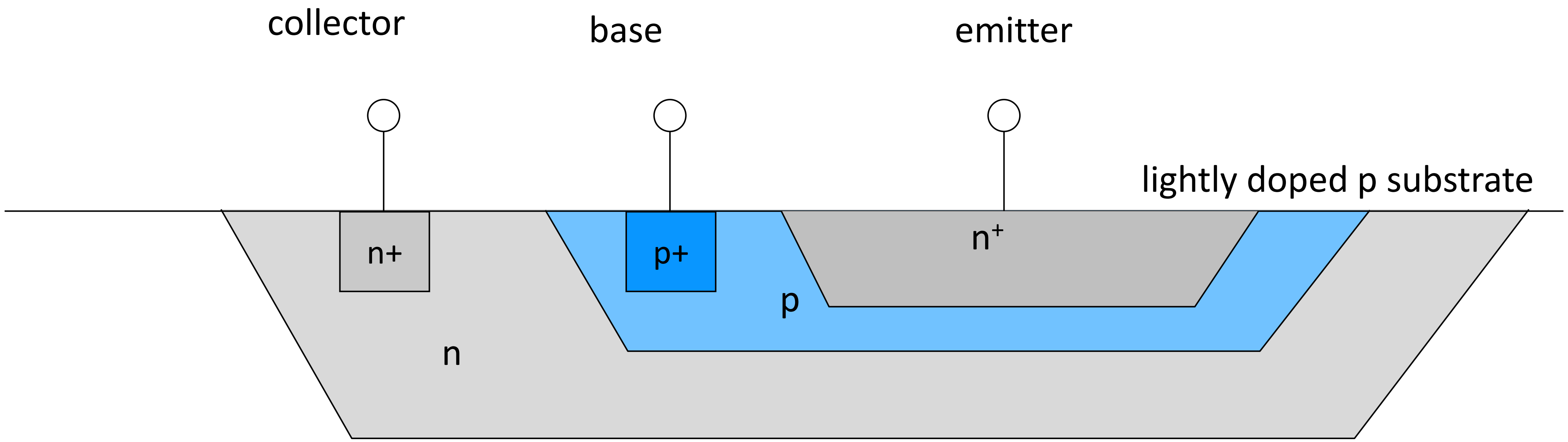
11

Bipolar junction transistors (BJT)

January 2026

bipolar transistors

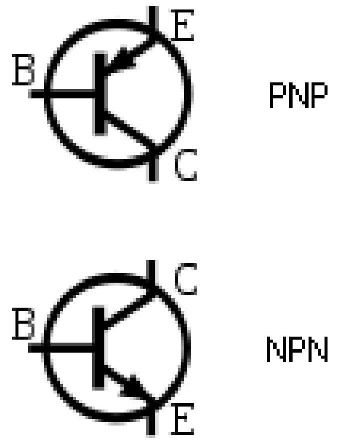
npn transistor

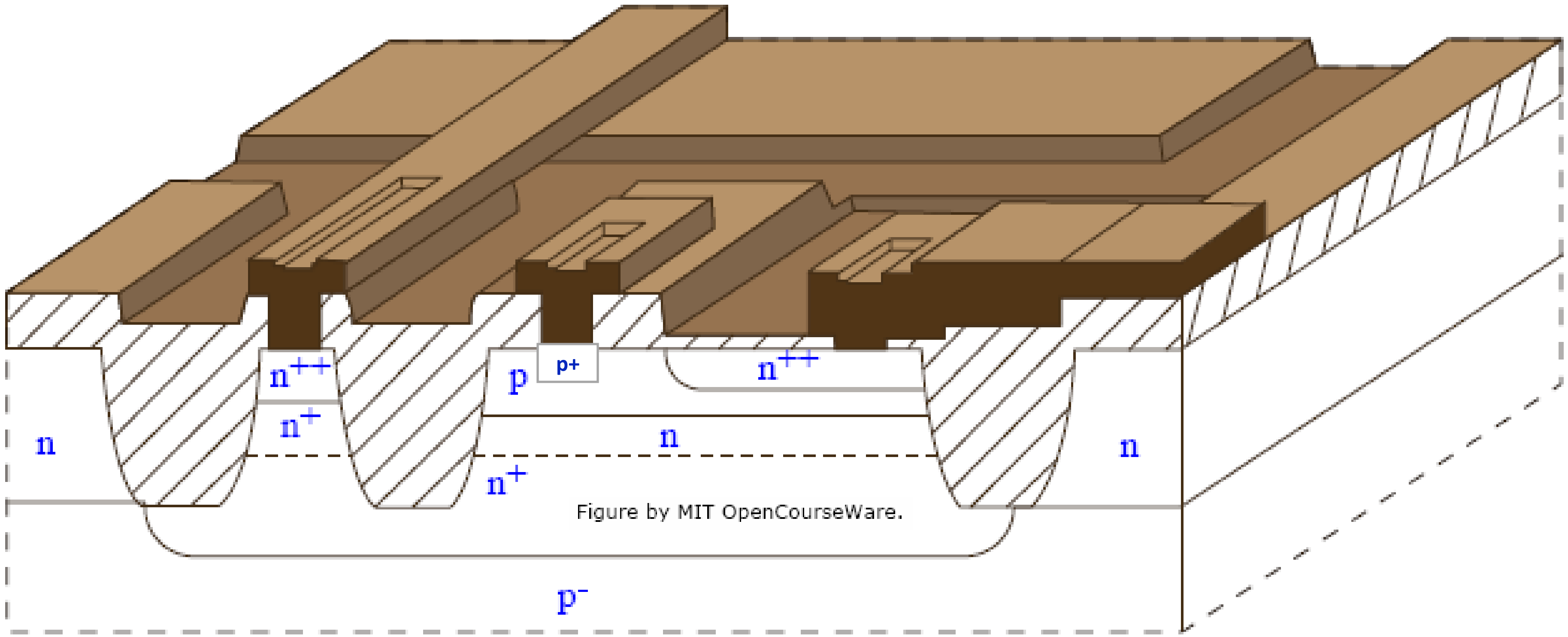


Used in

- front-end high-frequency receivers (mobile telephones)
- low input impedance amplifiers
- power devices

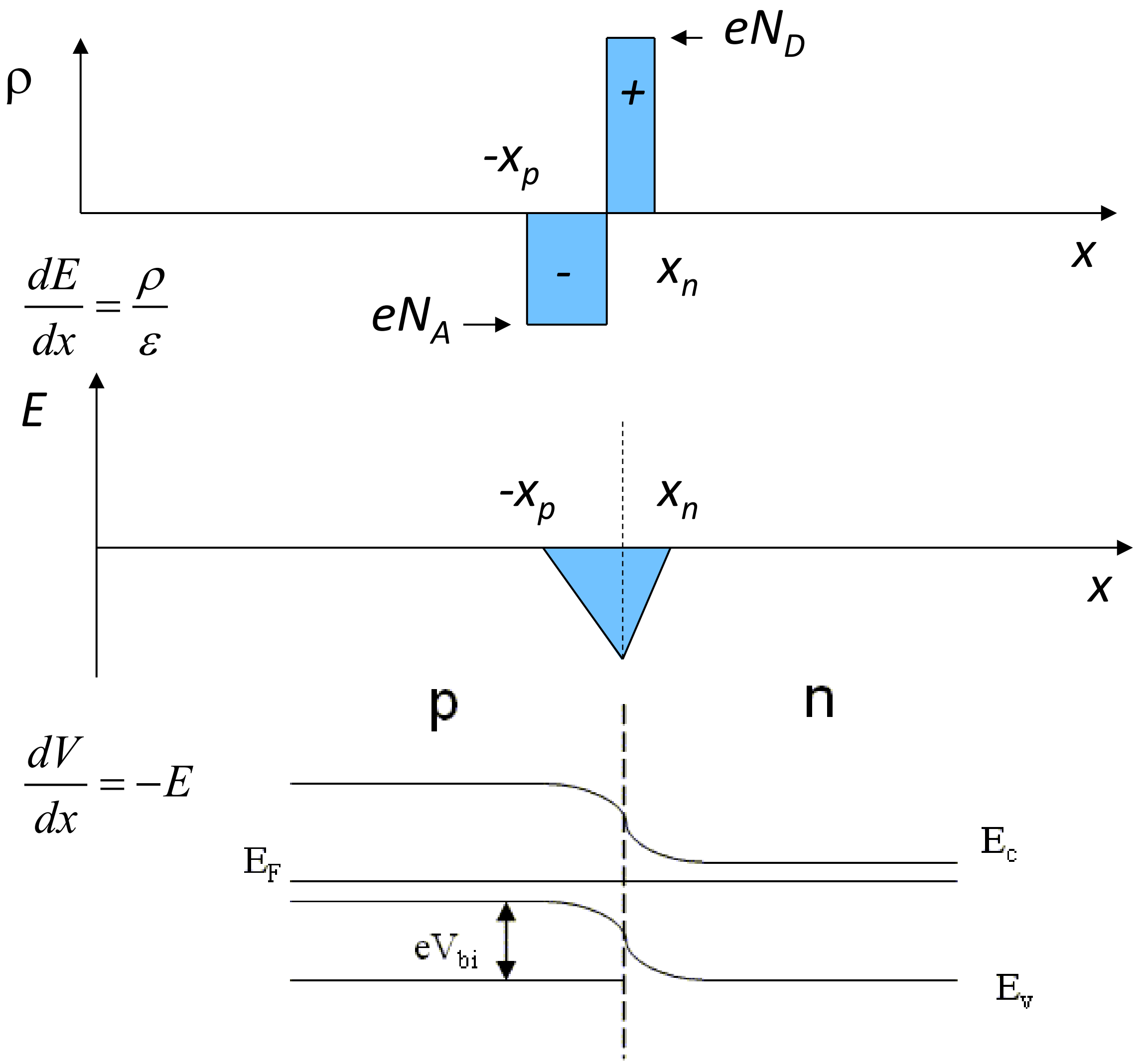
bipolar transistors





Oxide isolated integrated BJT - a modern process

abrupt junction



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

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

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

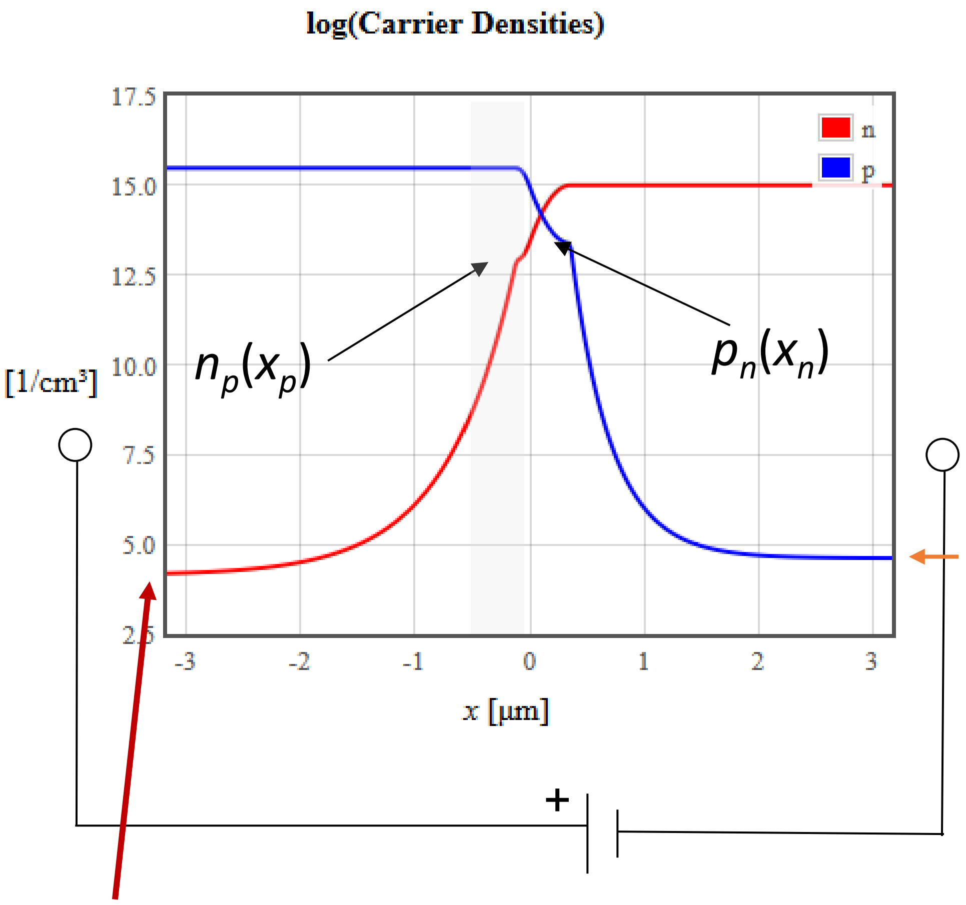
$$E = -\frac{eN_A}{\varepsilon}(x + x_p) \qquad -x_p > x > 0$$

