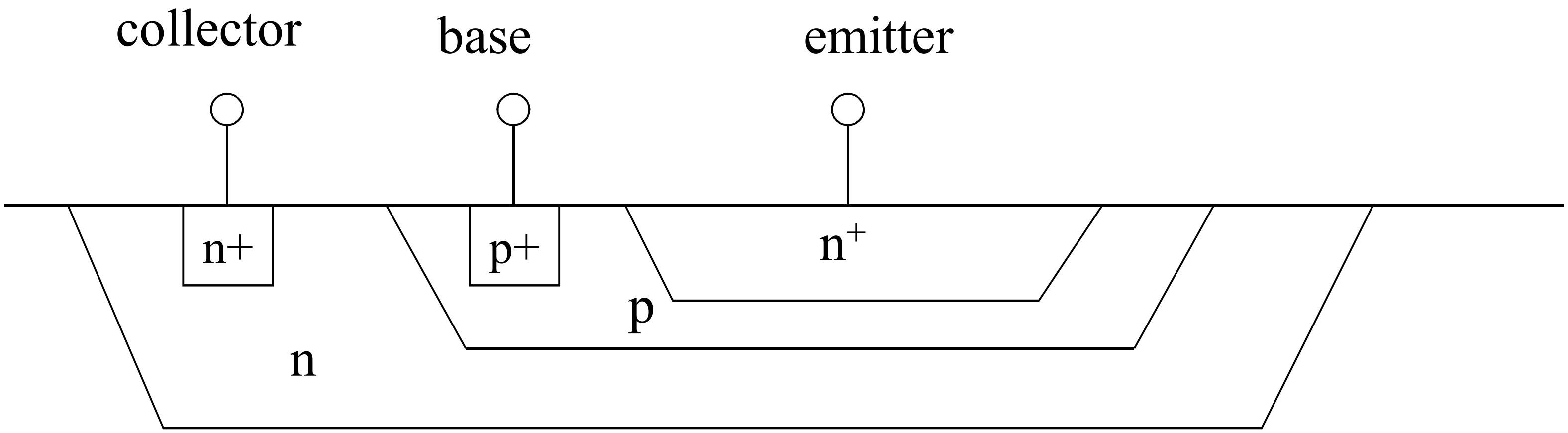
Bipolar transistors

bipolar transistors

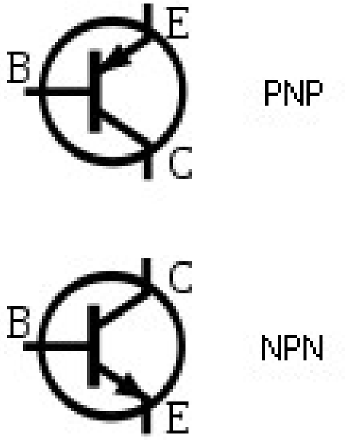
npn transistor



lightly doped p substrate

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

