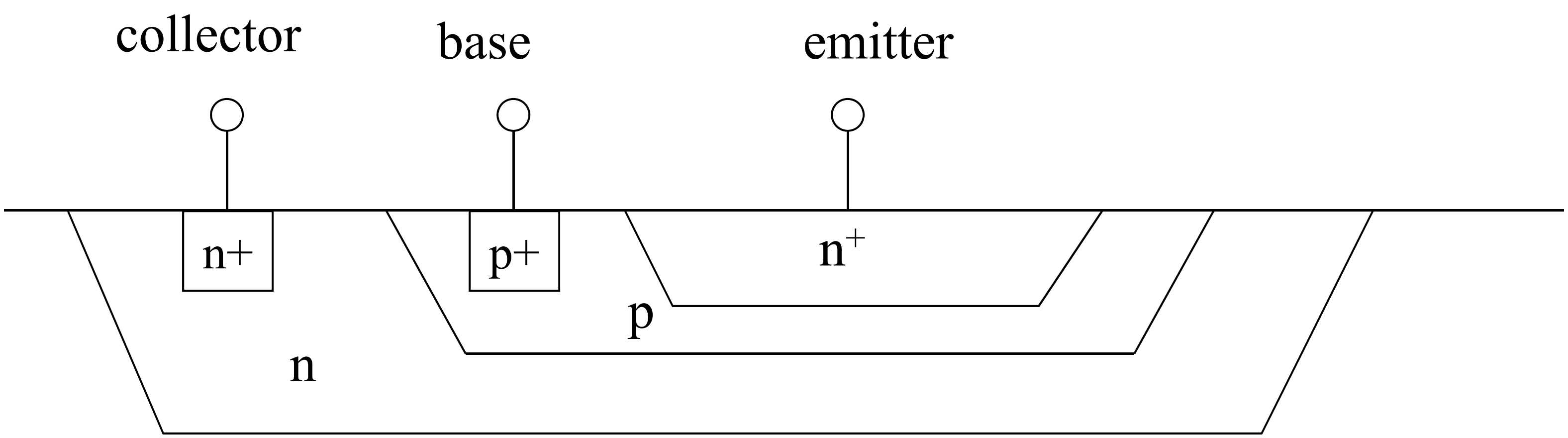
13. Bipolar transistors

Jan. 15, 2019

bipolar transistors

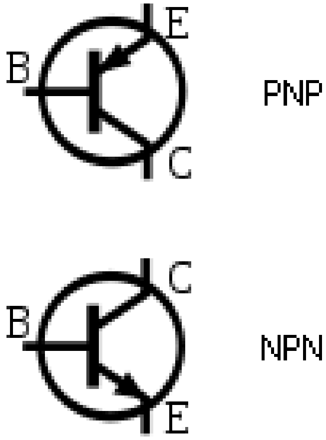
npn transistor

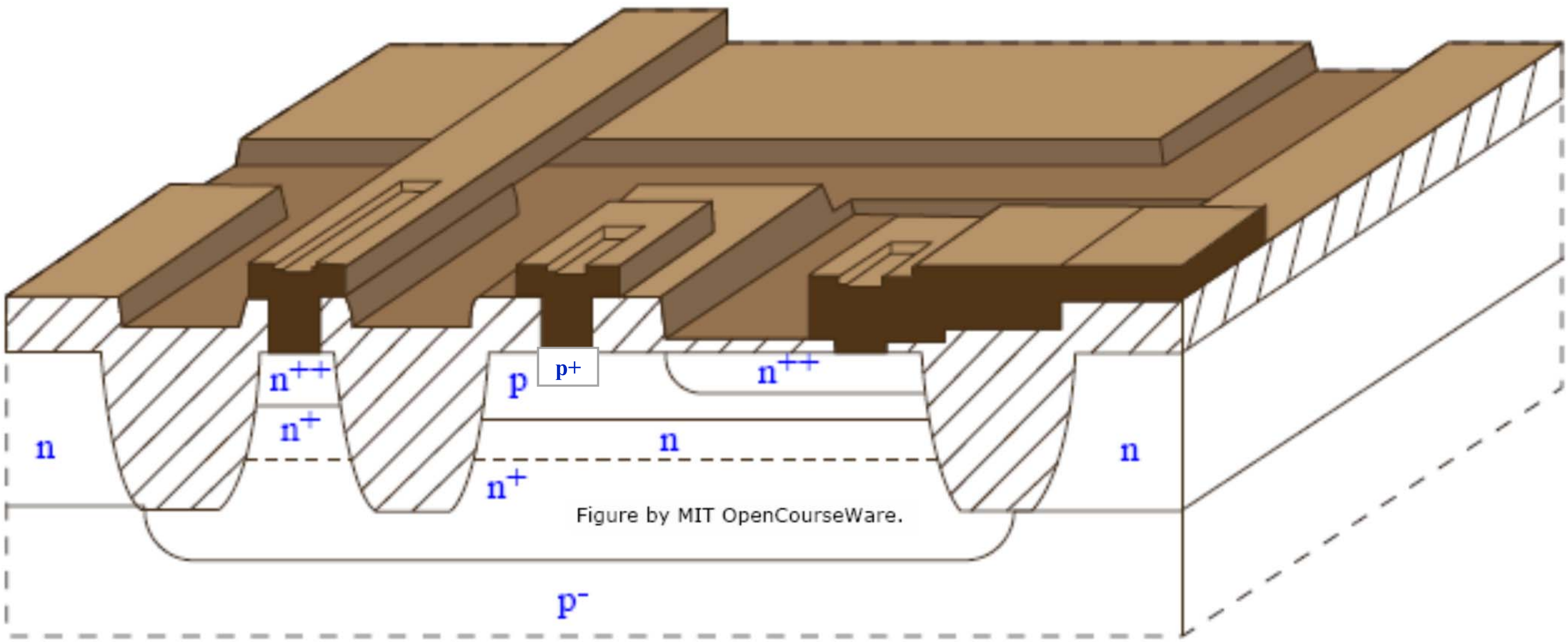


lightly doped p substrate

Used in front-end high-frequency receivers (mobile telephones).

bipolar transistors

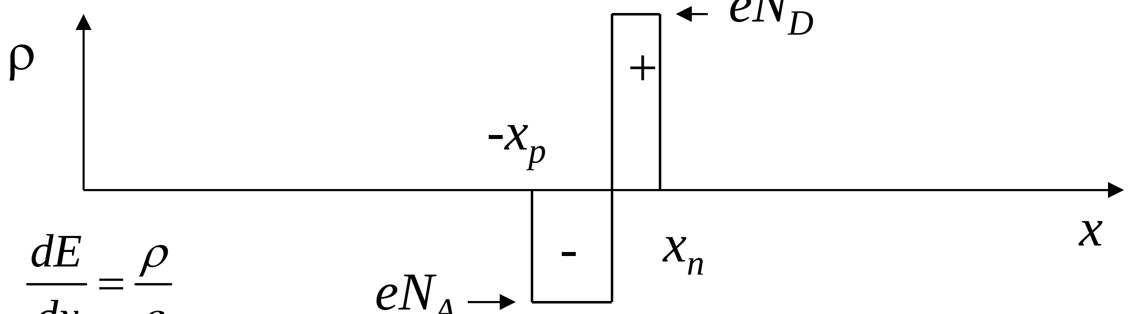




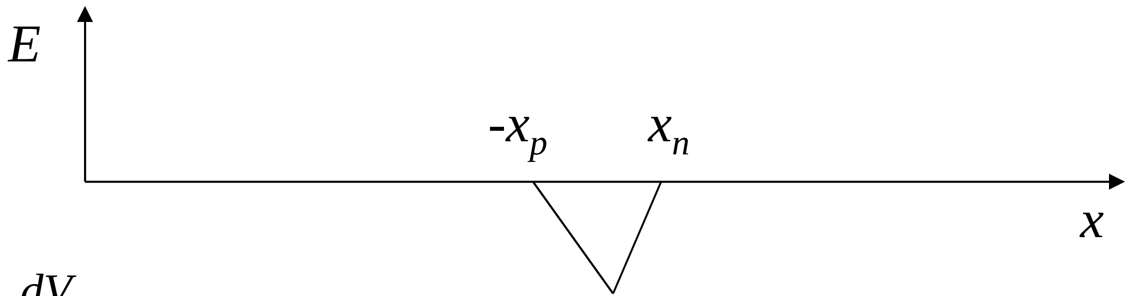
Oxide isolated integrated BJT - a modern process

abrupt junction

$$eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)$$



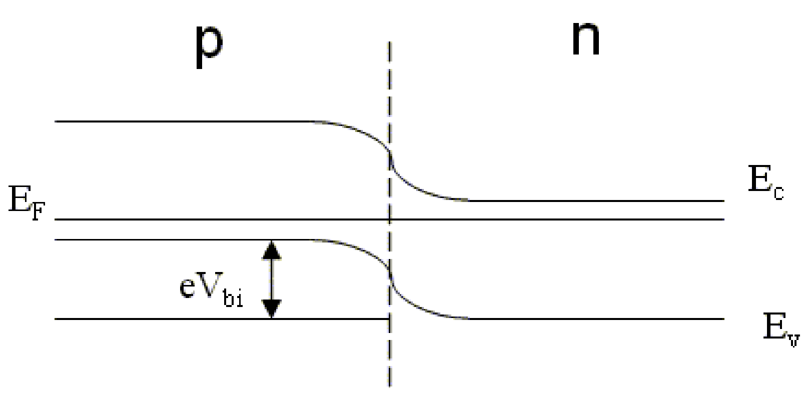
$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$



$$E = -\frac{eN_A}{\varepsilon}\left(x + x_p\right) \qquad -x_p > x > 0$$

$$E = \frac{eN_D}{\varepsilon}\left(x - x_n\right) \qquad 0 > x > x_n$$

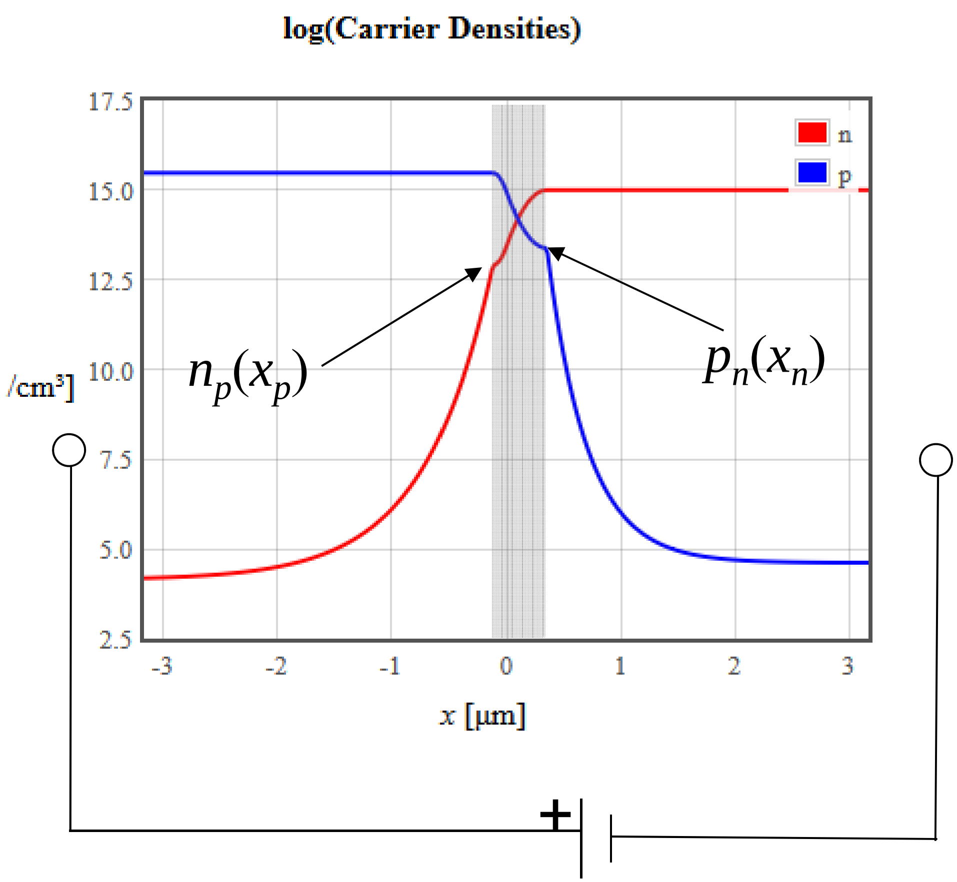
$$\frac{dV}{dx} = -E$$



$$V = \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + xx_p\right) \qquad -x_p > x > 0$$