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

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

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

forward bias V > 0



$$p_{n0} = \frac{n_i^2}{N_D}$$

$$n_{p0} = \frac{n_i^2}{N_A}$$

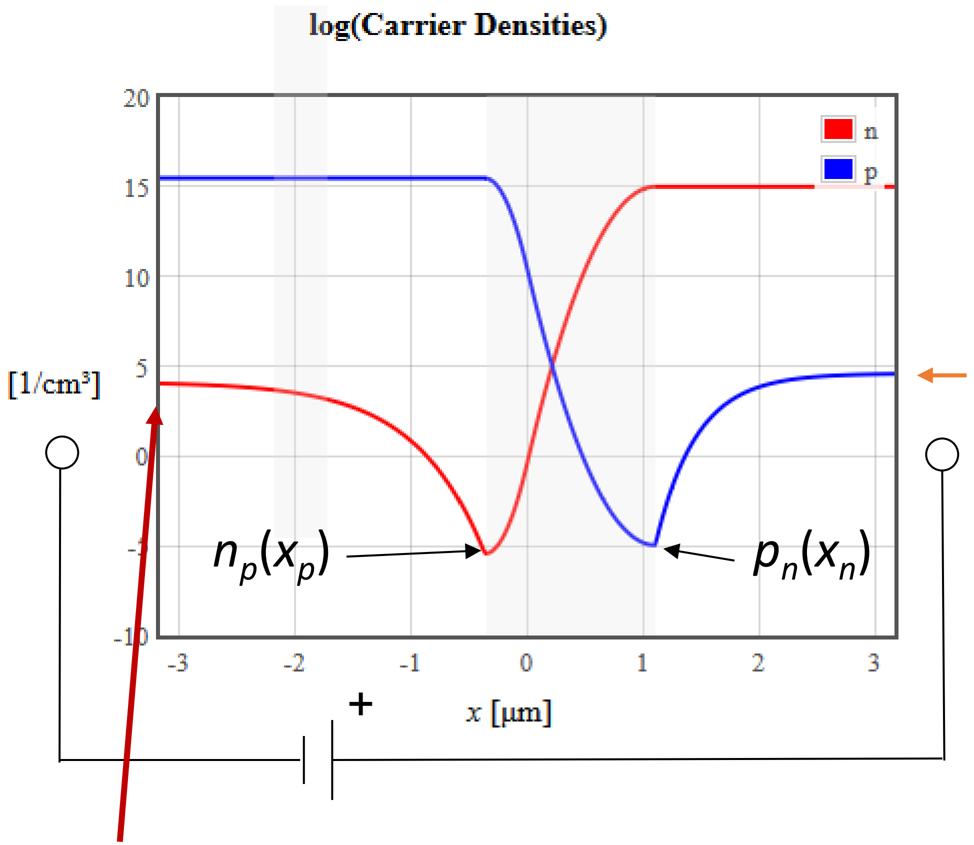
- electrons and holes are driven towards the junction
- depletion region becomes narrower

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

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

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

reverse bias, V < 0



$$p_{n0} = \frac{n_i^2}{N_D}$$

$$n_{p0} = \frac{n_i^2}{N_A}$$

- electrons and holes are driven away from the junction
- 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

long / short diodes

$N_A =$ 1E15 1/cm³ $N_D =$ 1E15 1/cm³ $E_g =$ 1.166-4.73E-4*T*T/(T+636) eV $d_p =$ -2 µm

$N_v(300) =$ 9.84E18 1/cm³ $N_c(300) =$ 2.78E19 1/cm³ $\epsilon_r =$ 12 $T =$ 300 K $d_n =$ 2 µm

$\mu_p =$ 480 cm²/V s $\mu_n =$ 1350 cm²/V s $\tau_p =$ 1E-7 s $\tau_n =$ 1E-7 s

$V =$ 0.2 V

Submit

V

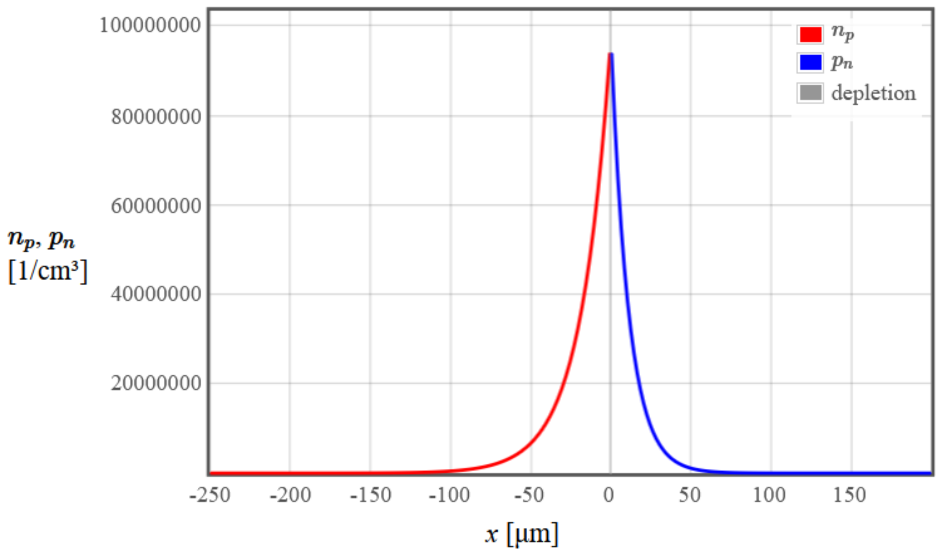
$E_g = 1.12$ eV $W = |x_n| + |x_p| = 1.05$ µm $x_p =$ -0.527 µm $x_n = 0.527$ µm $V_{bi} = 0.618$ V $n_i = 6.41\text{e+}9$ cm^{-3}

$D_p = 12.4$ cm²/s $D_n = 34.9$ cm²/s $L_p = 11.1$ µm $L_n = 18.7$ µm $n_{p0} = 4.10\text{e+}4$ cm^{-3} $p_{n0} = 4.10\text{e+}4$ cm^{-3}

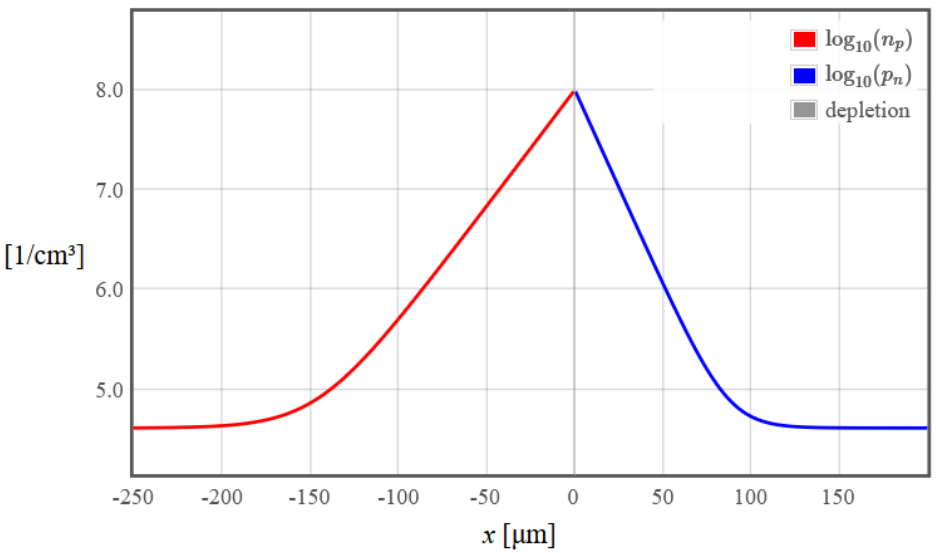
$A_n =$ -5.35e+8 cm^{-3} $B_n = 6.62\text{e+}8$ cm^{-3} $A_p = 4.24\text{e+}8$ cm^{-3} $B_p =$ -2.96e+8 cm^{-3}

$j_n = 0.00000357$ A cm^{-2} $j_p = 0.00000128$ A cm^{-2} $j_{\text{diff}} = 0.00000485$ A cm^{-2}

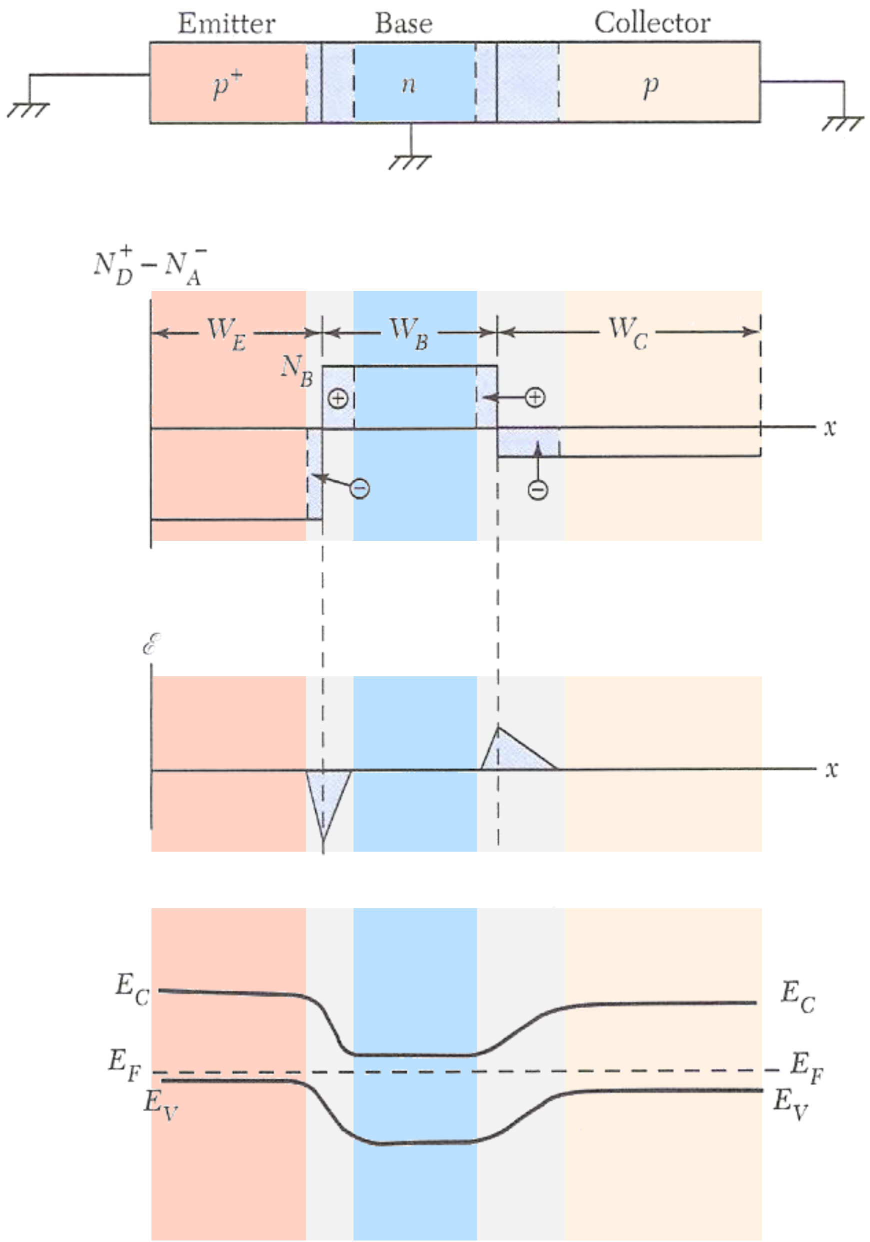
Minority Carrier Densities



log$_{10}$(Minority Carrier Densities)