bipolar transistors



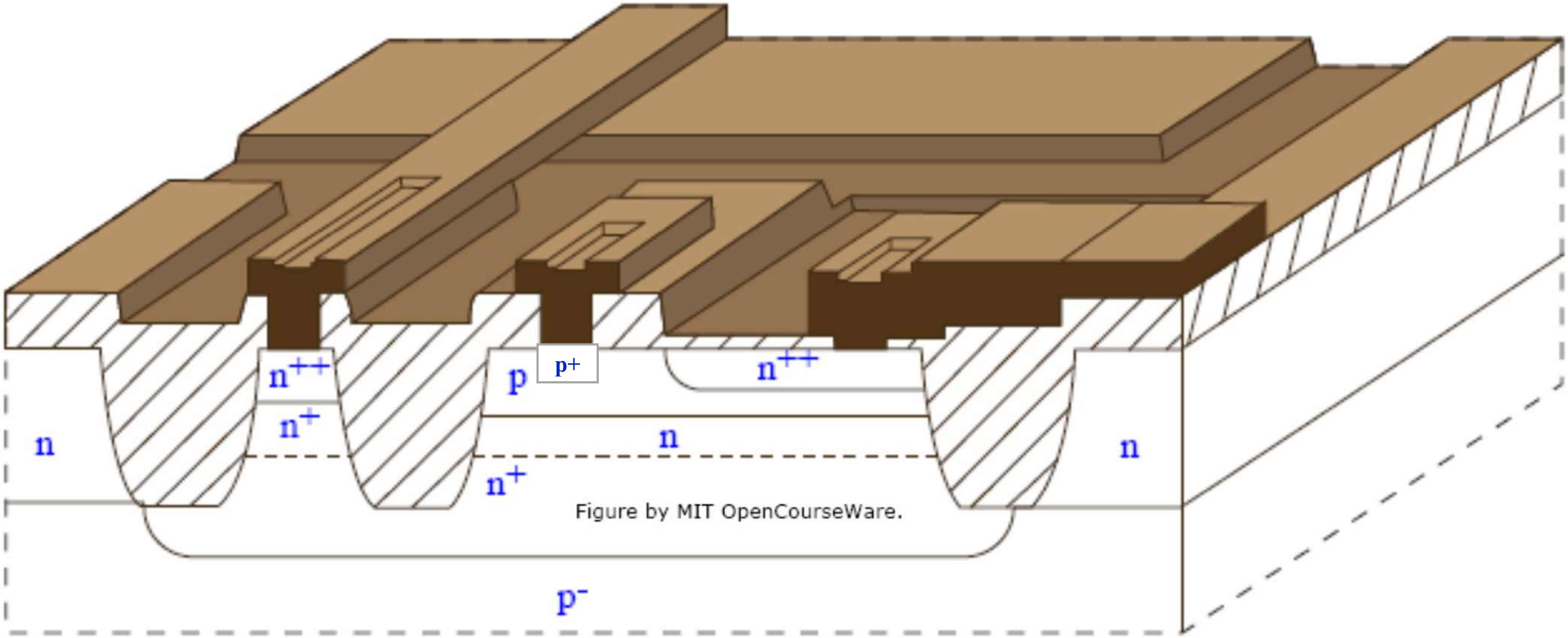
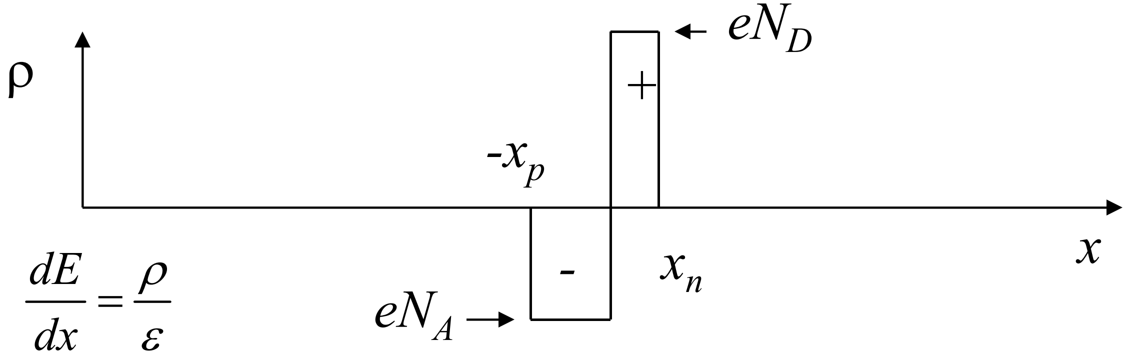


Figure by MIT OpenCourseWare.

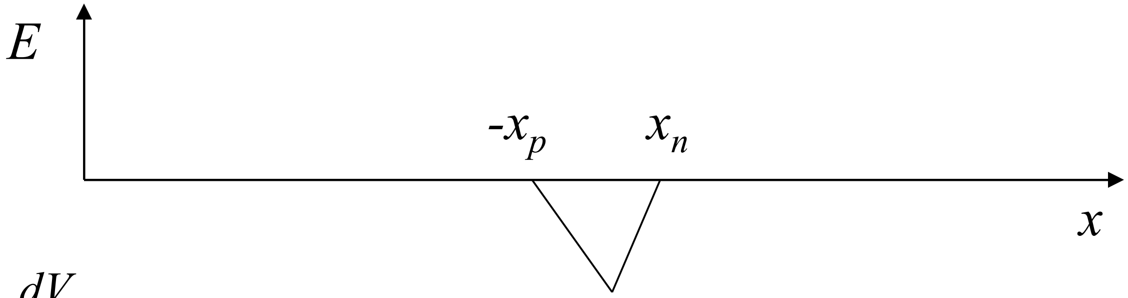
Oxide isolated integrated BJT - a modern process