$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - xx_n\right) \qquad 0 > x > x_n$$

Forward bias, V > 0



Electrons and holes are driven towards the junction.
The depletion region becomes narrower

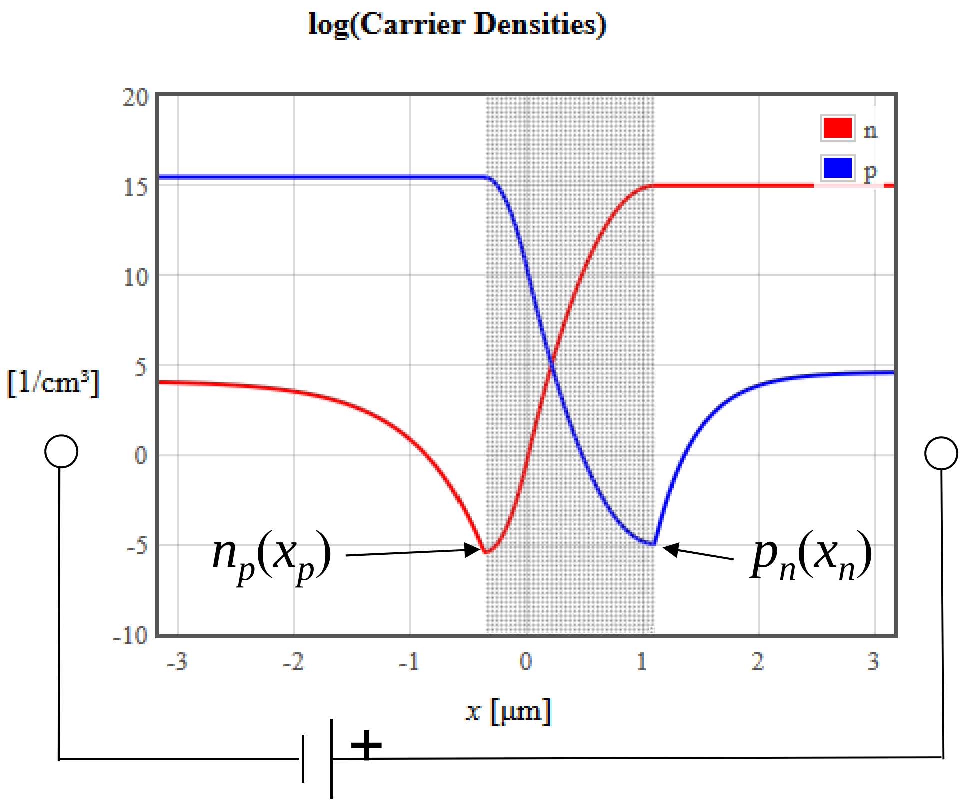
$$n_p(x_p) = n_{p0} \exp\left(\frac{eV}{k_B T}\right)$$

$$p_n(x_n) = p_{n0} \exp\left(\frac{eV}{k_B T}\right)$$

$$p_{e0} \exp\left(\frac{eV_{be}}{k_B T}\right)$$

Minority electrons are injected into the p-region
Minority holes are injected into the n-region

Reverse bias, V < 0



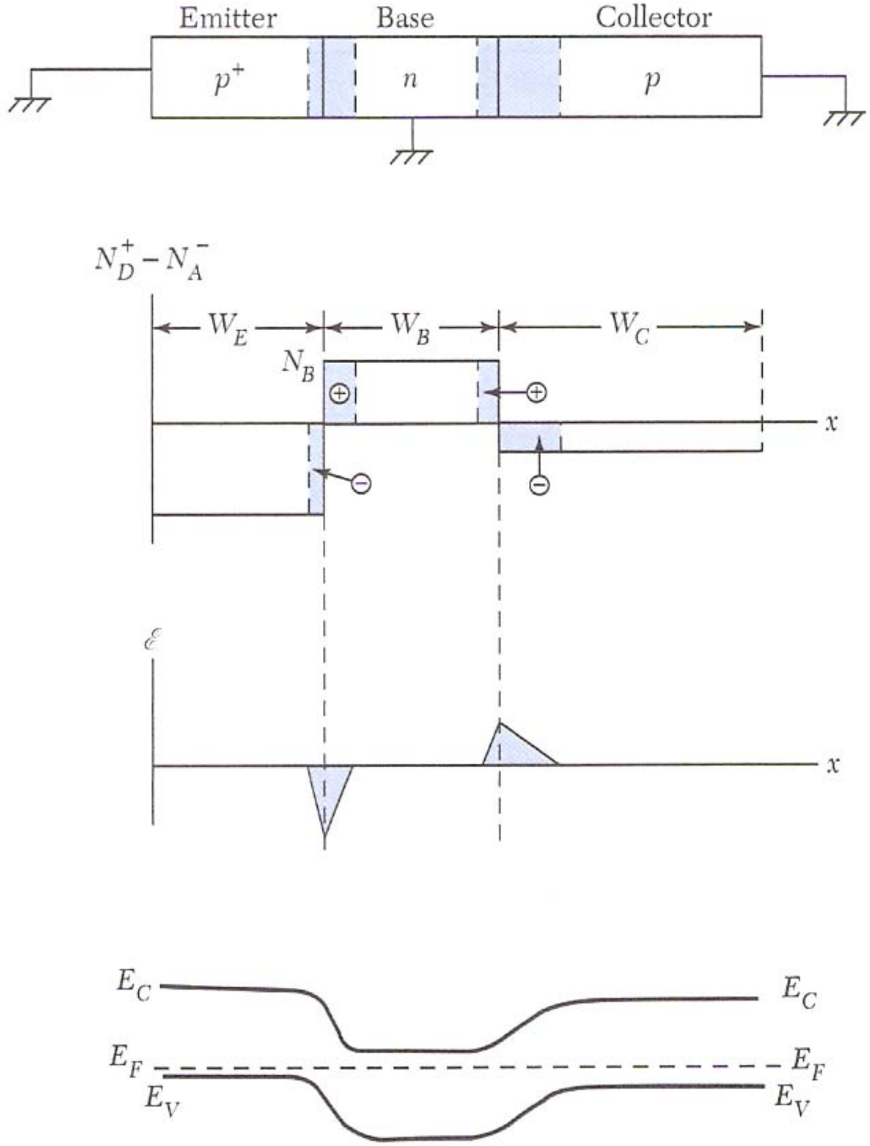
Electrons and holes are driven away from the junction.
The depletion region becomes wider

$$n_p(x_p) = n_{p0} \exp\left(\frac{eV}{k_B T}\right)$$

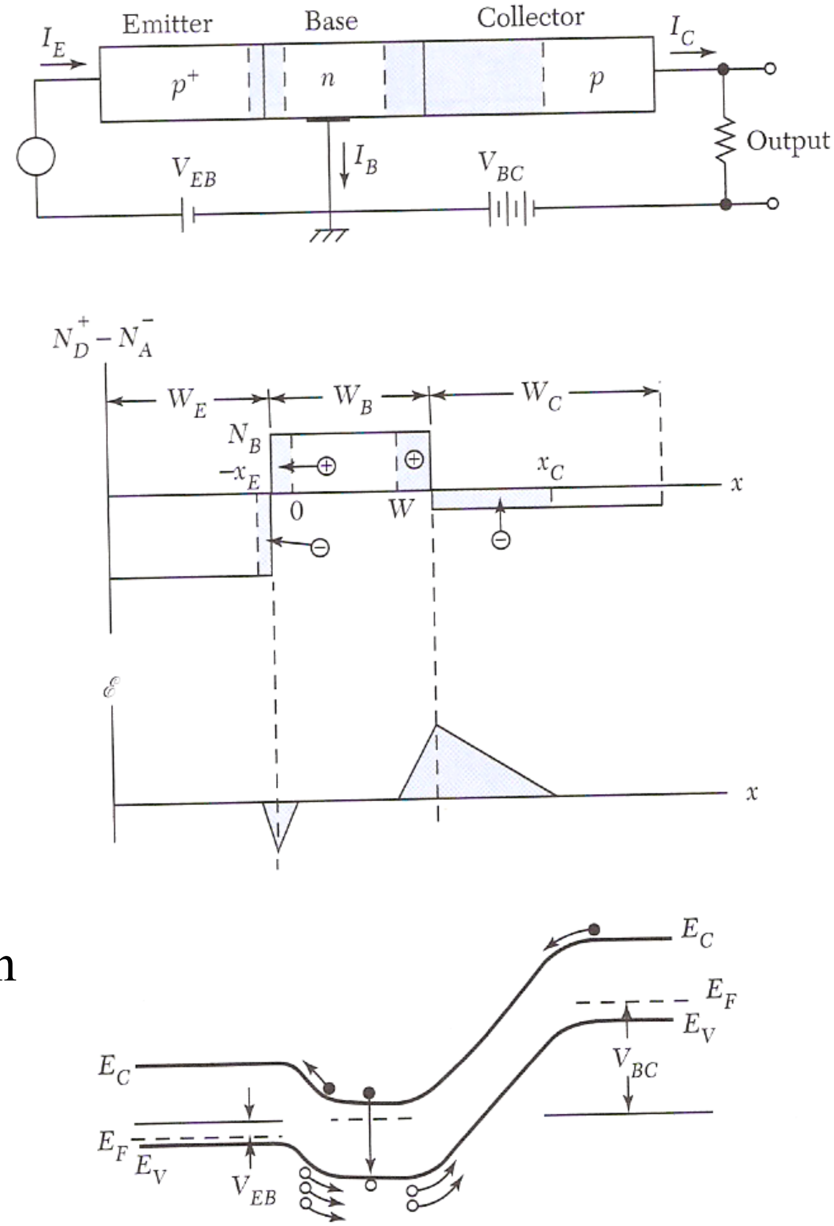
$$p_n(x_n) = p_{n0} \exp\left(\frac{eV}{k_B T}\right)$$