pnp transistor, no bias



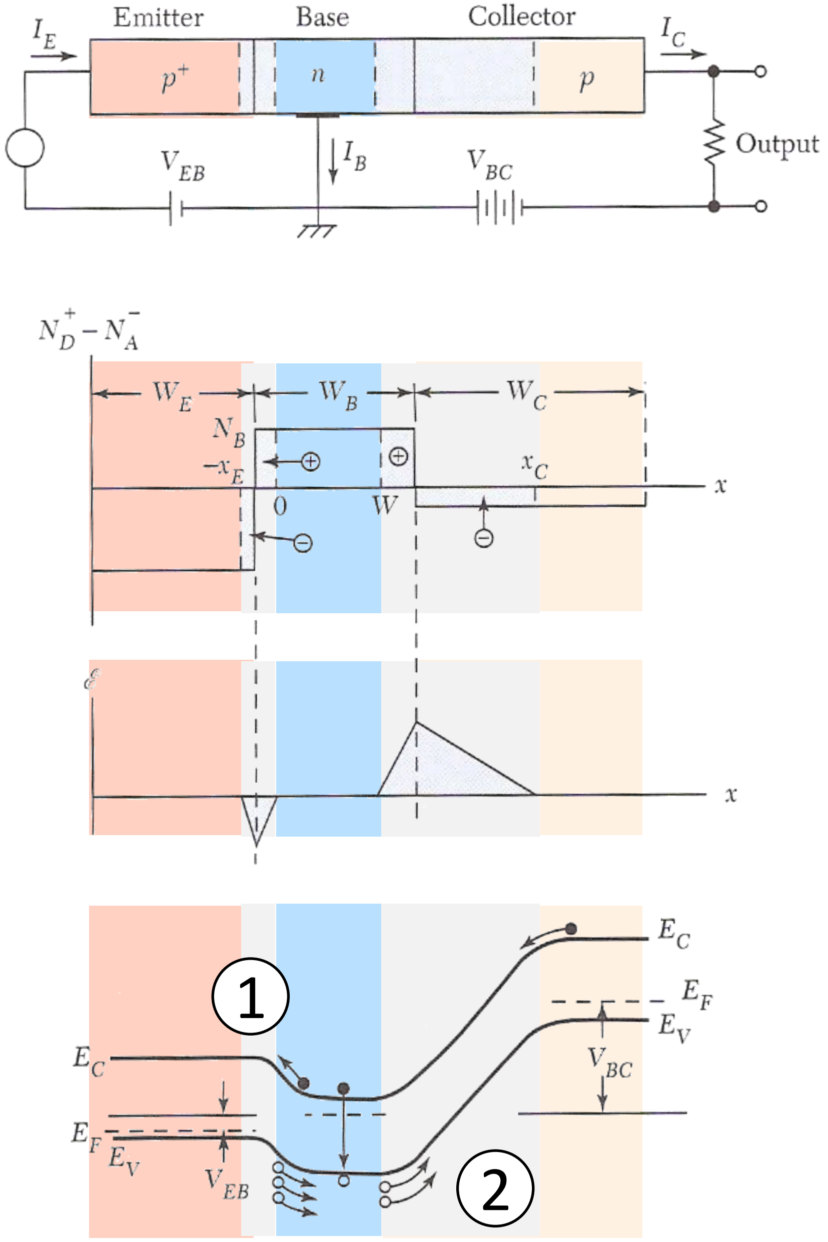
pnp transistor, forward active bias

1 **base-emitter voltage**:

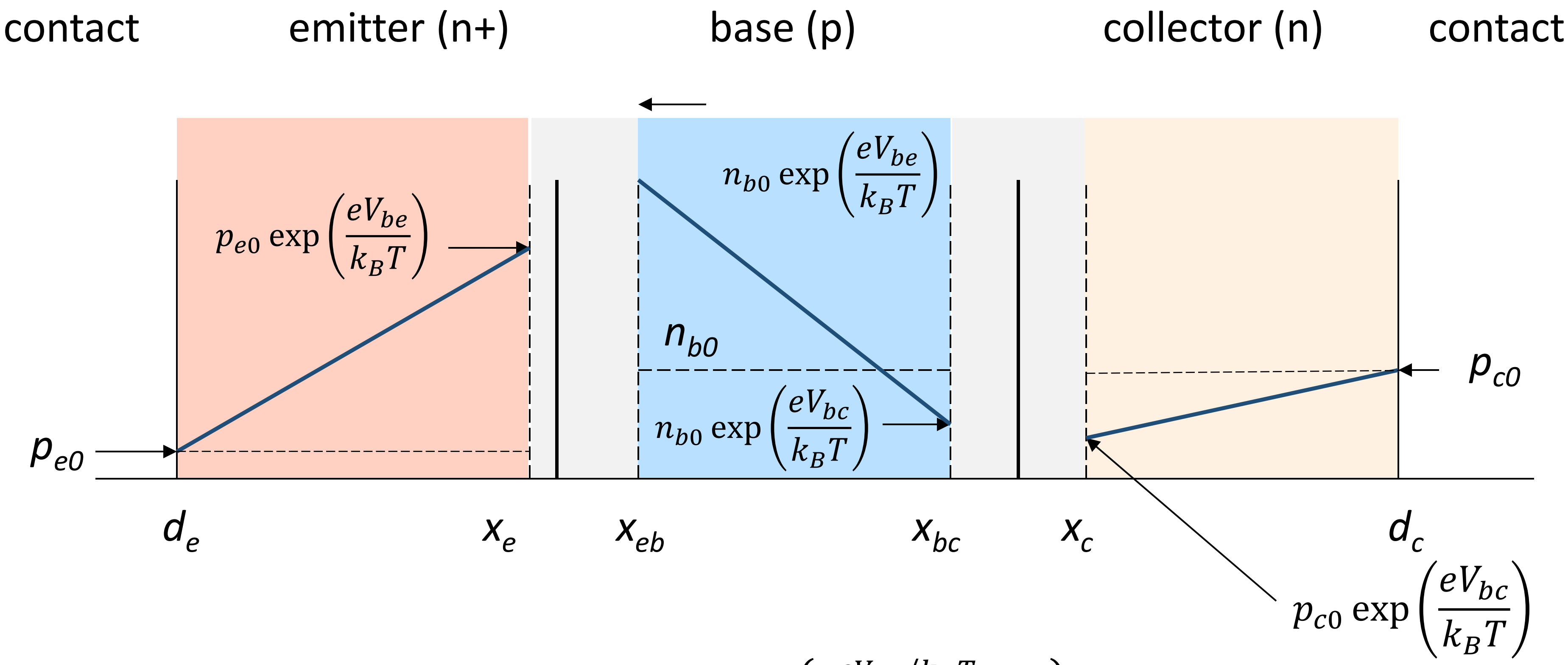
controls the minority carriers injected from the emitter to the base

2 minority carriers
diffuse to the base-collector junction
and are swept into the collector

