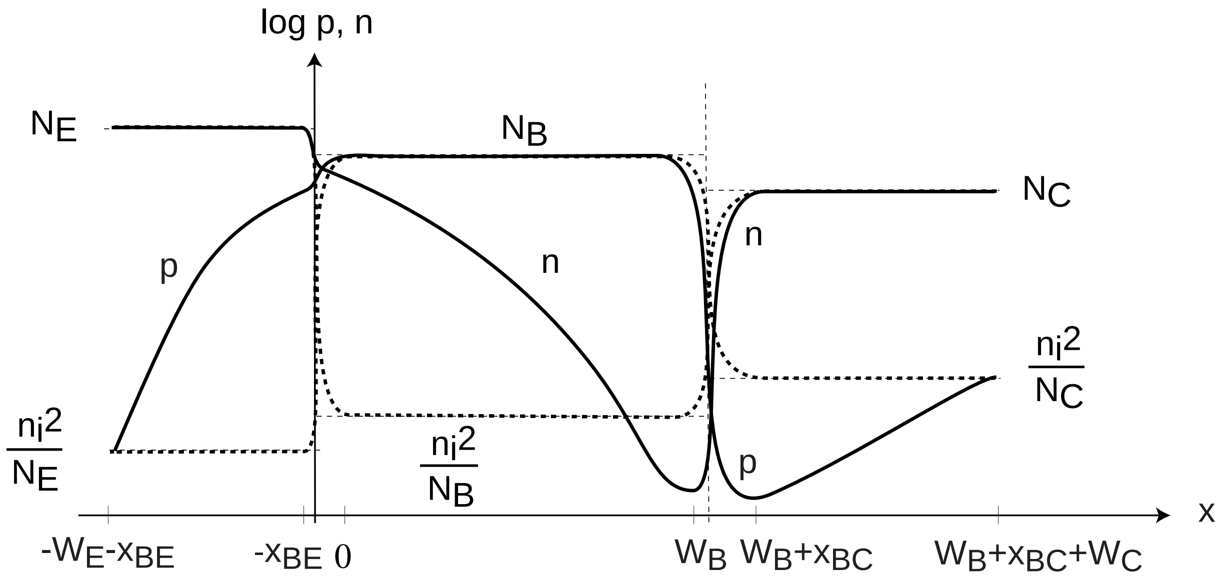
$$I_C \simeq -I_E \gg I_B$$

In forward-active regime:

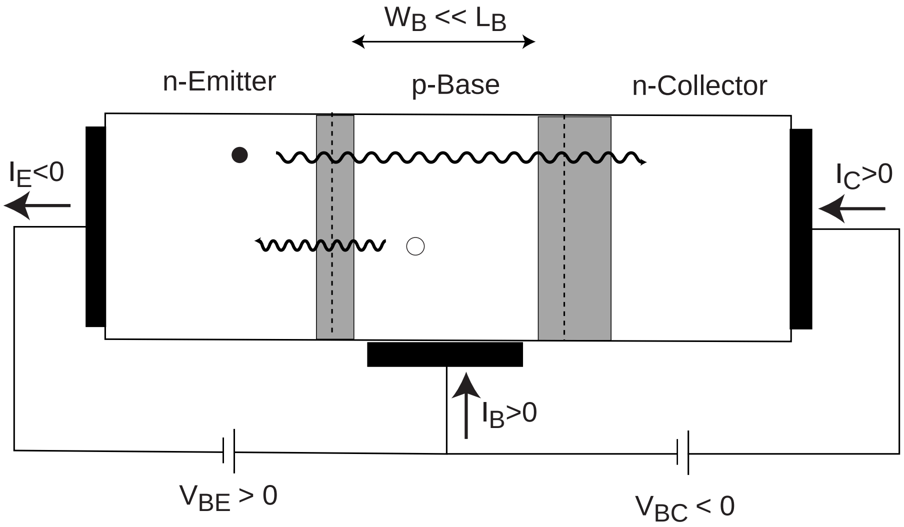
- V_{BE} controls I_C ("transistor effect")
- I_C independent of V_{BC} ("isolation")
- price to pay for control: I_B

Carrier profiles in TE and FAR:





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*

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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:

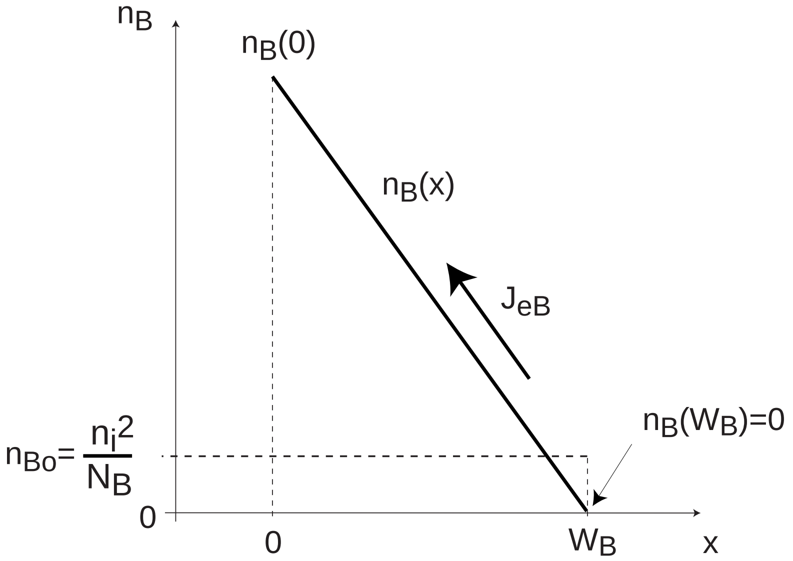
feature	**ideal BJT in FAR**	**ideal MOSFET in saturation**
controlling terminal	base	gate
controlled terminal	collector	drain
common terminal	emitter	source
functional dependence of controlled current	exponential	quadratic
DC current in controlling terminal	exponential	0

Figure of merit for BJT:

common-emitter current gain: $\beta_F = \frac{I_C}{I_B}$ (want big)

□ **Forward-active regime** $(V_{BE} > 0,\ V_{BC} < 0)$

- *Collector current*



Boundary conditions:

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

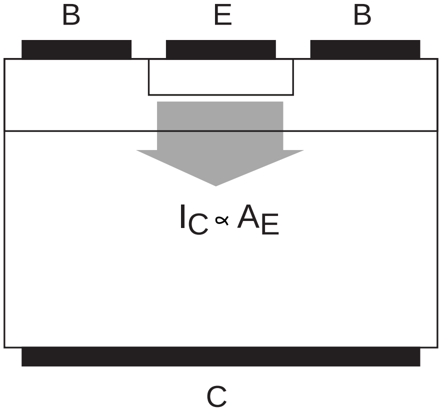
Electron profile:

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

Electron current density:

$$J_{eB} = qD_B\frac{dn_B}{dx} = -qD_B\frac{n_B(0)}{W_B}$$

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



Collector terminal current:

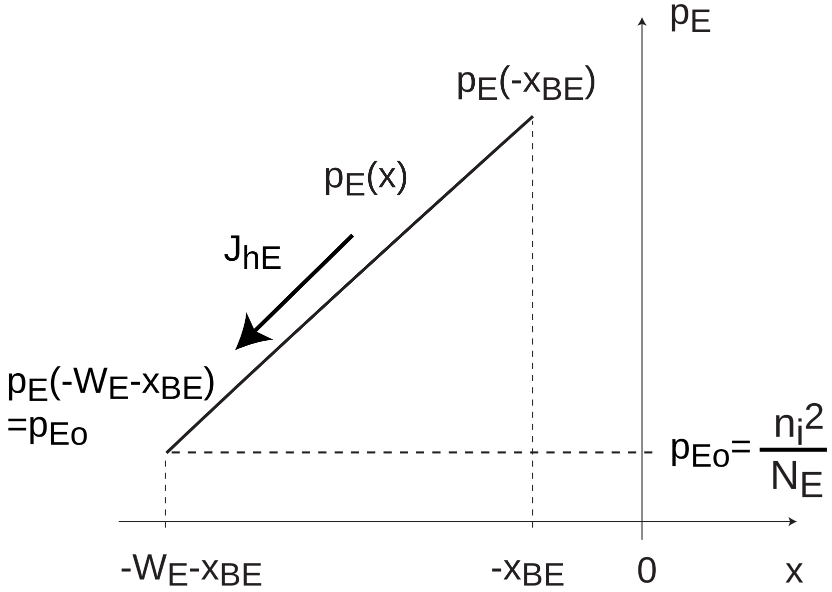
$$I_C = -J_{eB} A_E = q A_E \frac{n_i^2}{N_B} \frac{D_B}{W_B} \exp \frac{qV_{BE}}{kT}$$