Minority electrons are extracted from the p-region by the electric field
Minority holes are extracted from the n-region by the electric field

pnp transistor, no bias



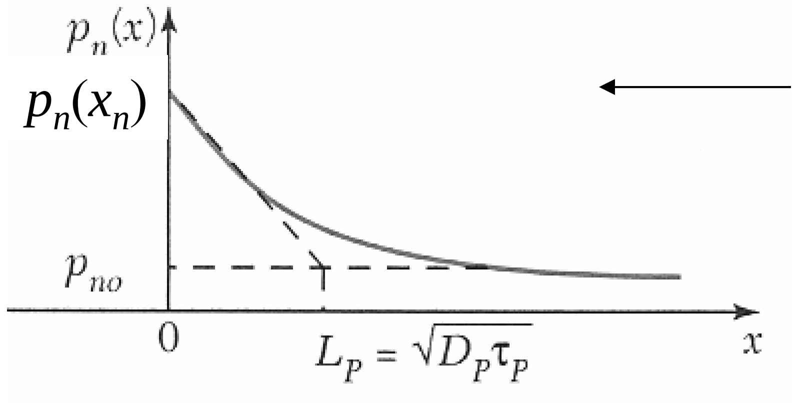
pnp transistor, forward active bias



Always dissipate power due to the forward bias

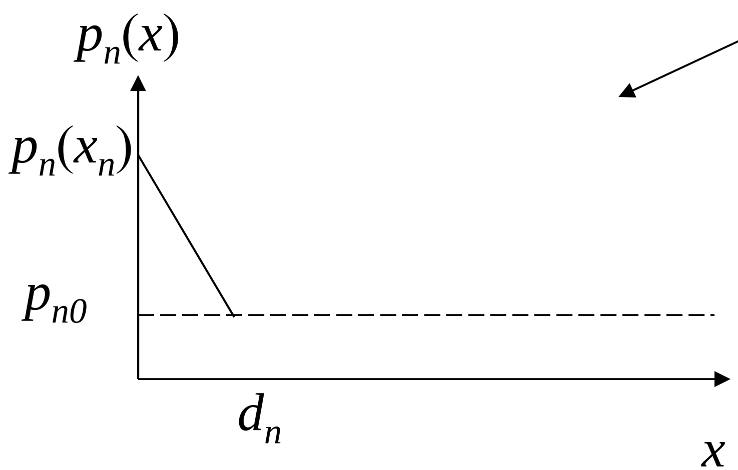
The base-emitter voltage controls the minority carriers injected from the emitter to the base. These diffuse to the base-collector junction and are swept into the collector.

Long/Short diode



Long diode $d_n >> L_p$

Short diode



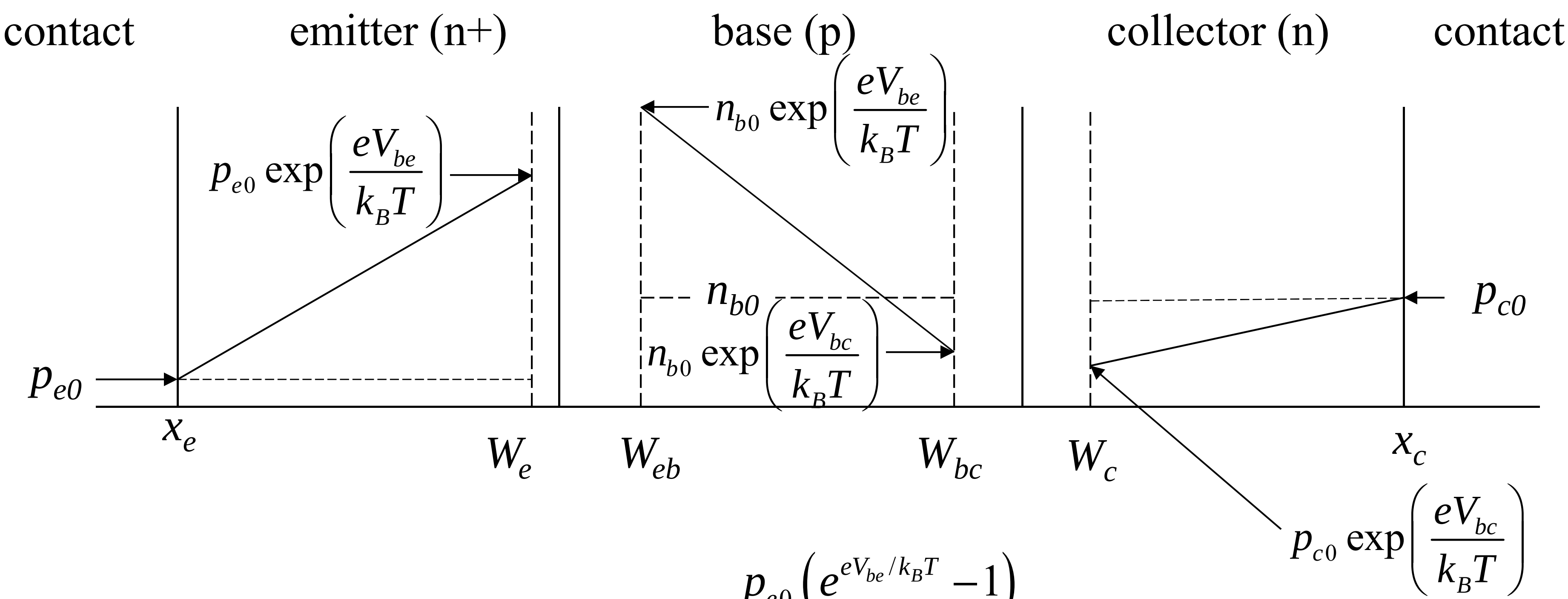
$d_n << L_p$

Metal contact is much closer to the depletion region than the diffusion length

$$J_{diff,p} = eD_p \frac{dp}{dx}$$

$$J_{diff,p} = eD_p \frac{dp}{dx} = eD_p \frac{\left(p_n(x_n) - p_{n0}\right)}{d_n}$$

Minority carrier concentration



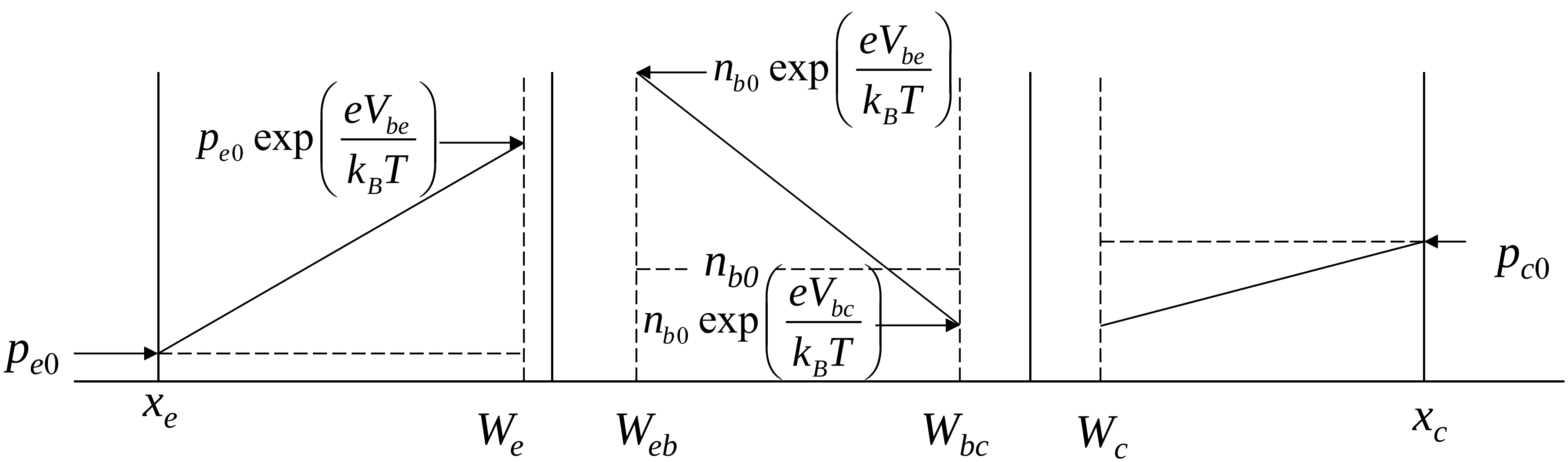
$$I_{Ep} = eA_{be}D_p \frac{p_{e0}\left(e^{eV_{be}/k_BT} - 1\right)}{W_e - x_e}$$

$$I_{En} = -eA_{be}D_n \frac{n_{b0}\left(e^{eV_{be}/k_BT} - e^{eV_{bc}/k_BT}\right)}{W_{bc} - W_{be}}$$

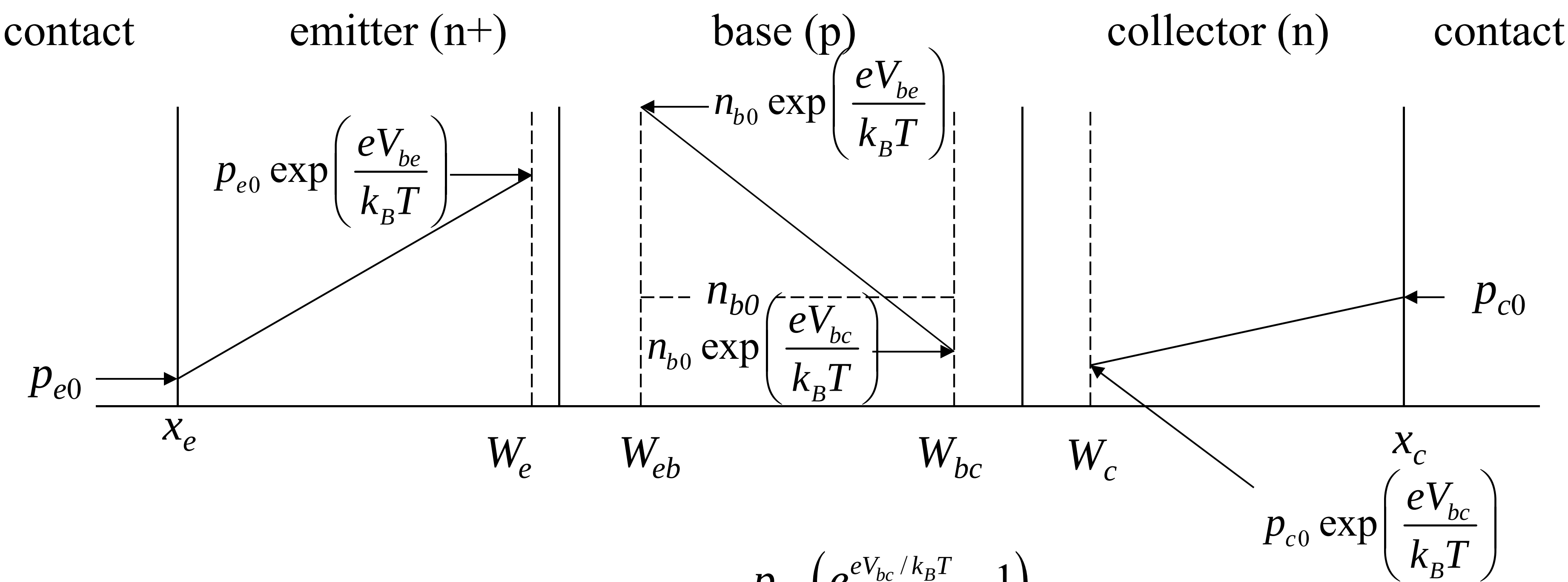
Emitter current

$$I_E = I_{En} + I_{Ep} = \left[\frac{eA_{be} D_p p_{e0}}{W_{eb} - x_e} + \frac{eA_{be} D_n n_{b0}}{W_{bc} - W_{be}} \right] \left(e^{eV_{be}/k_B T} - 1 \right) - \frac{eA_{be} D_n n_{b0}}{W_{bc} - W_{be}} \left(e^{eV_{bc}/k_B T} - 1 \right)$$

$$I_E = I_{ES} \left(e^{eV_{be}/k_B T} - 1 \right) - \alpha_R I_{CS} \left(e^{eV_{bc}/k_B T} - 1 \right)$$