always dissipate power due to the forward bias



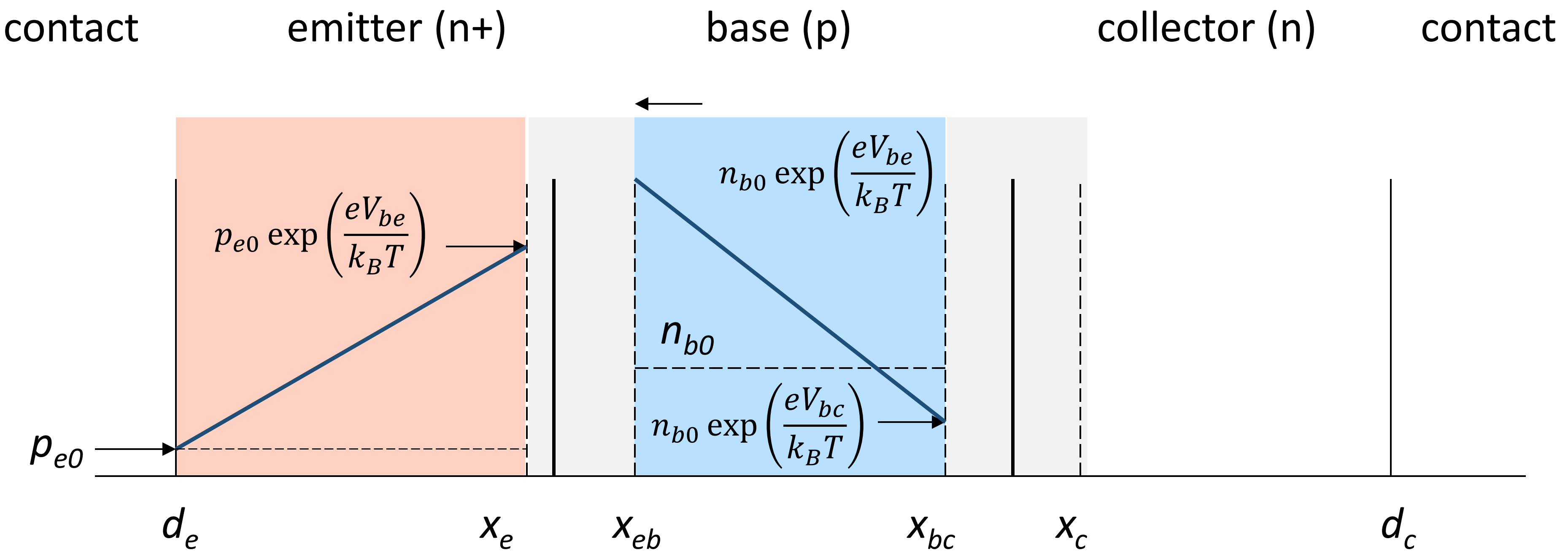
minority carrier concentration



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

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

emitter current



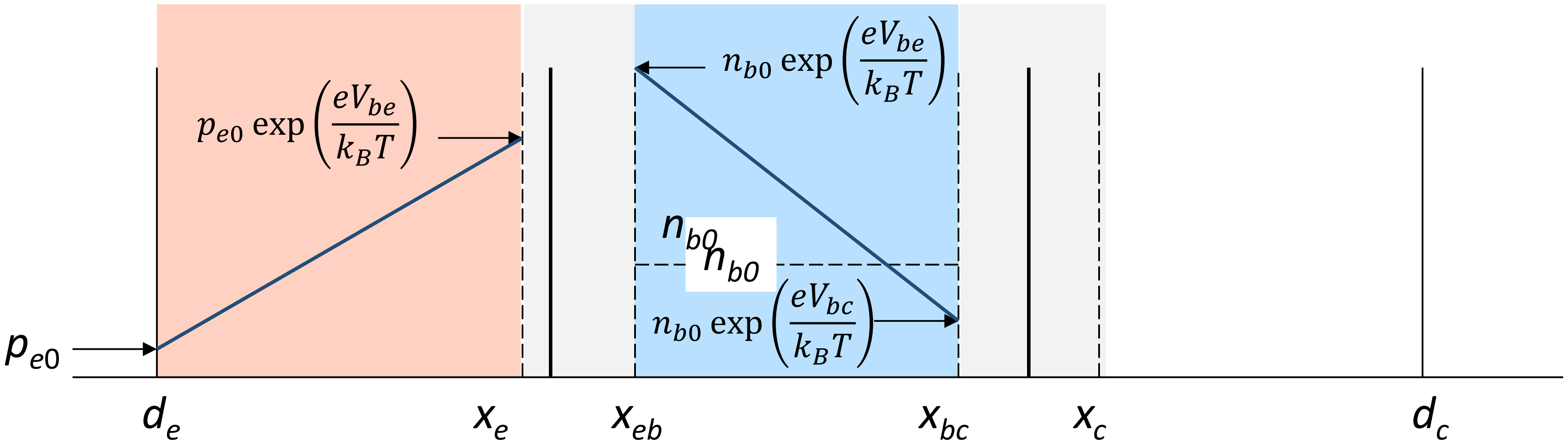
$$I_{Ep} = -eA_{be}D_p \frac{p_{e0}\left(e^{eV_{be}/k_BT} - 1\right)}{x_e - d_e}$$

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

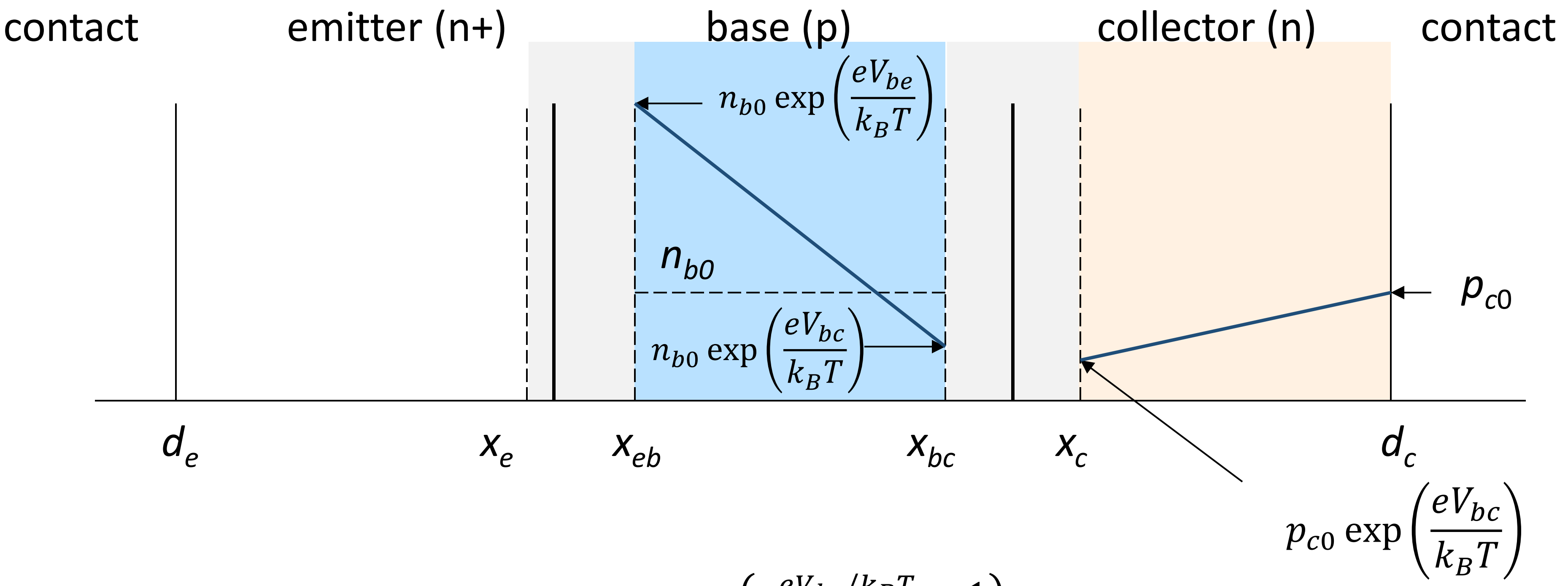
Emitter current

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

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



collector current



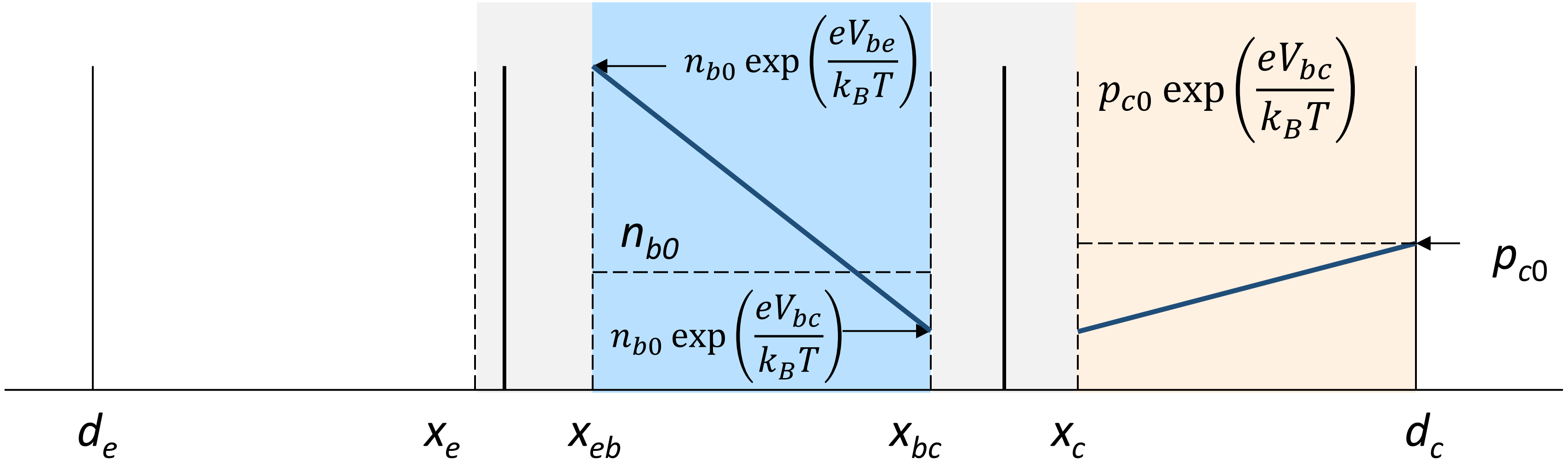
$$I_{Cp} = -eA_{bc}D_p \frac{p_{c0}\left(e^{eV_{bc}/k_B T} - 1\right)}{d_c - x_c}$$

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

Collector current

$$I_C = I_{Cp} + I_{Cn} = \frac{eA_{bc}D_n n_{b0}}{x_{bc} - x_{be}}\left(e^{eV_{be}/k_BT} - 1\right) - \left[\frac{eA_{bc}D_p p_{c0}}{d_c - x_c} + \frac{eA_{bc}D_n n_{b0}}{x_{bc} - x_{be}}\right]\left(e^{eV_{bc}/k_BT} - 1\right)$$