or

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

$$I_S \equiv \textit{collector saturation current}$$

- *Base current*: focus on hole injection and recombination in emitter (assume "short" or "transparent" and $S = \infty$ at surface)



Boundary conditions:

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

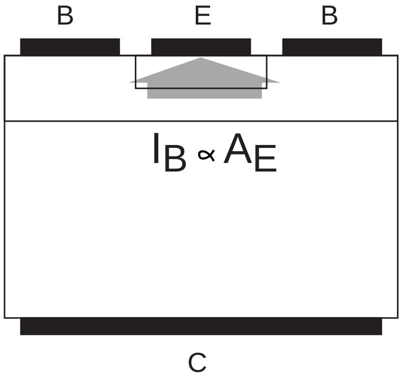
Hole profile:

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

Hole current density:

$$J_{hE} = -qD_E\frac{dp_E}{dx} = -qD_E\frac{p_E(-x_{BE}) - p_{Eo}}{W_E}$$

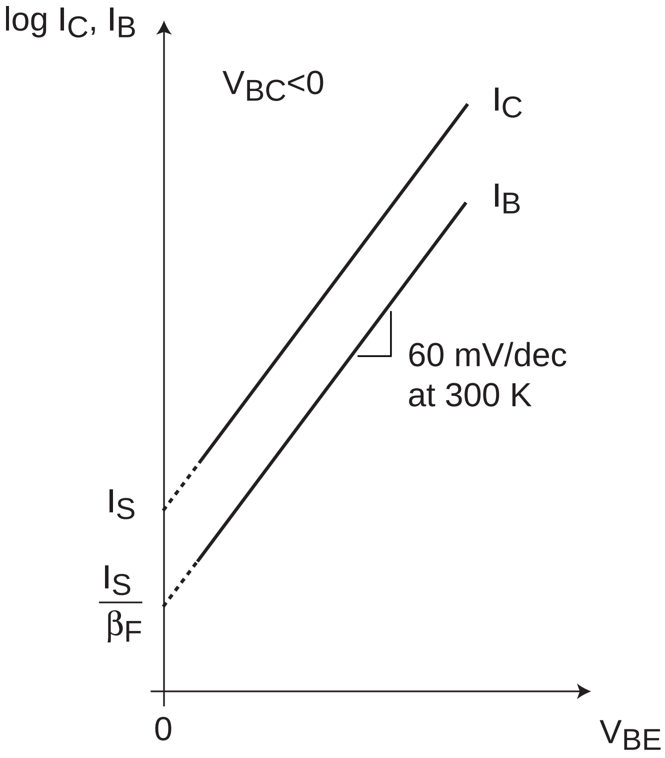
Base current scales with area of base-emitter junction A_E:

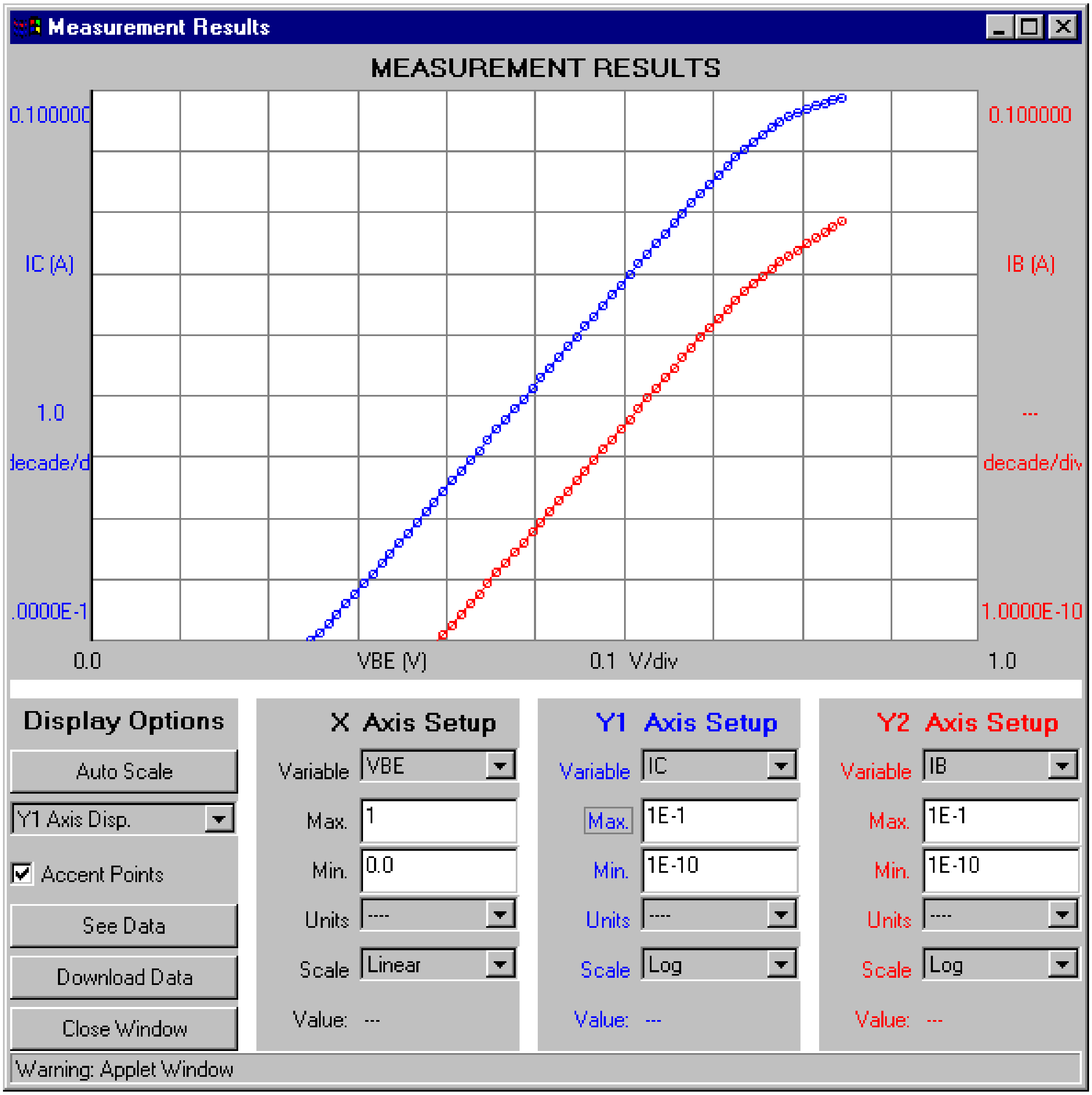


Base terminal current:

$$I_B = -J_{hE} A_E = q A_E \frac{n_i^2}{N_E} \frac{D_E}{W_E} (\exp \frac{qV_{BE}}{kT} - 1) = \frac{I_S}{\beta_F} (\exp \frac{qV_{BE}}{kT} - 1)$$

☐ *Gummel plot*:





X Axis Setup

Variable: VBE
Max.: 1
Min.: 0.0
Units: ----
Scale: Linear
Value: ---

Y1 Axis Setup

Variable: IC
Max.: 1E-1
Min.: 1E-10
Units: ----
Scale: Log
Value: ---

Y2 Axis Setup

Variable: IB
Max.: 1E-1
Min.: 1E-10
Units: ----
Scale: Log
Value: ---

Warning: Applet Window

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Key conclusions

- BJT is minority-carrier type device: in npn BJT in forward active regime: Emitter "injects" electrons into Base, Collector "collects" electrons from Base.
- I_C controlled by V_{BE}, but independent of V_{BC} (*transistor effect*):

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

- Base injects holes into Emitter ⇒ I_B depends only on V_{BE}:

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

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