Collector current



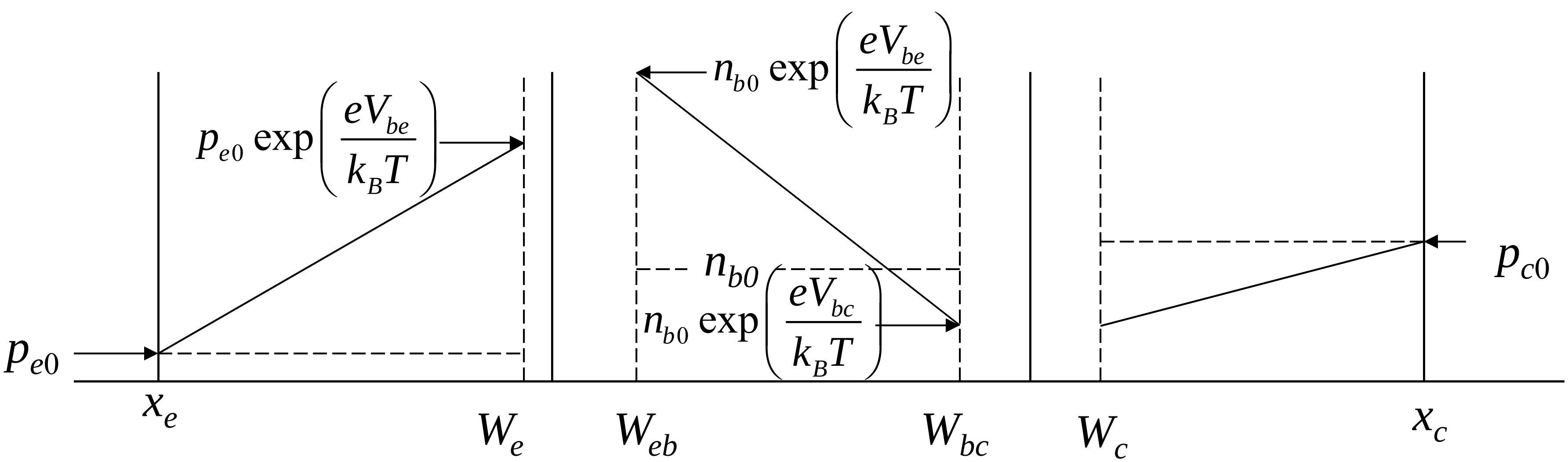
$$I_{cp} = -eA_{bc}D_p \frac{p_{c0}\left(e^{eV_{bc}/k_BT} - 1\right)}{x_c - W_c}$$

$$I_{cn} = -eA_{bc}D_n \frac{n_{b0}\left(e^{eV_{be}/k_BT} - e^{eV_{bc}/k_BT}\right)}{W_{bc} - W_{eb}}$$

Collector current

$$I_c = I_{cp} + I_{cn} = \frac{eA_{bc}D_n n_{b0}}{W_{bc} - W_{be}}\left(e^{eV_{be}/k_BT} - 1\right) - \left[\frac{eA_{bc}D_p p_{c0}}{x_c - W_c} + \frac{eA_{bc}D_n n_{b0}}{W_{bc} - W_{be}}\right]\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_c = I_{cp} + I_{cn} = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

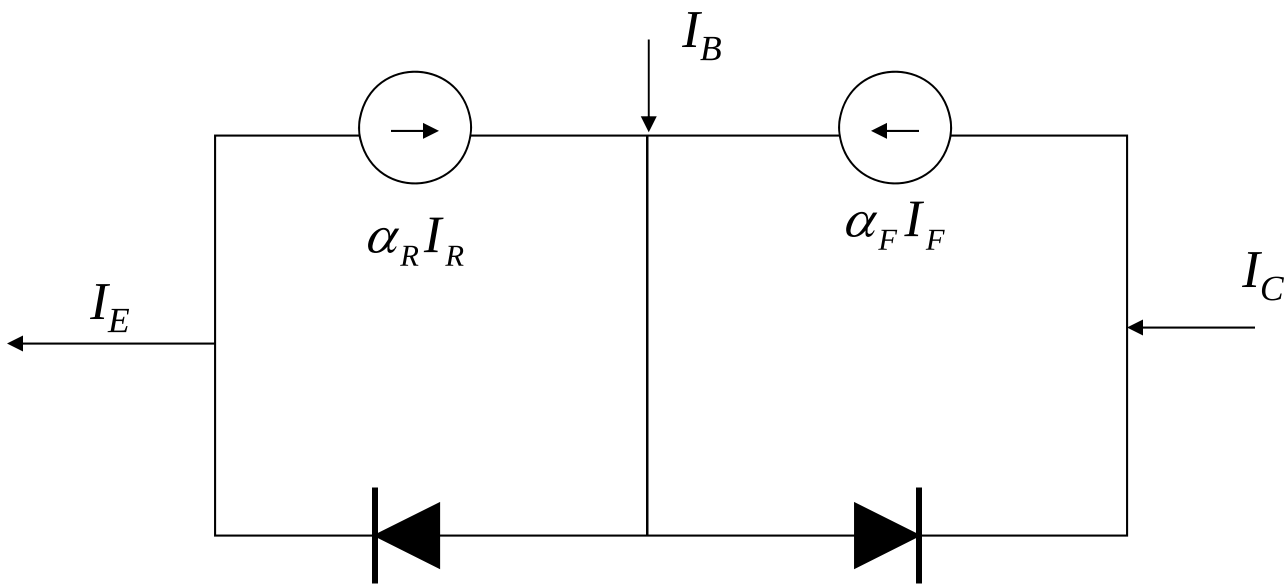


Ebers-Moll model

$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

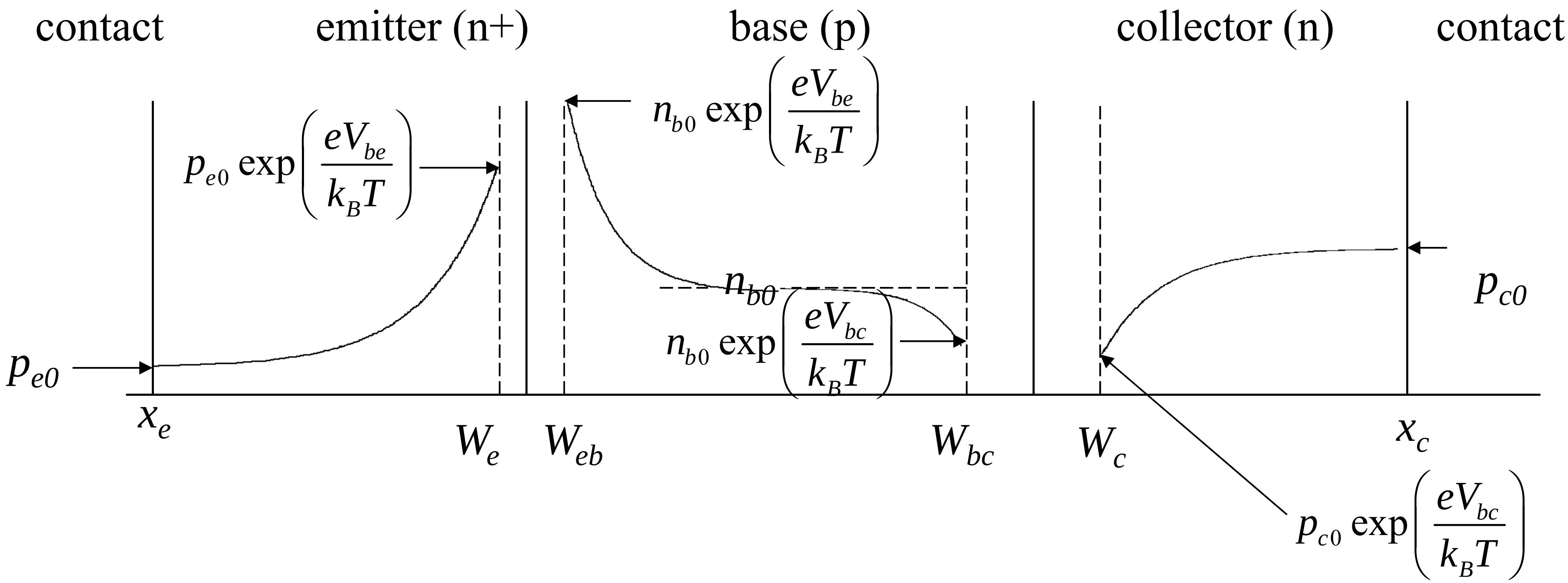
$$I_C = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$



$$I_F = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) \qquad I_R = I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

Not an npn transistor



Emitter efficiency

$$\gamma_e = \frac{I_{En}}{I_{En} + I_{Ep}} = \frac{1}{1 + I_{Ep} / I_{En}}$$ ← for npn

$$I_{Ep} = eA_{be} D_p \frac{p_{e0}\left(e^{eV_{be}/k_B T} - 1\right)}{W_{eb} - x_e}$$

$$I_{En} = -eA_{be} D_n \frac{n_{b0}\left(e^{eV_{be}/k_B T} - e^{eV_{bc}/k_B T}\right)}{W_{bc} - W_{be}}$$

For $\gamma_e \sim 1$, $W_{bc} - W_{be} << L_b$, $W_{eb} - x_e$ and $n_{b0} >> p_{e0}$