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

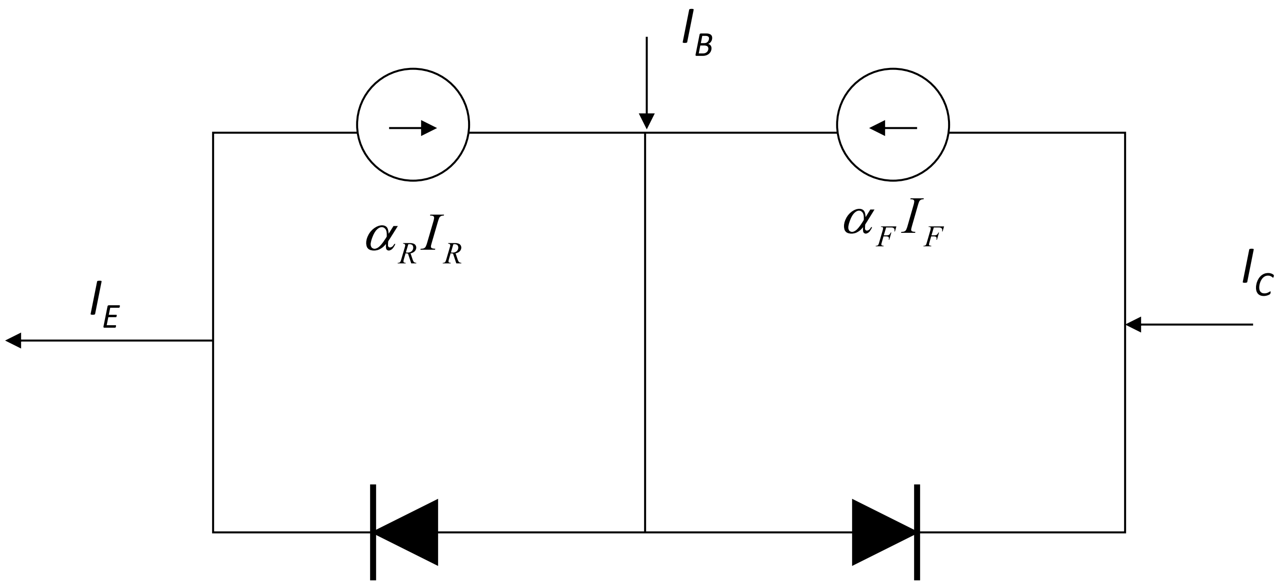


Ebers-Moll model

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

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

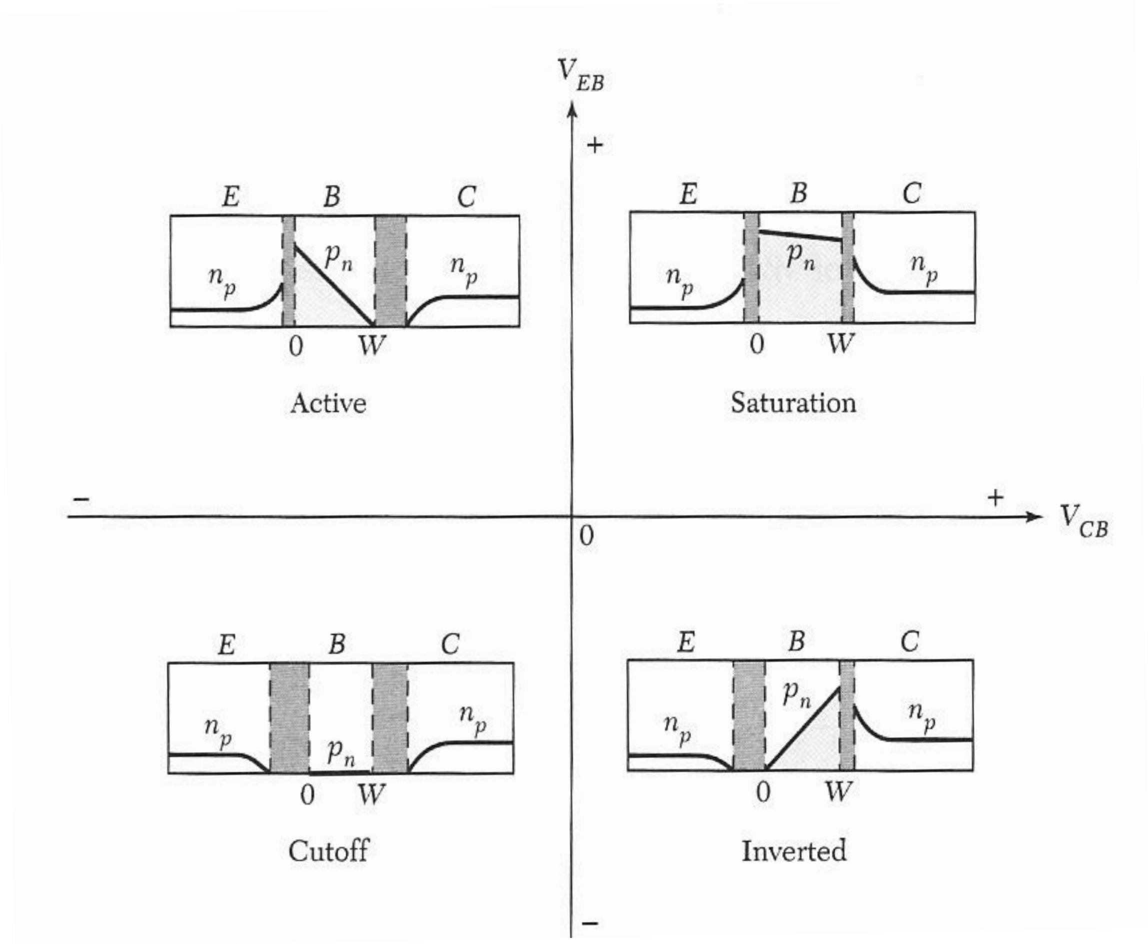
$$I_B = I_E - I_C$$



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

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**

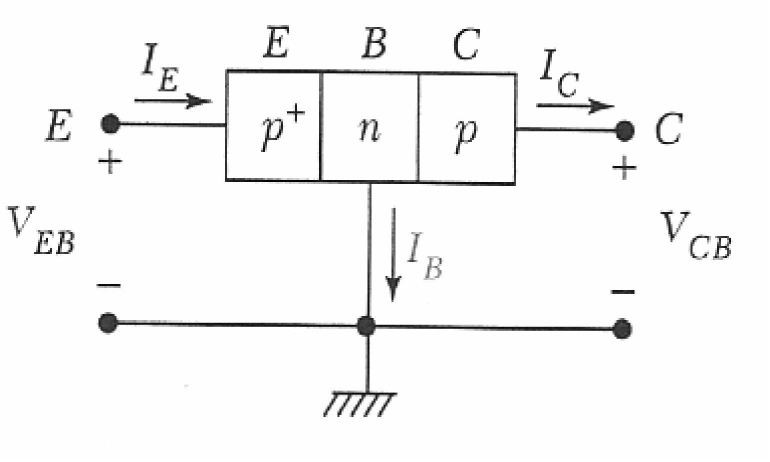
4. **cut-off**:
emitter-base **reverse**,
base-collector **reverse**

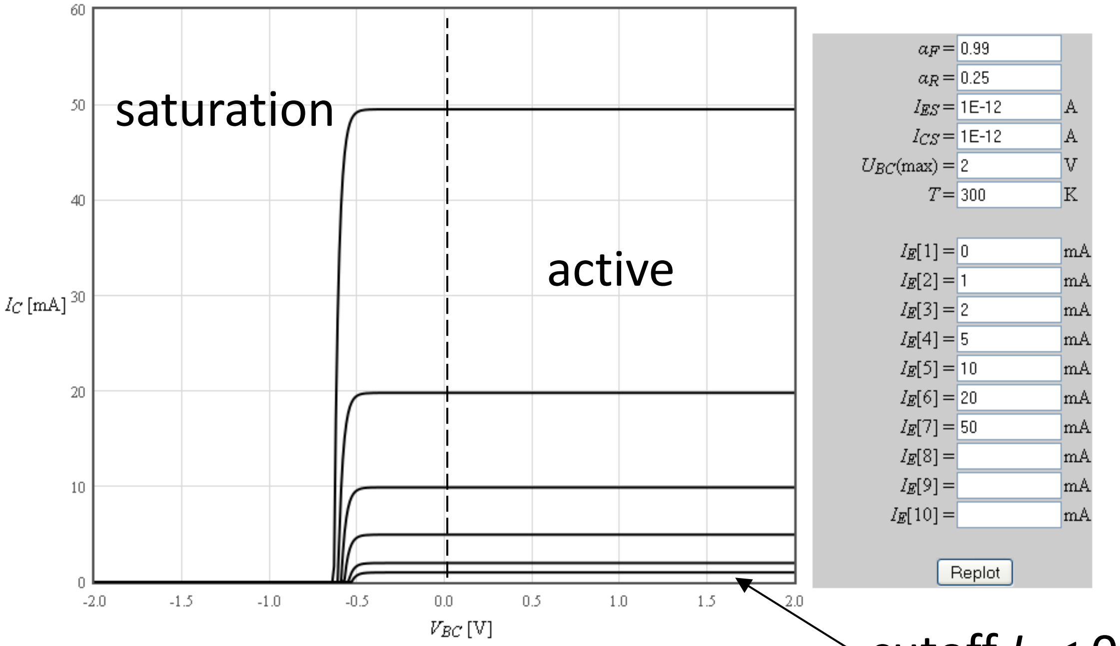
common base configuration

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

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

solve for V_{be}





cutoff $I_E < 0$

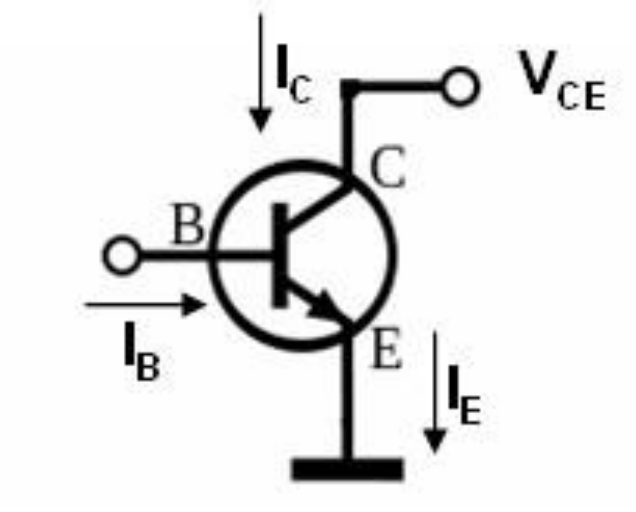
http://lampz.tugraz.at/~hadley/psd/L13/commonbase/pnp_current.html

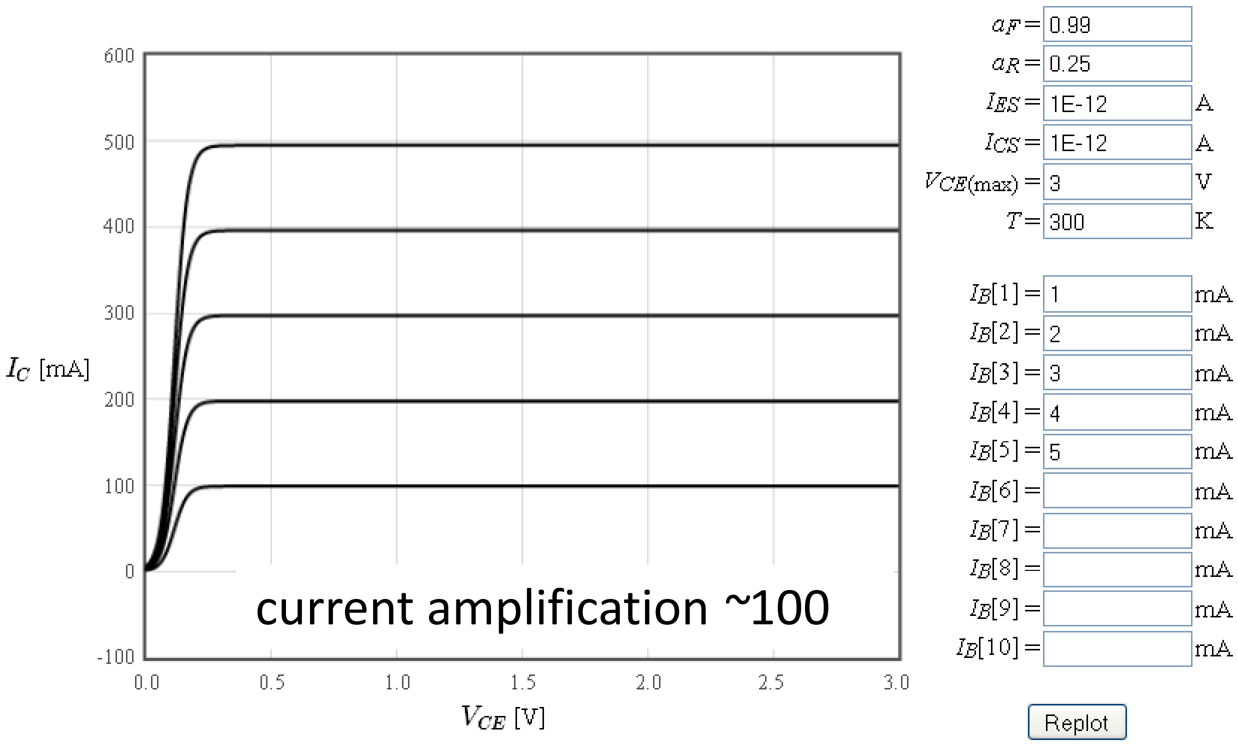
common emitter configuration

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

$$I_B = I_E - I_C$$

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





http://lampz.tugraz.at/~hadley/psd/L13/commonemitter.php

Emitter efficiency

for npn

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

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

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

For $\gamma_e \sim 1$, $x_{bc} - x_{be} \ll L_b, x_{eb} - d_e$ and $n_{b0} \gg p_{e0}$

neutral base width

$$\frac{n_i^2}{N_{Ab}}$$

$$\frac{n_i^2}{N_{De}}$$

Small base width and heavy emitter doping

Zegbroek gets a simpler formula by setting $V_{bc} = 0$ so that the exponential terms are the same.