abrupt junction

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



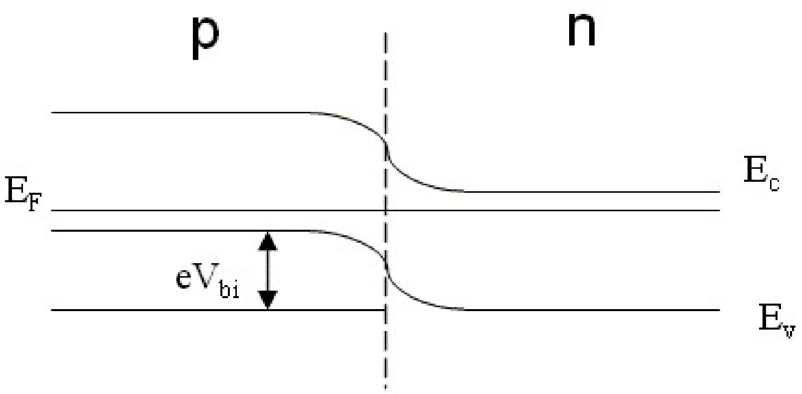
$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$



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

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

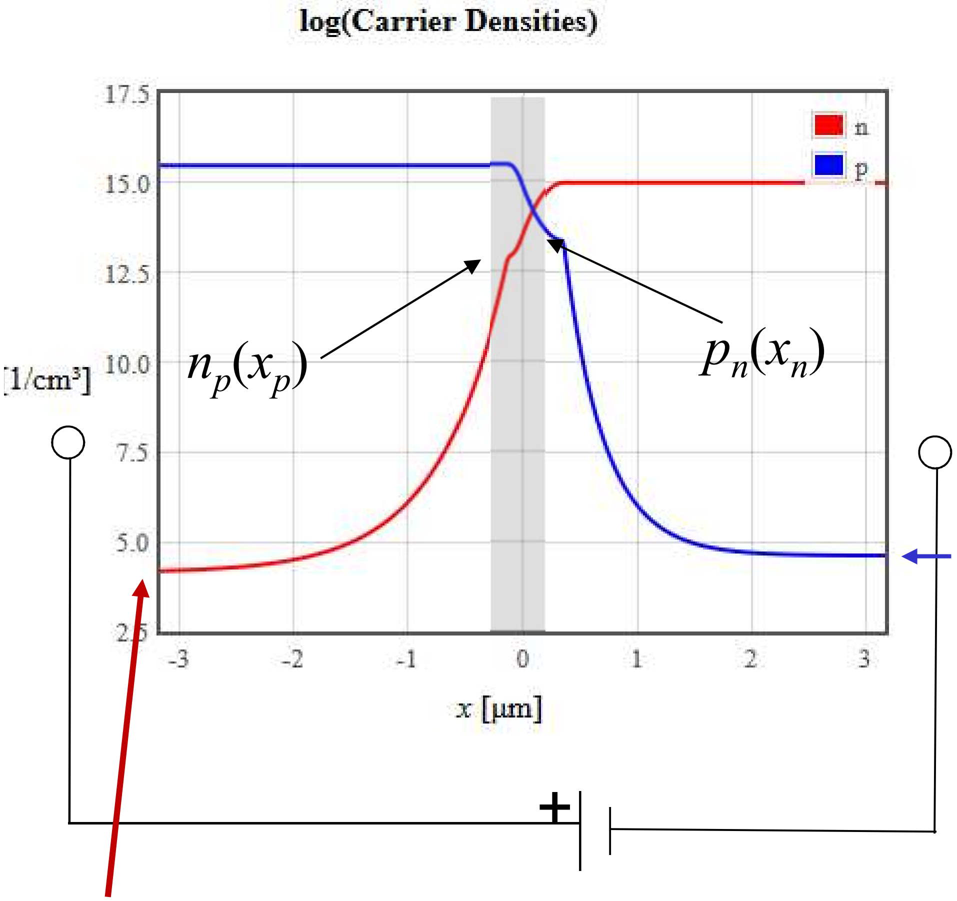
$$\frac{dV}{dx} = -E$$