$W_{bc} - W_{be}$: neutral base width

$n_{b0} = \frac{n_i^2}{N_{Ab}}$, $p_{e0} = \frac{n_i^2}{N_{De}}$

Small base width and heavy emitter doping

Base transport factor

$$B = \frac{I_c}{I_{En}}$$

ratio of the injected current to the collected current

recombination in the base would reduce the base transport factor

A thin base with low doping results in a base transport factor ~ 1

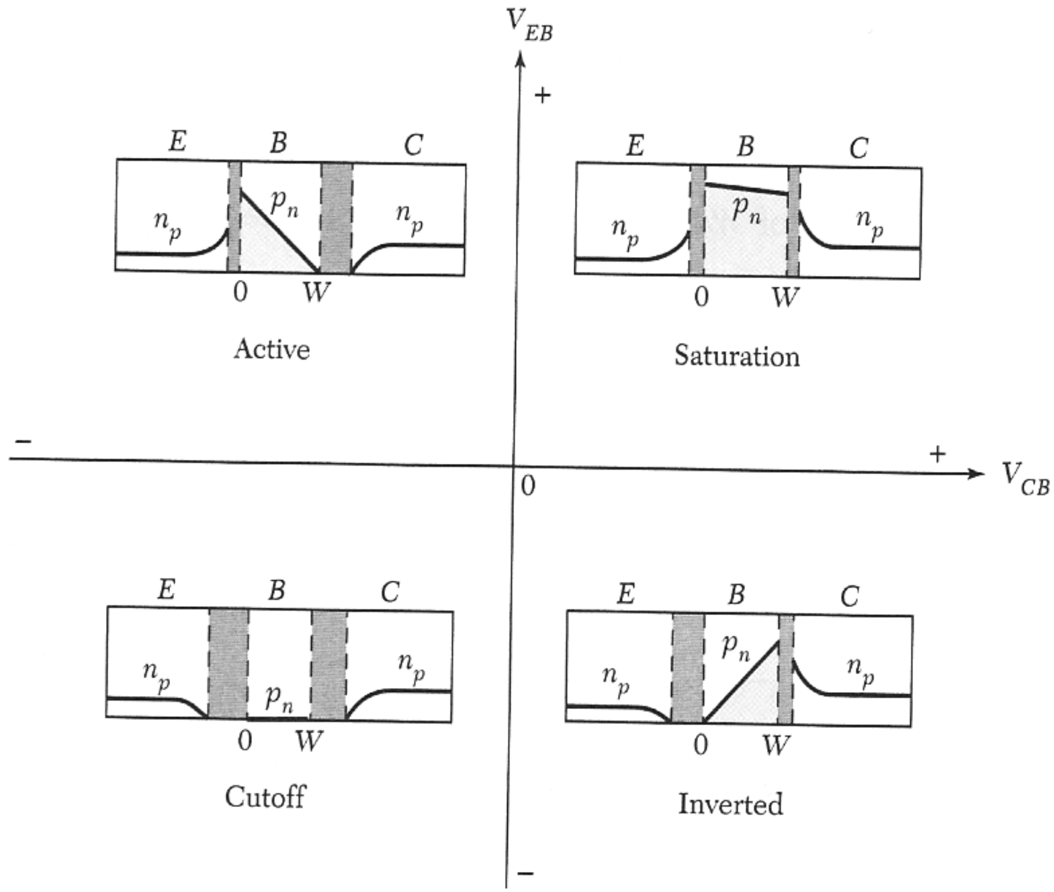
Current transfer ratio

$$\alpha = \frac{I_C}{I_E} = B\gamma_e$$

$\alpha \sim 1$ for a good BJT

Transistor modes

1. Forward active: emitter-base **forward**, base-collector **reverse**
2. Saturation: emitter-base **forward**, base-collector **forward**
3. Reverse active: emitter-base **reverse**, base-collector **forward**
4. Cut-off: emitter-base **reverse**, base-collector **reverse**

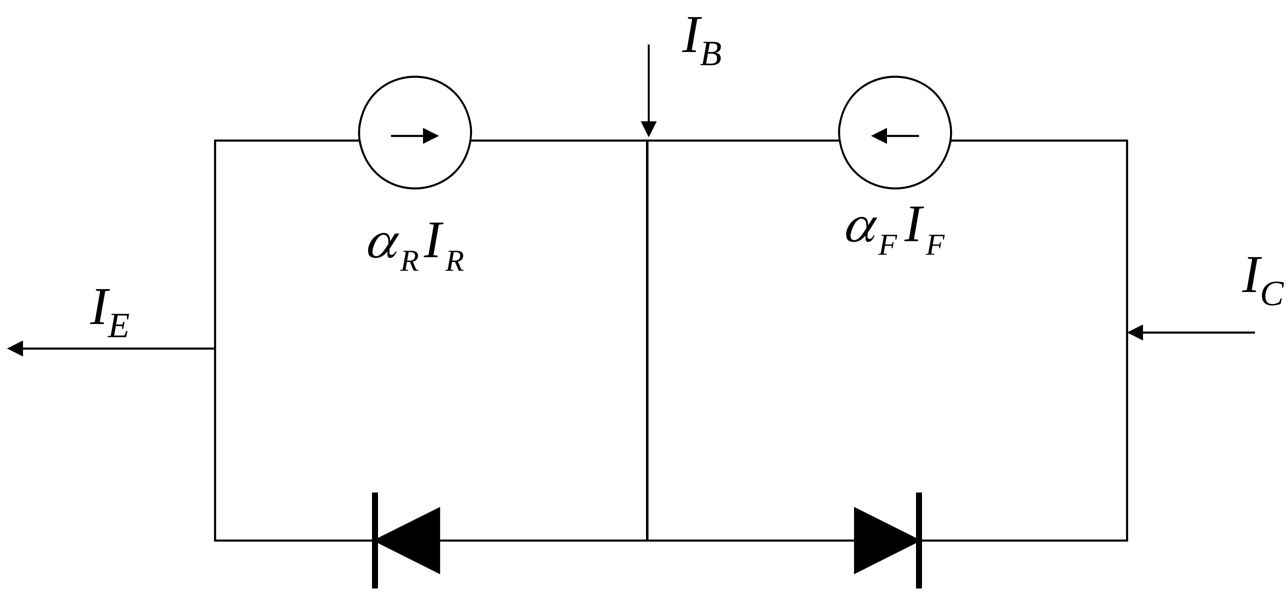


Ebers-Moll model

$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_C = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$



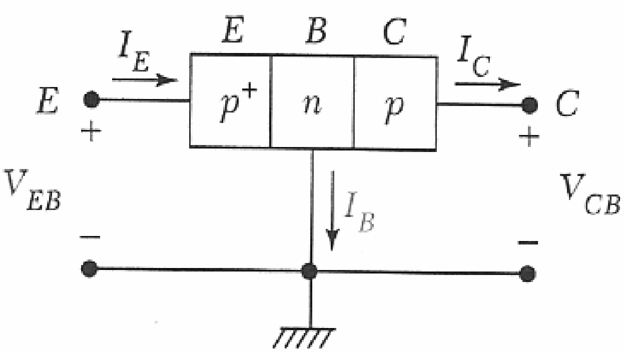
$$I_F = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) \qquad I_R = I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

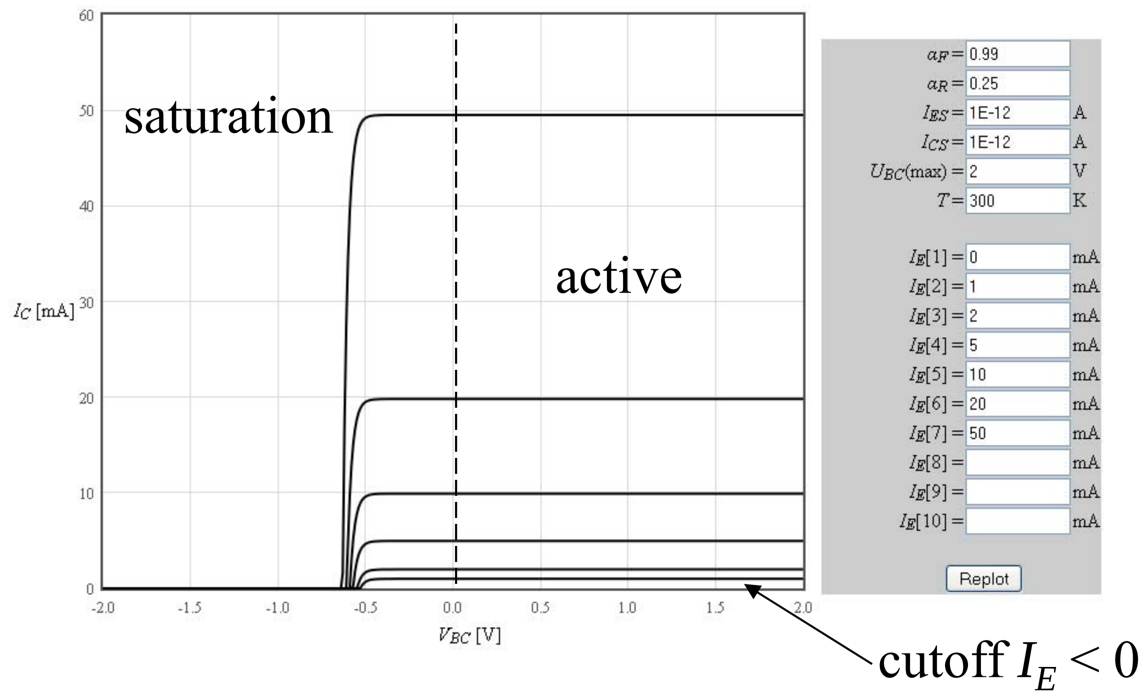
Common base configuration

$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

solve for V_{be}

$$I_c = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$





http://lamp.tu-graz.ac.at/~hadley/psd/L13/commonbase/pnp_current.html

Ebers - Moll Model

$$I_{ES} = \left[\frac{eA_{be}D_p p_{e0}}{W_{eb} - x_e} + \frac{eA_{be}D_n n_{b0}}{W_{bc} - W_{be}} \right]$$

$$\alpha_R I_{CS} = \frac{eA_{be}D_n n_{b0}}{W_{bc} - W_{be}}$$

$$\alpha_F I_{ES} = \frac{eA_{bc}D_n n_{b0}}{W_{bc} - W_{be}}$$

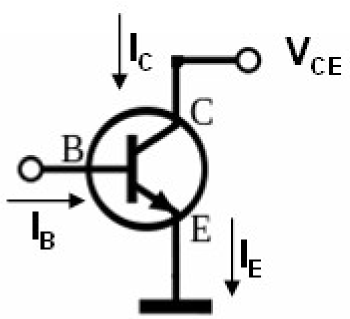
$$I_{CS} = \left[\frac{eA_{bc}D_p p_{c0}}{x_c - W_c} + \frac{eA_{bc}D_n n_{b0}}{W_{bc} - W_{be}} \right]$$