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

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

α ~ 1 for a good BJT

current amplification factor

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

$$I_B = I_E - I_C$$

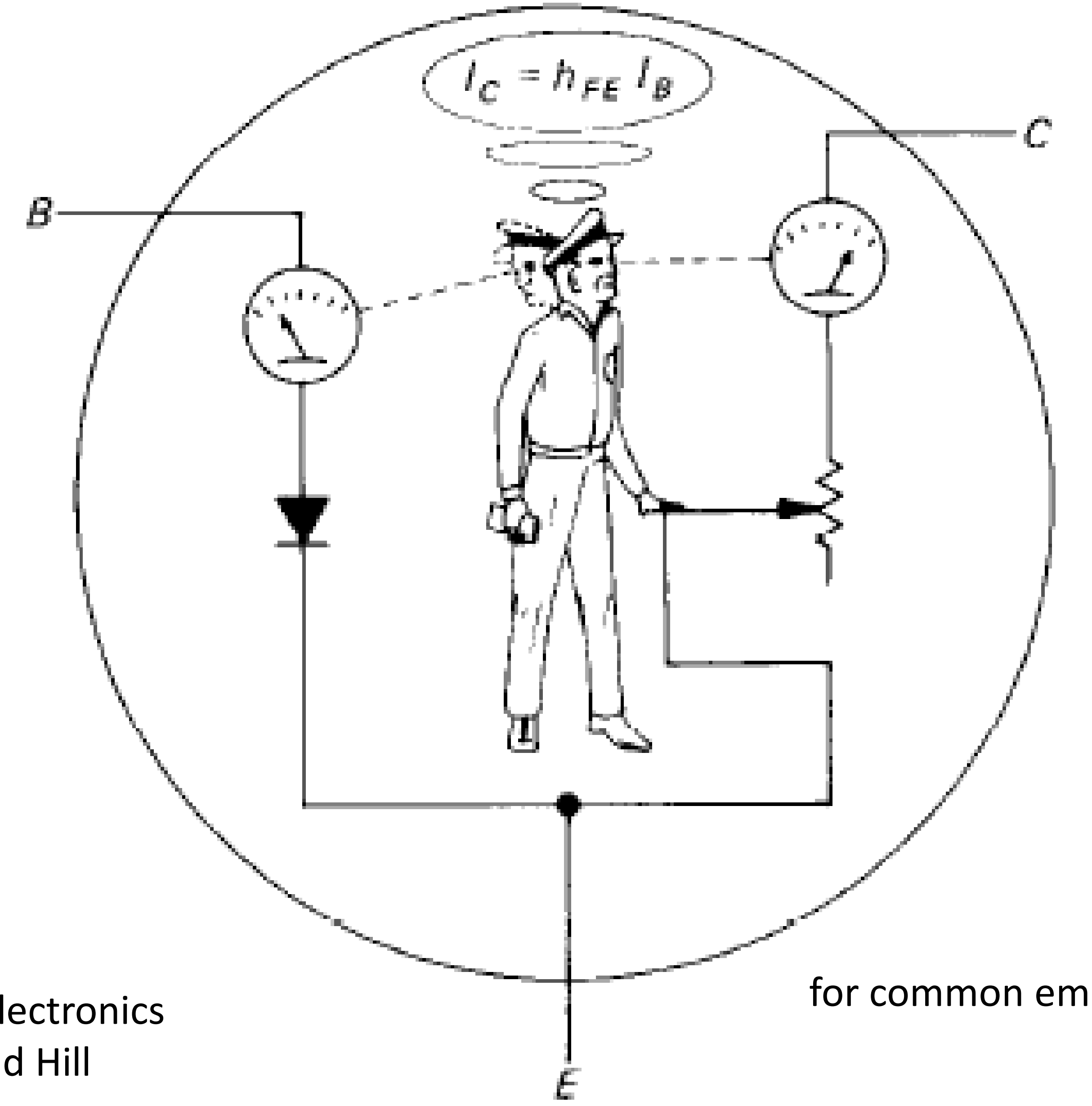
$$I_C = \alpha I_E$$

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

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

β ~ 50 - 500

no causality: $I_B \rightarrow I_C$



"Transistor man"

The Art of Electronics
Horowitz and Hill

for common emitter configuration

Transconductance

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

operated in forward active mode

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

first term depends on V_{be}

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

The transconductance can be very high.

Early effect

Ebers - Moll:

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

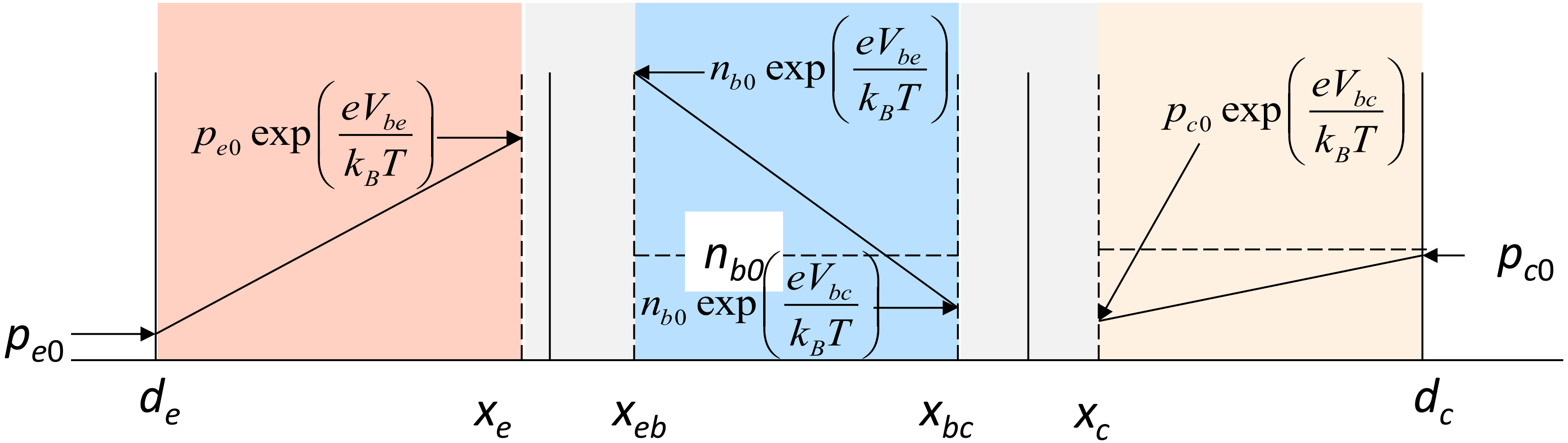
$$I_C = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$

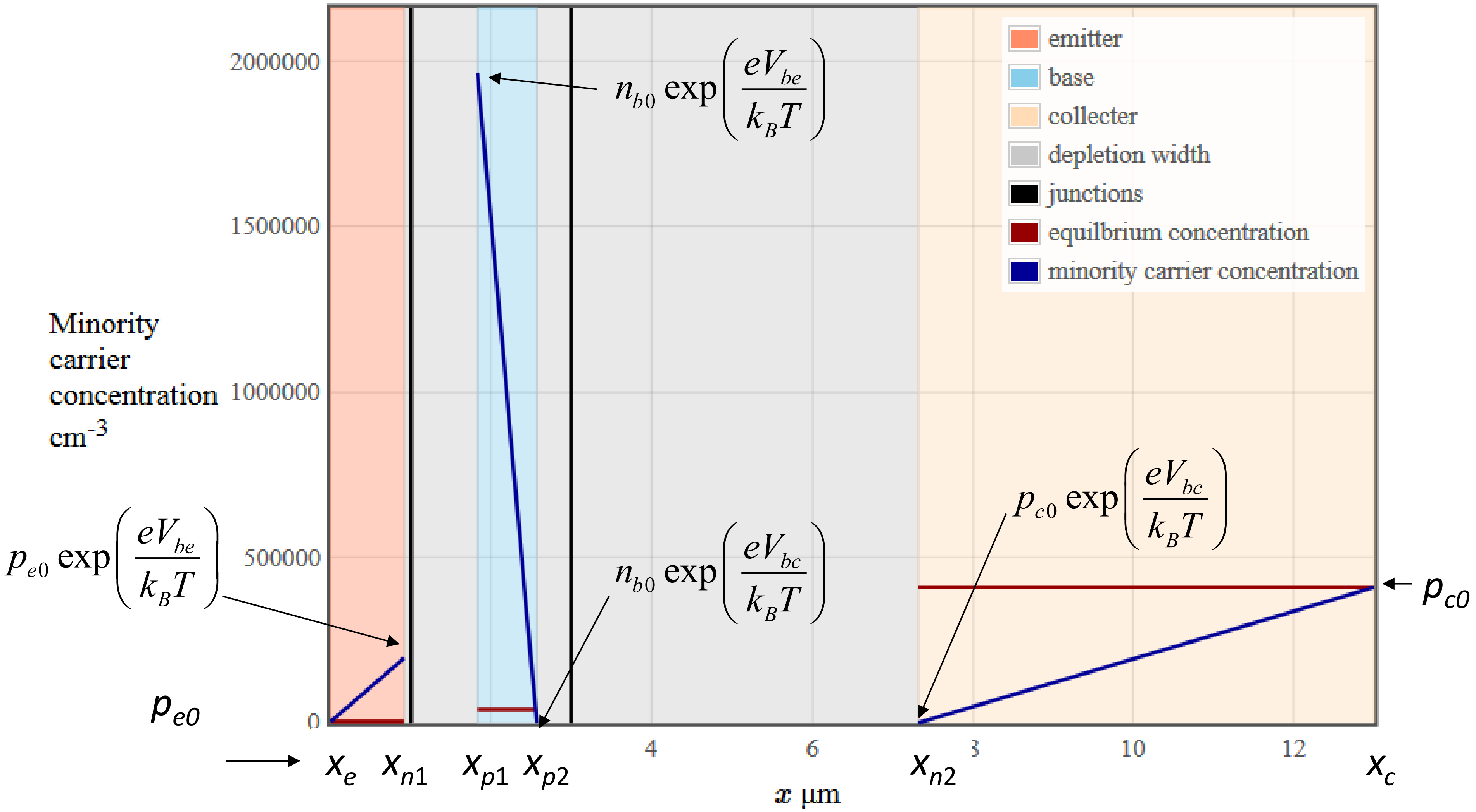
$$I_{ES} = \left[\frac{eA_{be}D_p p_{e0}}{x_{eb} - d_e} + \frac{eA_{be}D_n n_{b0}}{x_{bc} - d_{be}}\right]$$

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

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.