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

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

Forward bias, V > 0



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

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

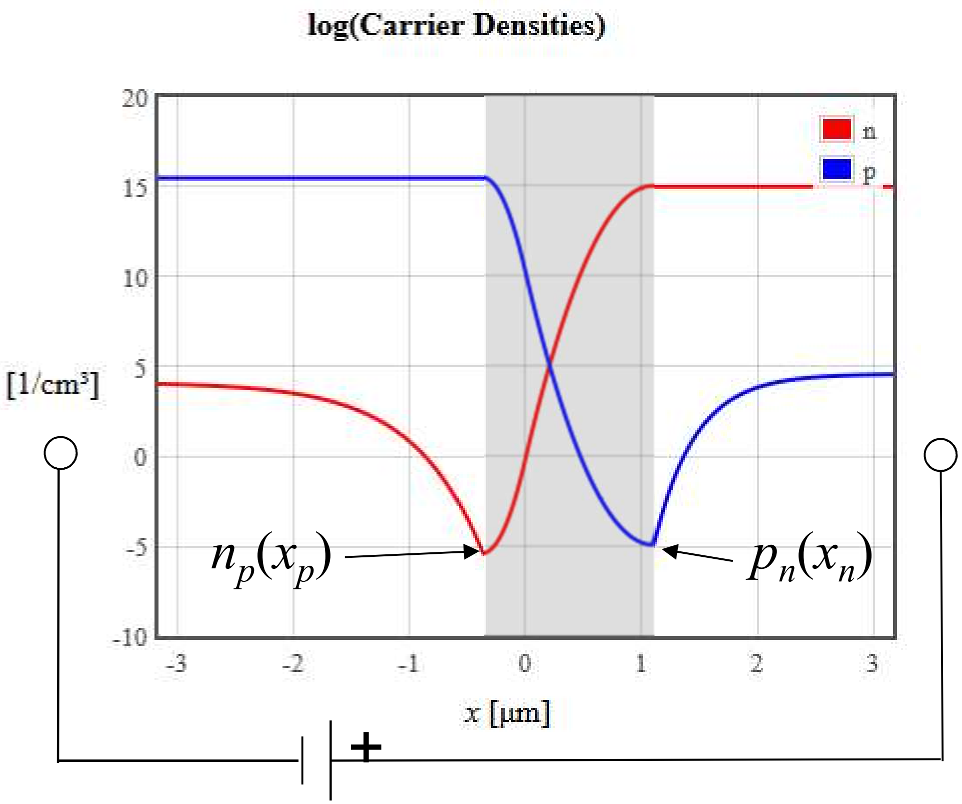
$$n_p(x_p) = n_{p0}\exp\left(\frac{eV}{k_BT}\right)$$