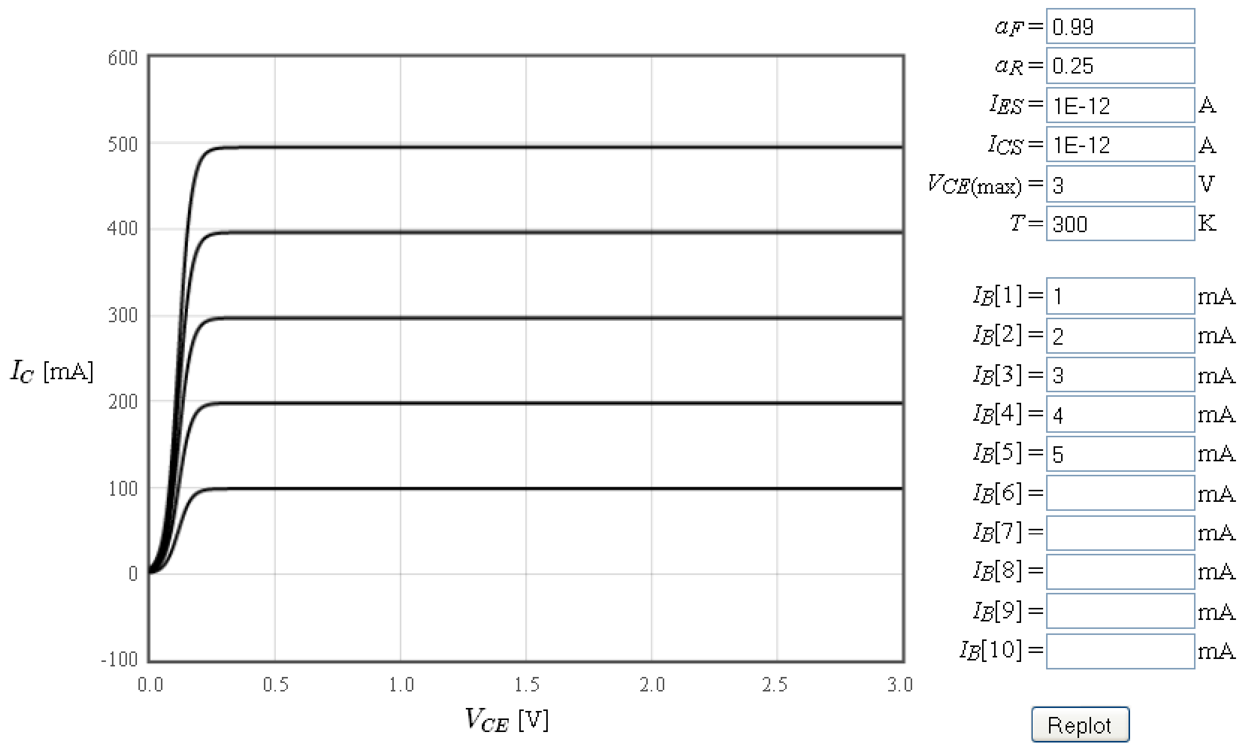
Common emitter configuration

$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$

$$I_c = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$





current amplification ~100

http://lamp.tu-graz.ac.at/~hadley/psd/L13/commonemitter.php

Current amplification factor

$$\beta = h_{fe} = \frac{I_C}{I_B}$$

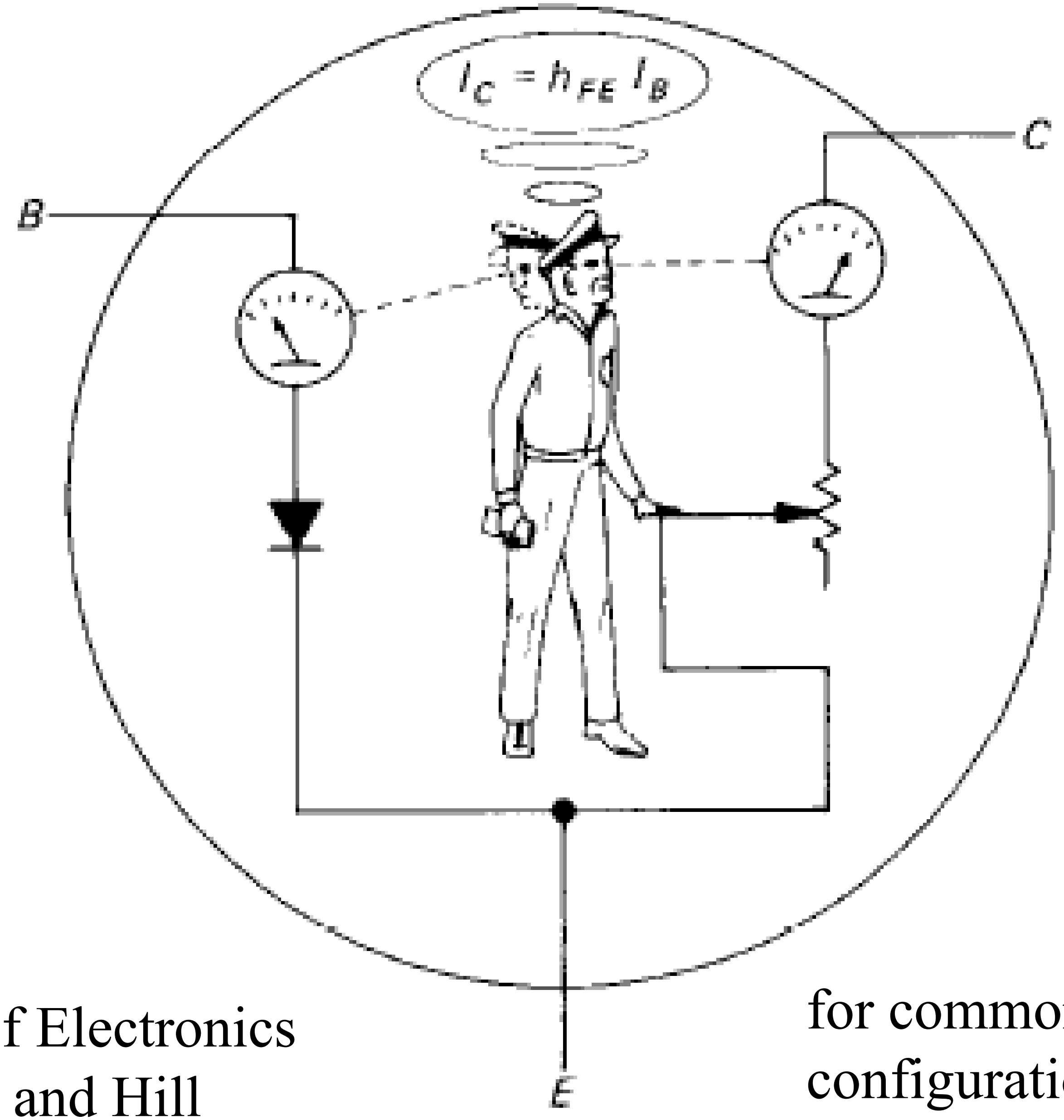
$$I_B = I_E - I_C$$

$$I_C = \alpha I_E$$

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

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} = \frac{B\gamma_e}{1 - B\gamma_e}$$

$\beta \sim 50 - 500$



The Art of Electronics
Horowitz and Hill

for common emitter configuration

“Transistor man”

Transconductance

$$g_m = \frac{\partial I_C}{\partial V_{be}}$$

$$I_c = \alpha_F I_{ES}\left(e^{eV_{be}/k_B T} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_B T} - 1\right)$$

The first term depends on V_{be}

$$g_m = \frac{e\alpha_F I_{ES}}{k_B T} e^{eV_{be}/k_B T} \approx \frac{eI_C}{k_B T} = \frac{e\beta I_B}{k_B T}$$

The transconductance can be very high.

Early effect

Ebers - Moll:

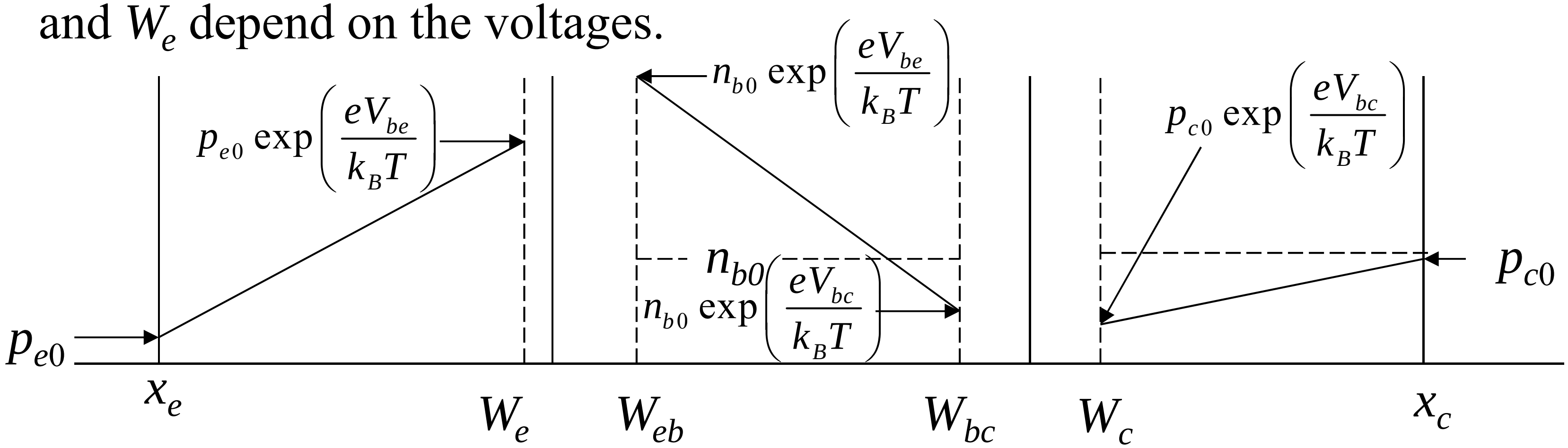
$$I_E = I_{ES}\left(e^{eV_{be}/k_BT}-1\right)-\alpha_R I_{CS}\left(e^{eV_{bc}/k_BT}-1\right)$$

$$I_c = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT}-1\right)-I_{CS}\left(e^{eV_{bc}/k_BT}-1\right)$$

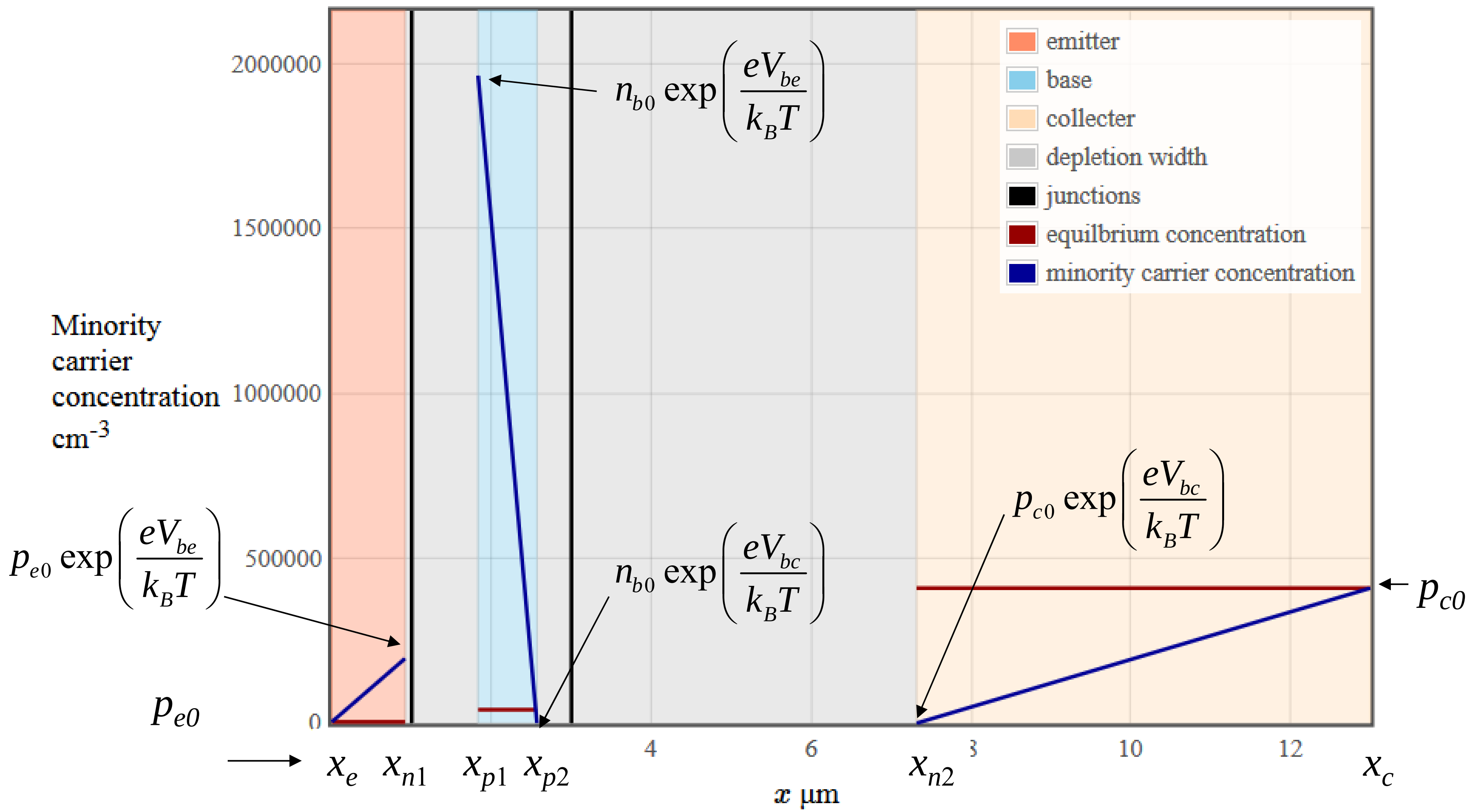
$$I_B = I_E - I_C$$

$$I_{ES} = \left[\frac{eA_{be}D_p p_{e0}}{W_{eb}-x_e}+\frac{eA_{be}D_n n_{b0}}{W_{bc}-W_{be}}\right] \qquad I_{CS} = \left[\frac{eA_{bc}D_p p_{c0}}{x_c-W_c}+\frac{eA_{bc}D_n n_{b0}}{W_{bc}-W_{be}}\right]$$