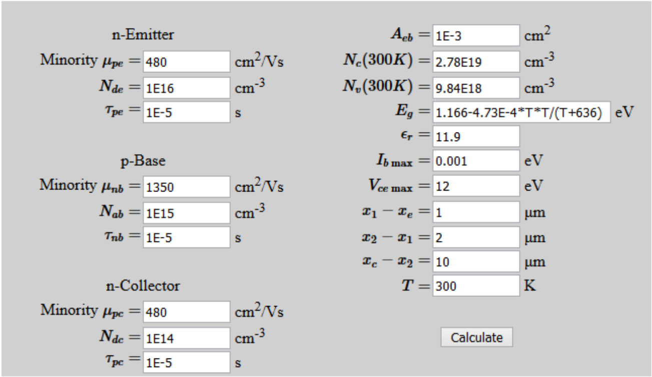


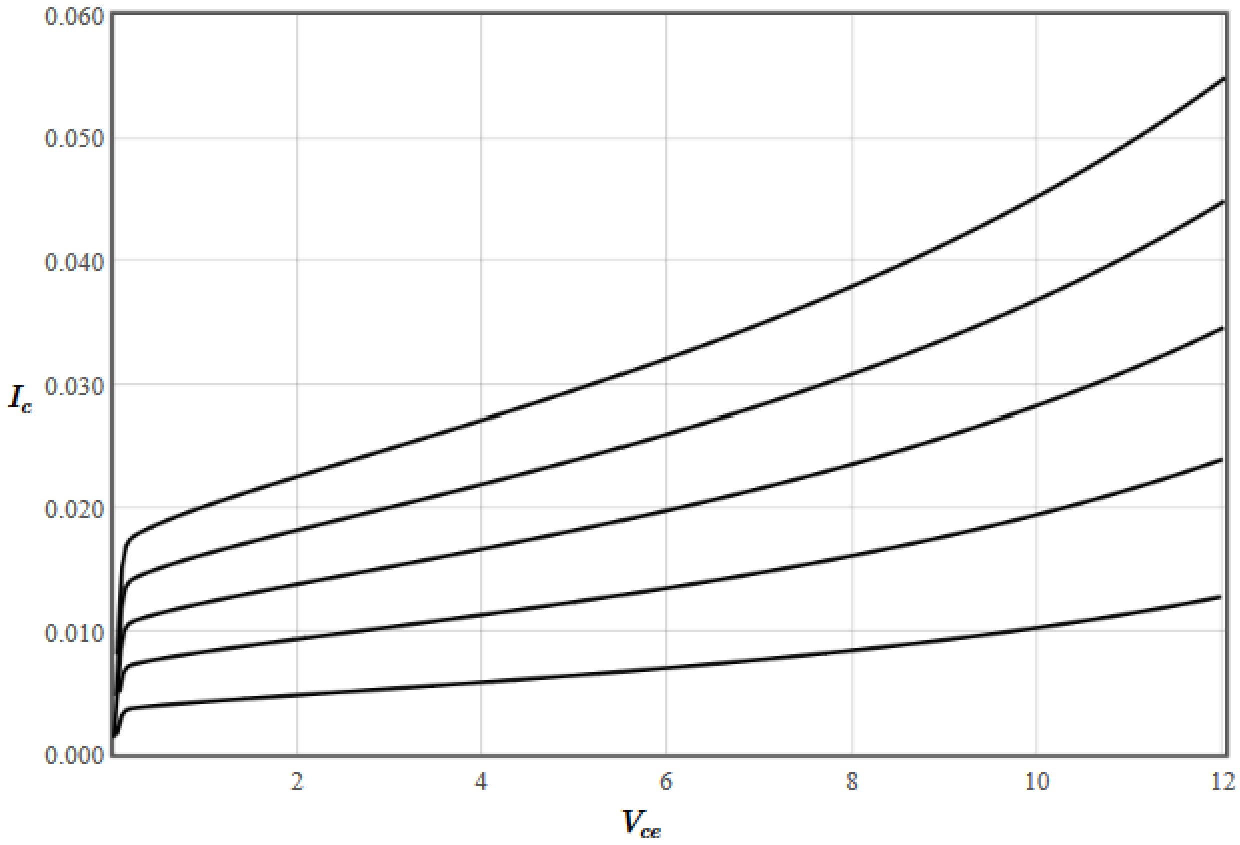
minority carrier concentration



NPN common emitter configuration

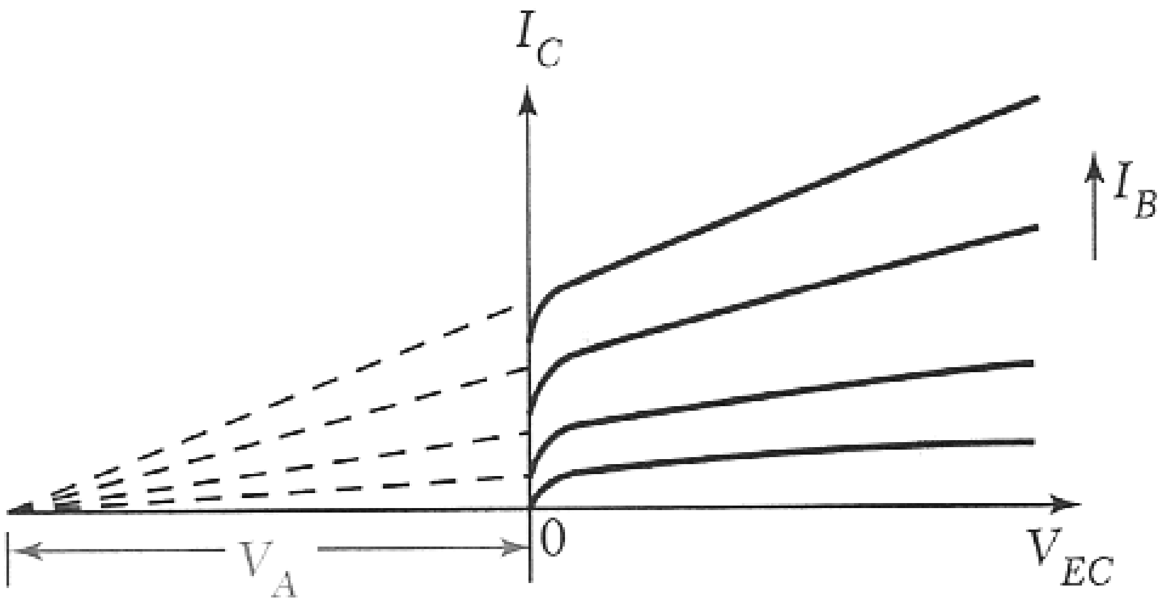
http://lampz.tugraz.at/~hadley/psd/L13/common_e_early.php





$I_C \sim \beta I_B$

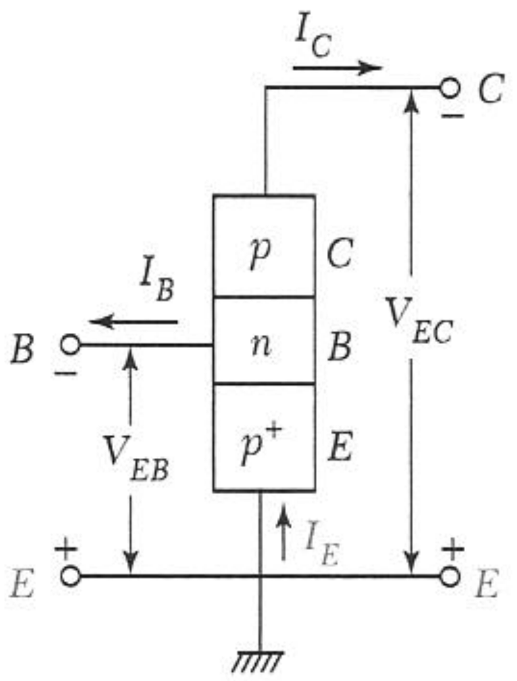
Early effect

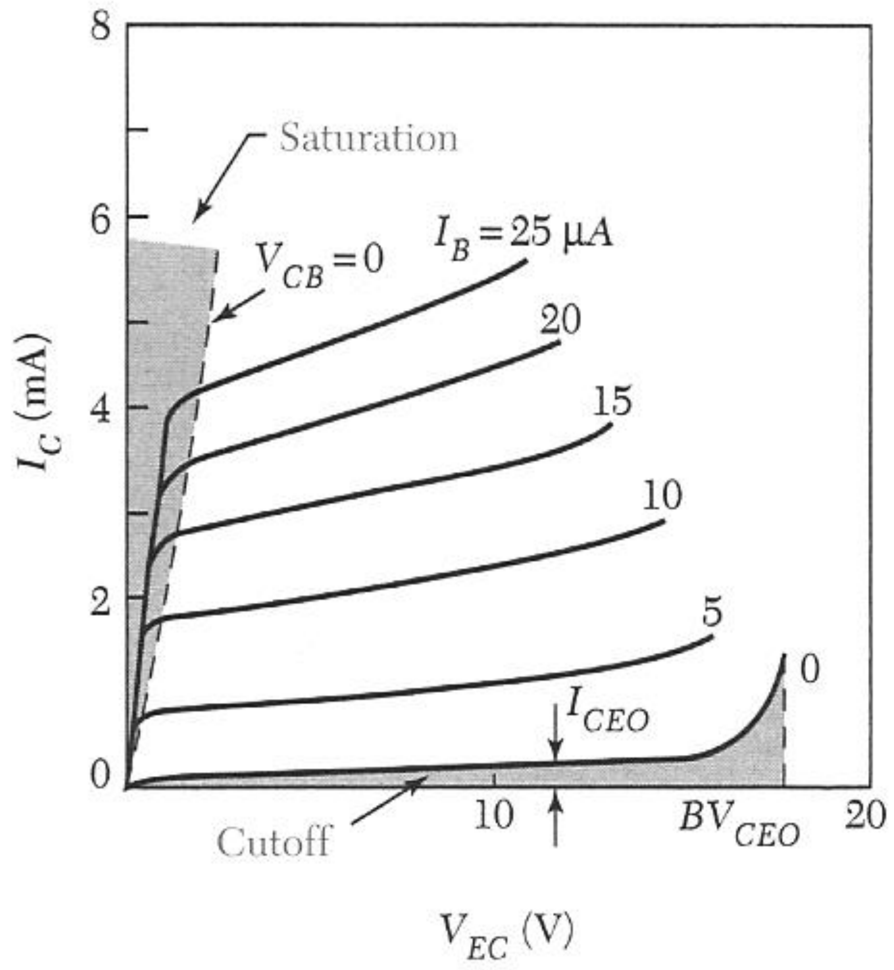


Common emitter configuration
Base width modulation: smaller width increases the diffusion current and increases the gain.