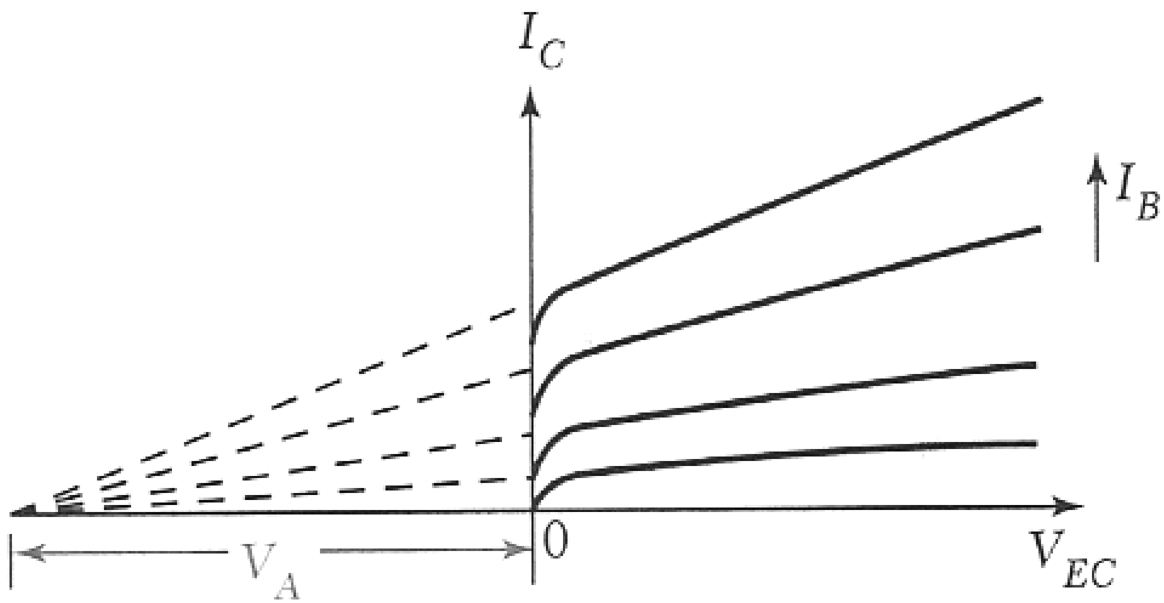
I_{ES} and I_{CS} are treated as constants but the depletion widths W_{bc}, W_{be}, W_c, and W_e depend on the voltages.



Minority carrier concentration



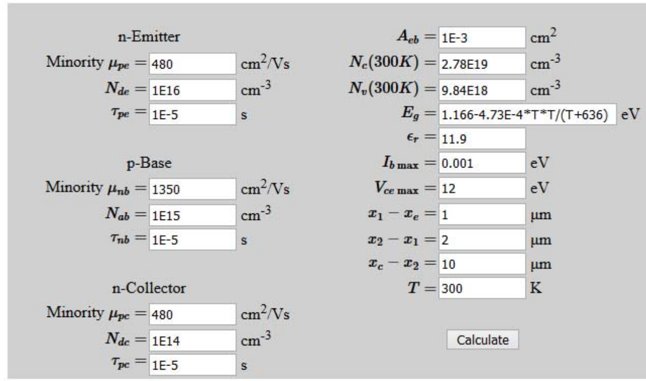
Early effect



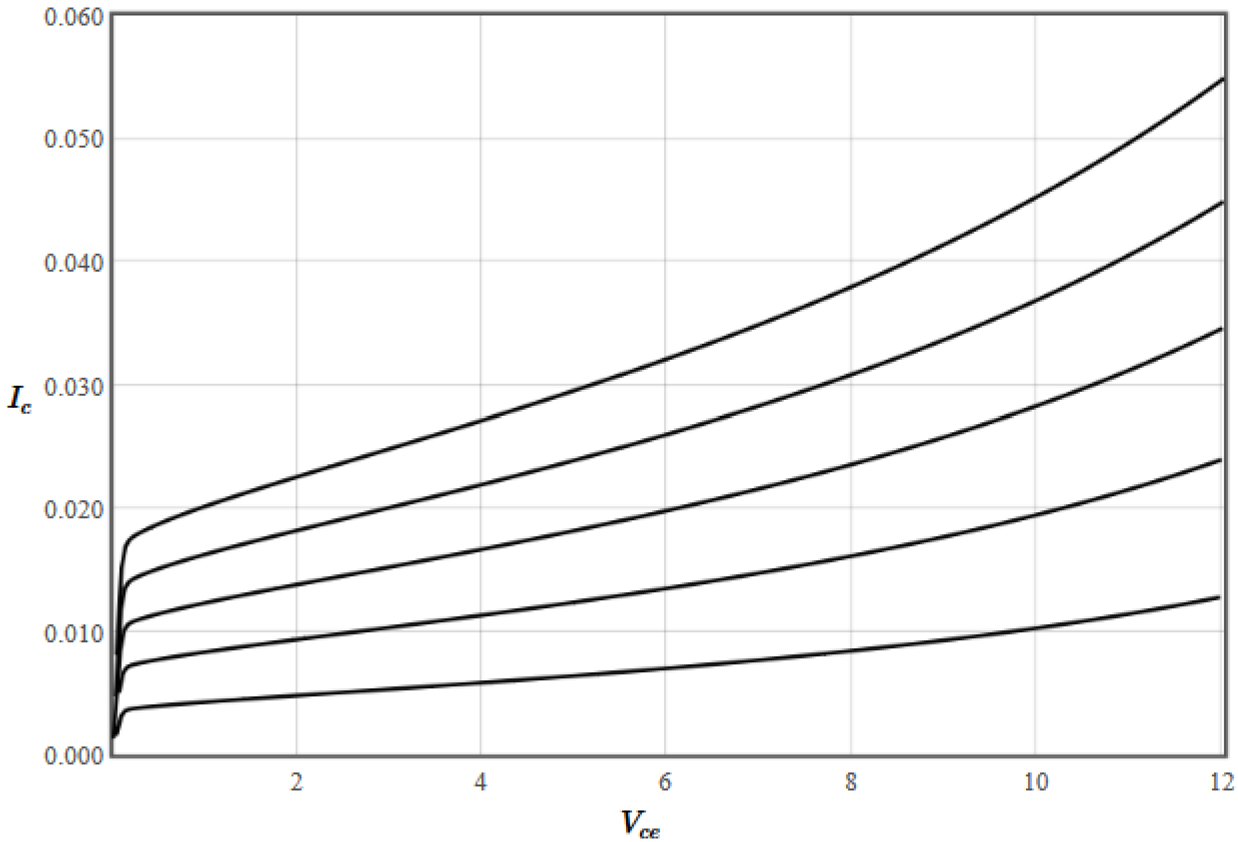
Common emitter configuration
Base width modulation: smaller width increases the diffusion current and increases the gain.

Punchthrough: The neutral base width goes to zero and all gain is lost.
Lightly dope the collector -> voltage drops in collector. Makes circuit slower.

NPN common emitter configuration

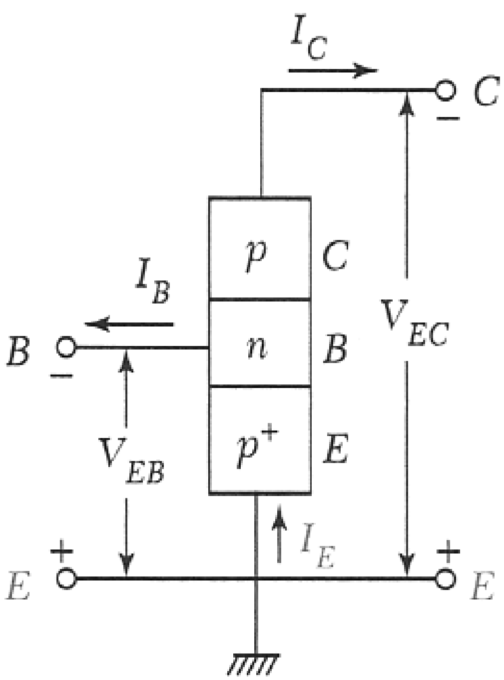


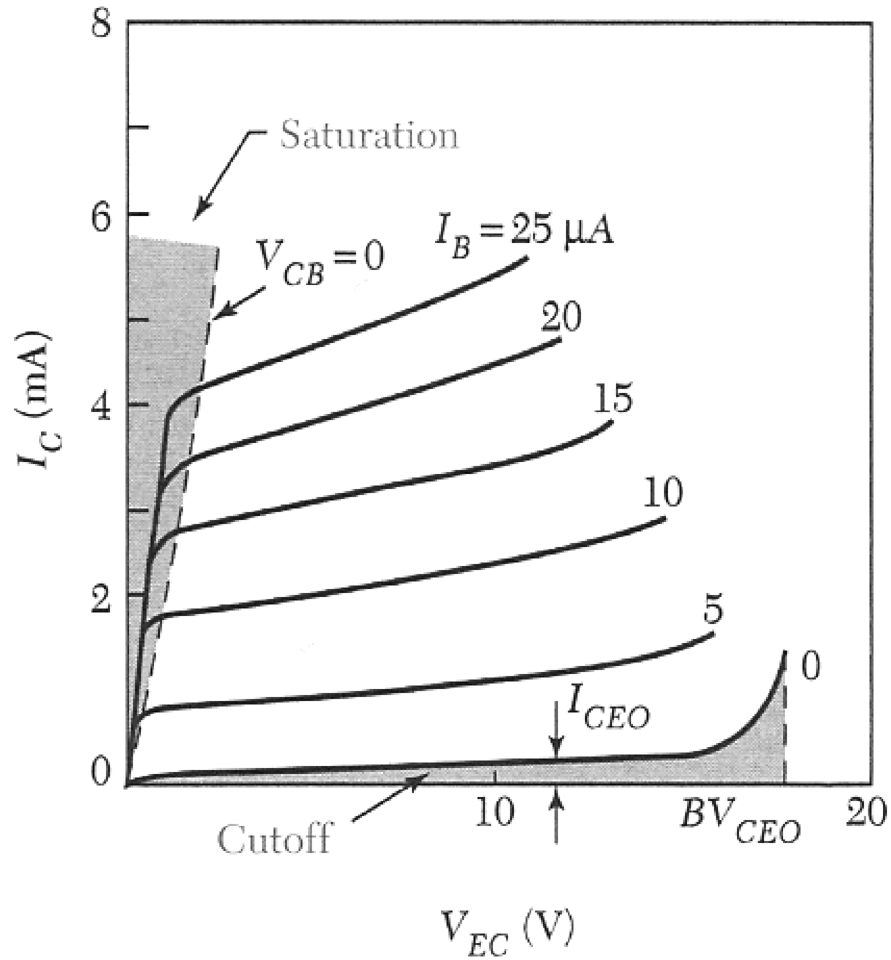
$$I_C \sim \beta I_B$$



http://lampx.tugraz.at/~hadley/psd/L13/common_e_early.php

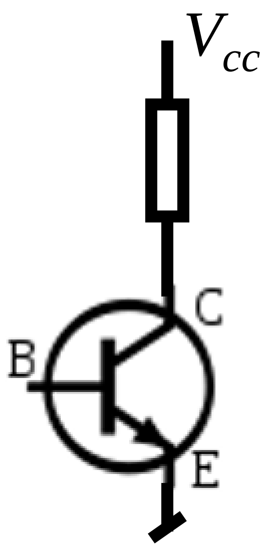
Common emitter configuration

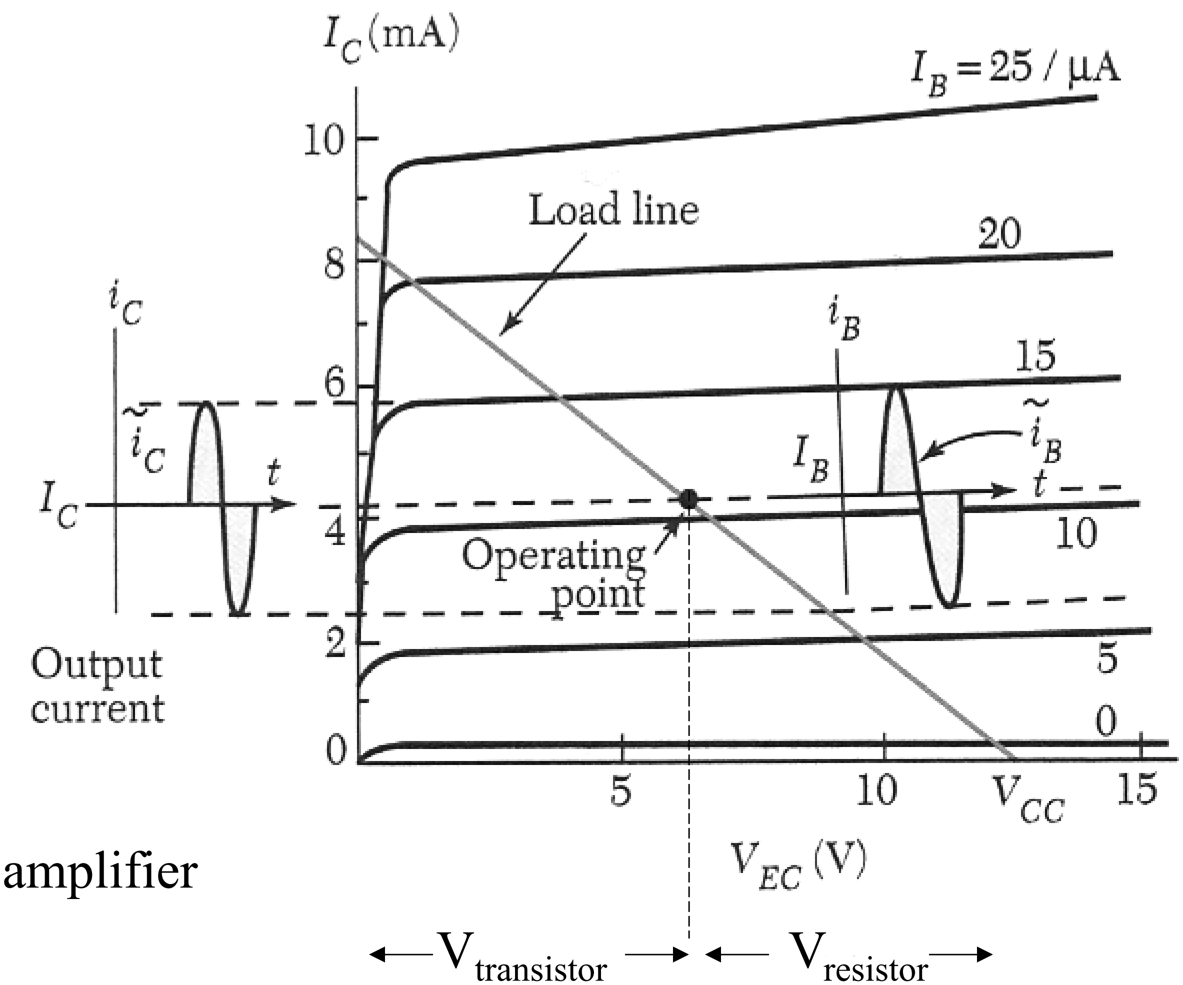




$I_C \sim \beta I_B$ amplifier

Small signal response

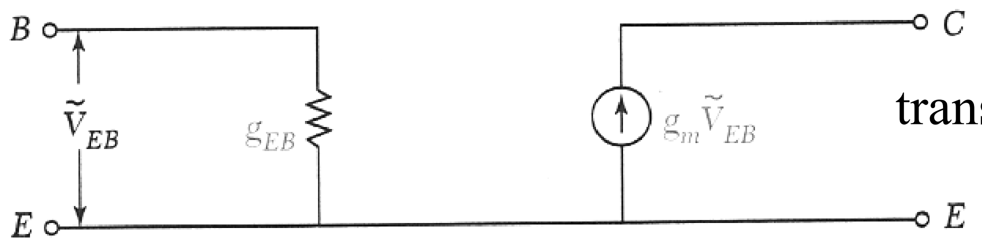




Low input impedance amplifier

Small signal response

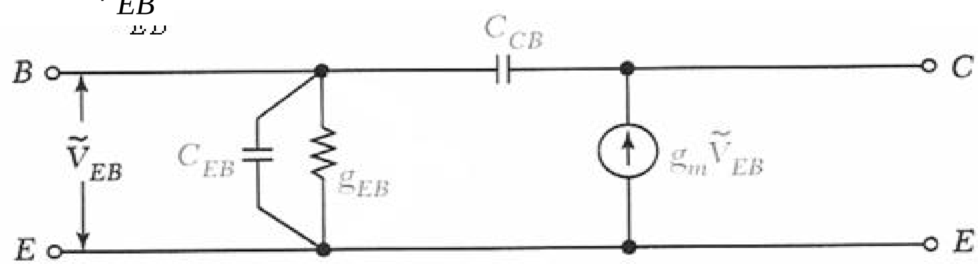
$$\tilde{i}_c = \beta \tilde{i}_B = \beta g_{EB} \tilde{v}_{EB}$$

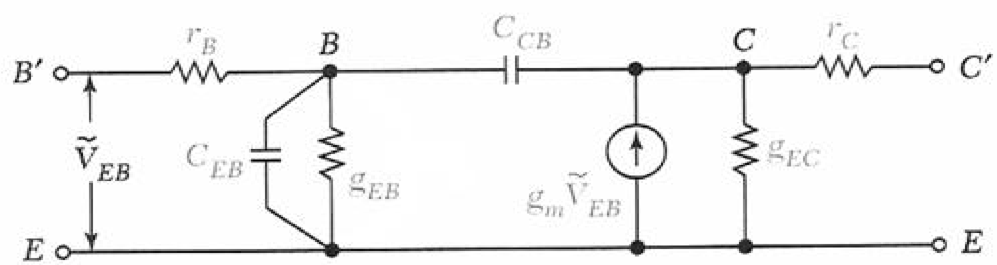


transistor man

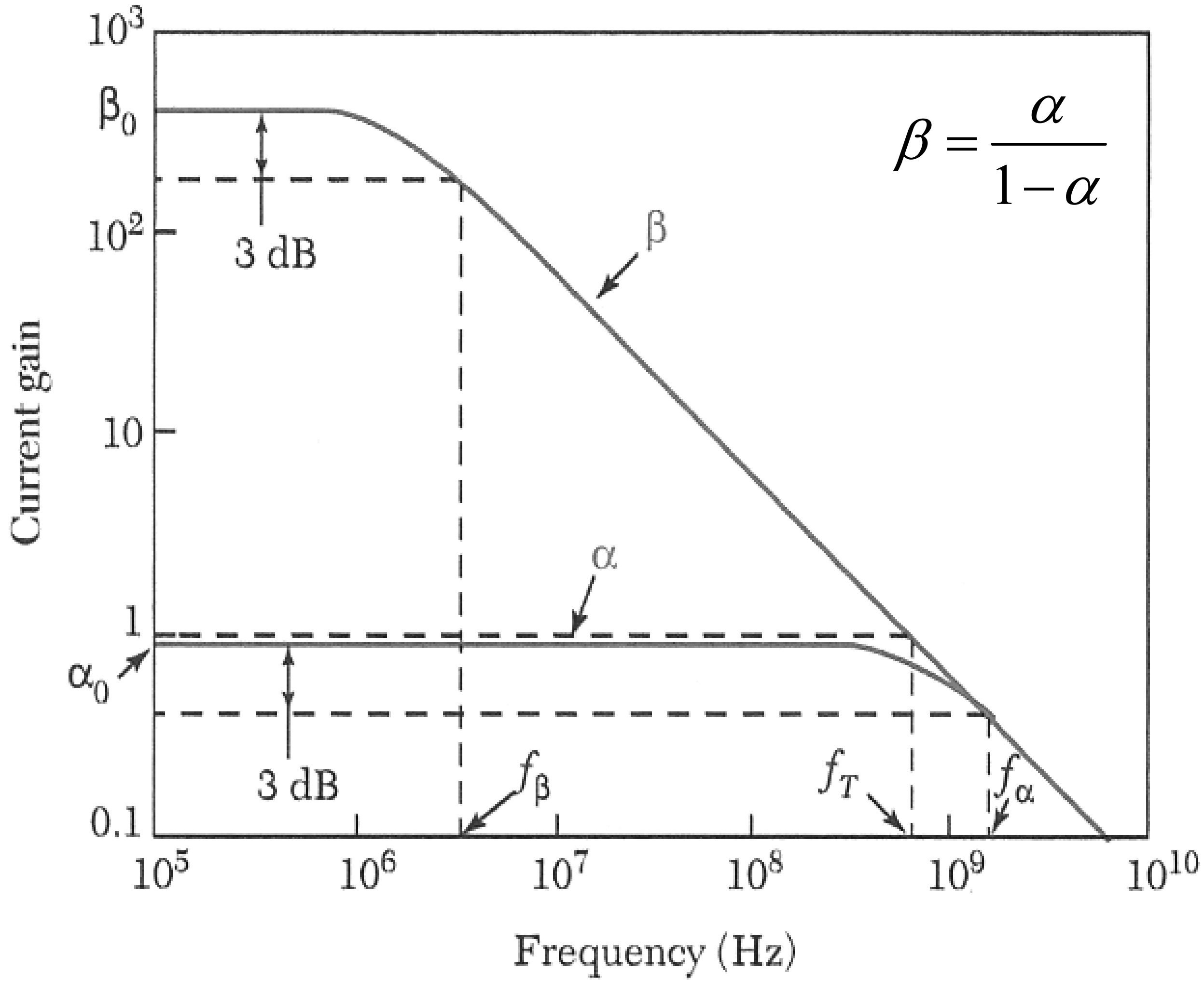
input conductance: $g_{EB} = \dfrac{\tilde{i}_B}{\tilde{v}_{EB}}$

transconductance: $g_m = \dfrac{\tilde{i}_c}{\tilde{v}_{EB}}$





Small signal response



$$f_\beta = (1-\alpha_0)\, f_\alpha \qquad f_T = \alpha_0 f_\alpha$$

Heterojunction bipolar transistors