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

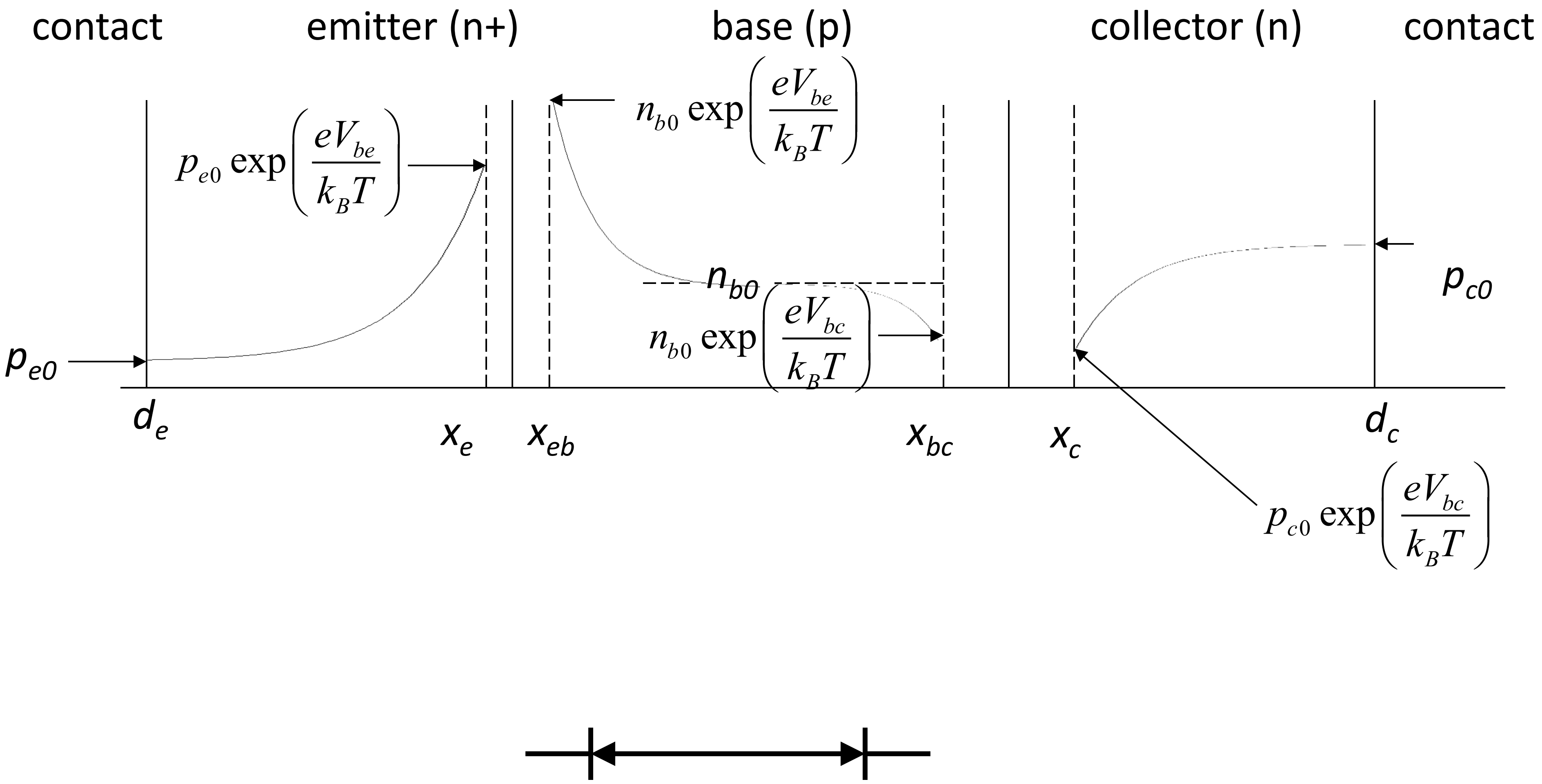
Common emitter configuration



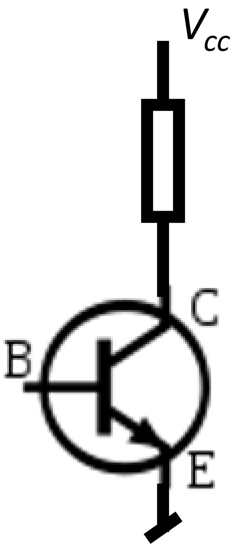


$I_C \sim \beta I_B$ amplifier

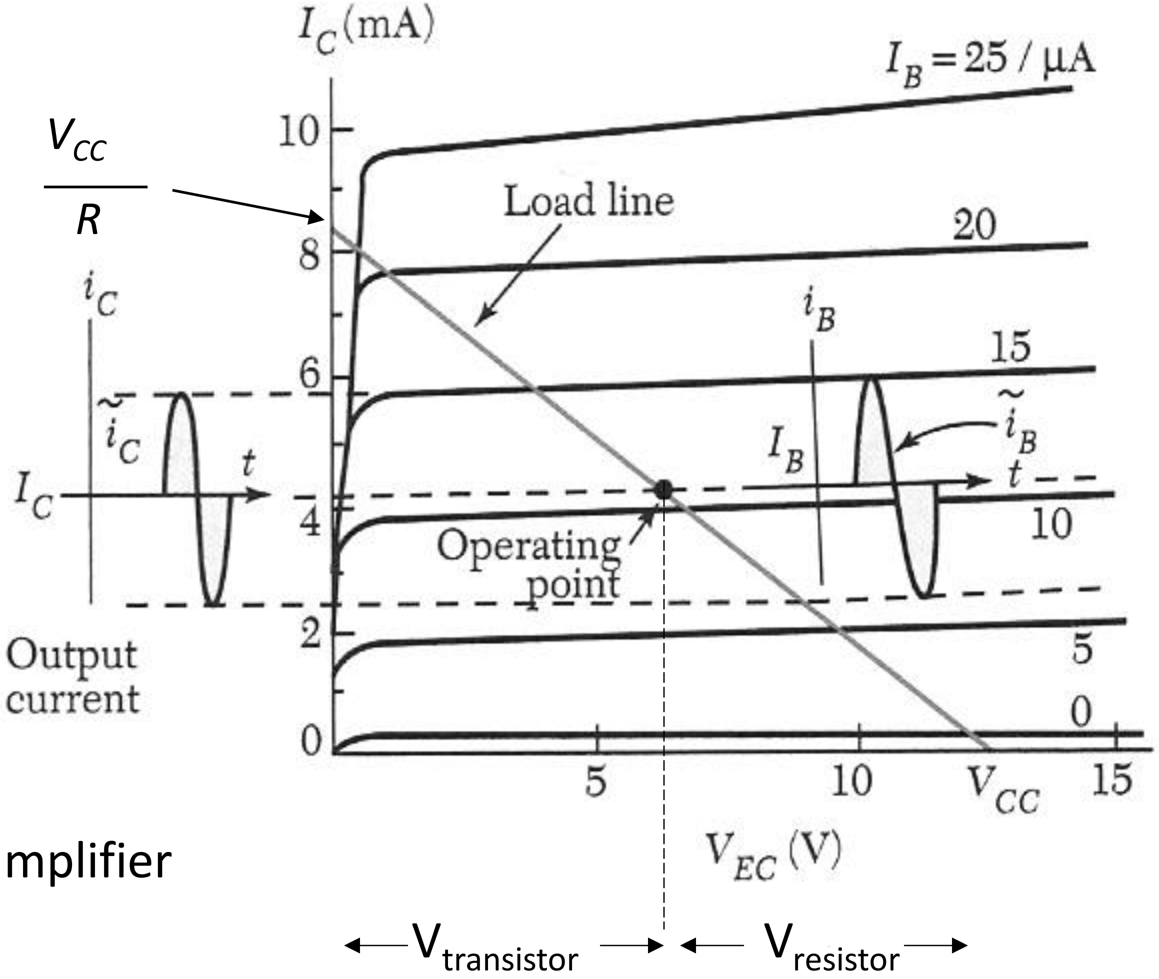
not an npn transistor



small signal response

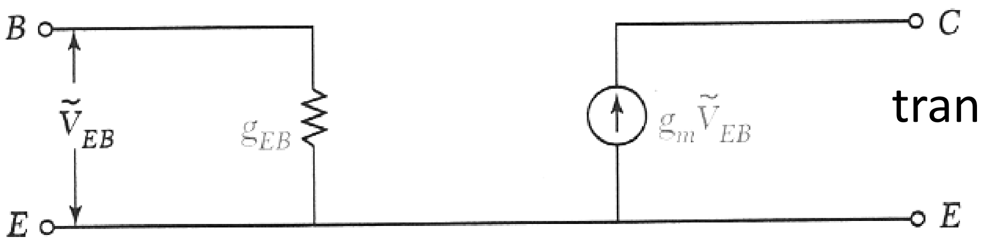


Low input impedance amplifier



small signal response

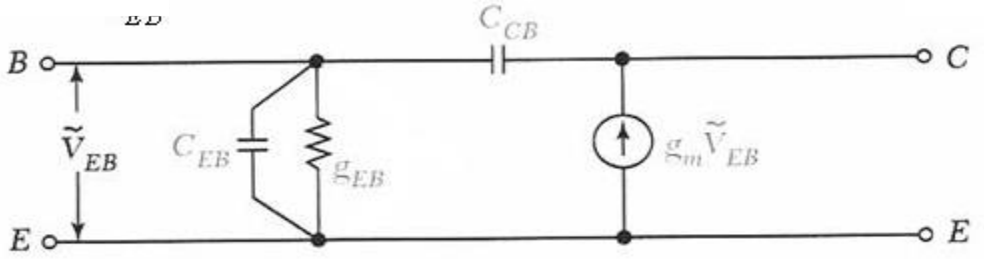
$\tilde{\imath}_c = \beta \tilde{\imath}_B = \beta g_{EB} \tilde{v}_{EB}$

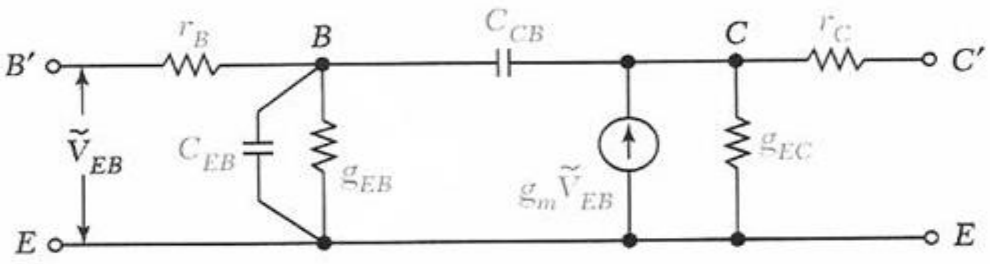


transistor man

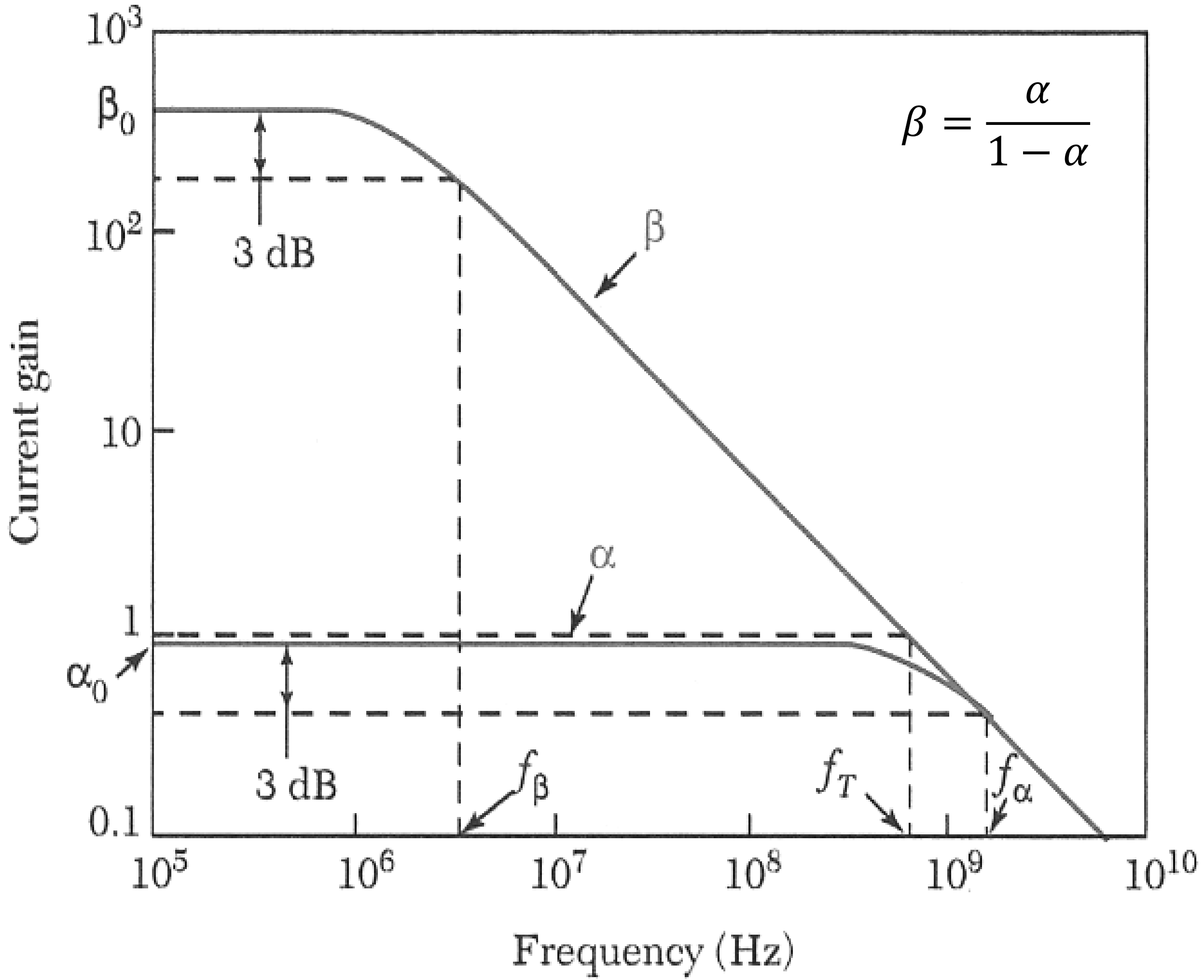
input conductance: $g_{EB} = \dfrac{\tilde{\imath}_B}{\tilde{v}_{EB}}$

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





small signal response



$$\beta = \frac{\alpha}{1-\alpha}$$

$f_\beta = (1-\alpha_0)f_\alpha$

$f_T = \alpha_0 f_\alpha$