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

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

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

Reverse bias, V < 0



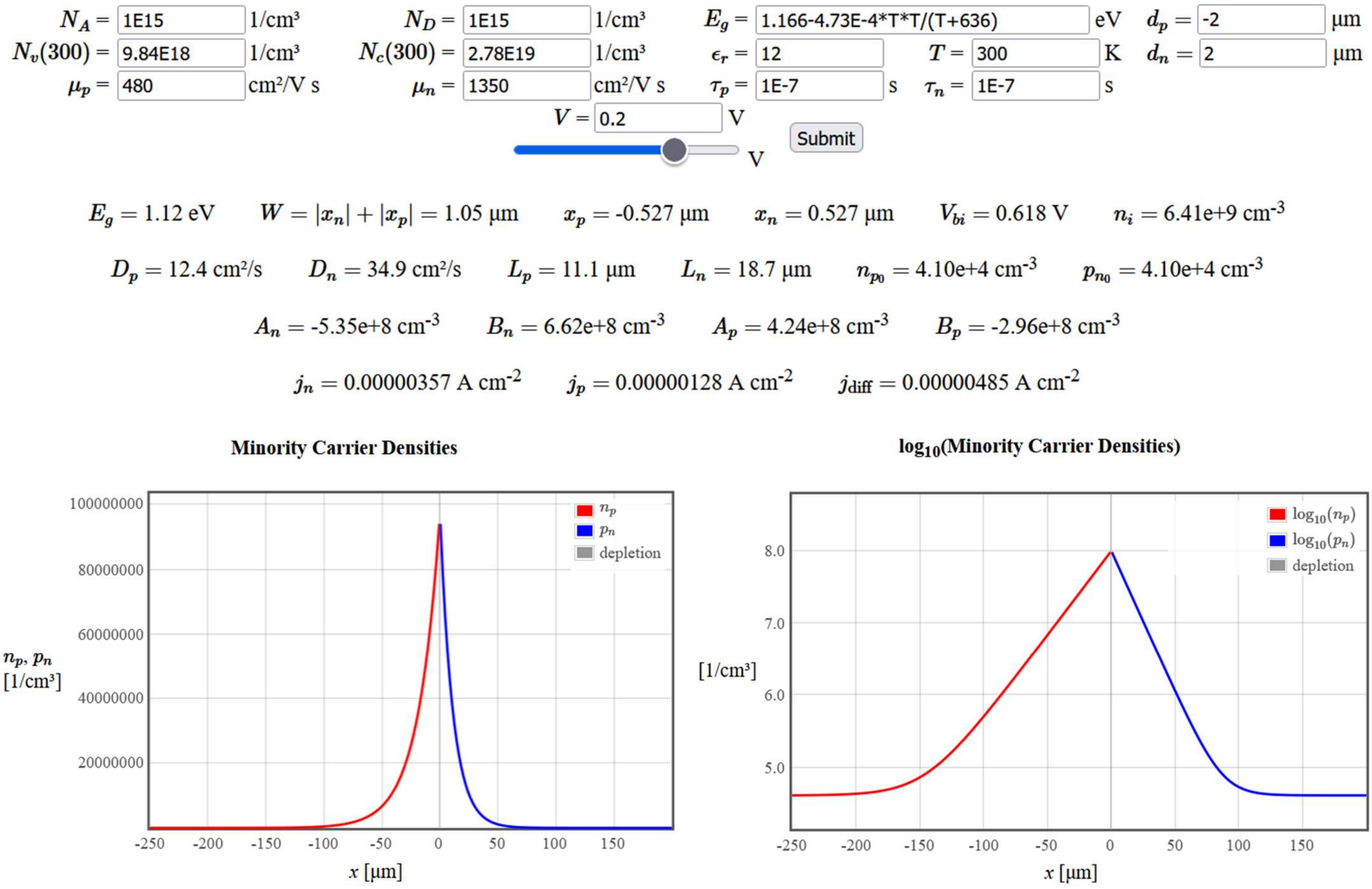
Electrons and holes are driven away from the junction.
The depletion region becomes wider

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

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

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

Long/Short diodes



$N_A =$ 1E15 $1/\text{cm}^3$ $N_D =$ 1E15 $1/\text{cm}^3$ $E_g =$ 1.166-4.73E-4*T*T/(T+636) eV $d_p =$ -2 µm

$N_v(300) =$ 9.84E18 $1/\text{cm}^3$ $N_c(300) =$ 2.78E19 $1/\text{cm}^3$ $\epsilon_r =$ 12 $T =$ 300 K $d_n =$ 2 µm

$\mu_p =$ 480 $\text{cm}^2/\text{V s}$ $\mu_n =$ 1350 $\text{cm}^2/\text{V s}$ $\tau_p =$ 1E-7 s $\tau_n =$ 1E-7 s

$V =$ 0.2 V

Submit

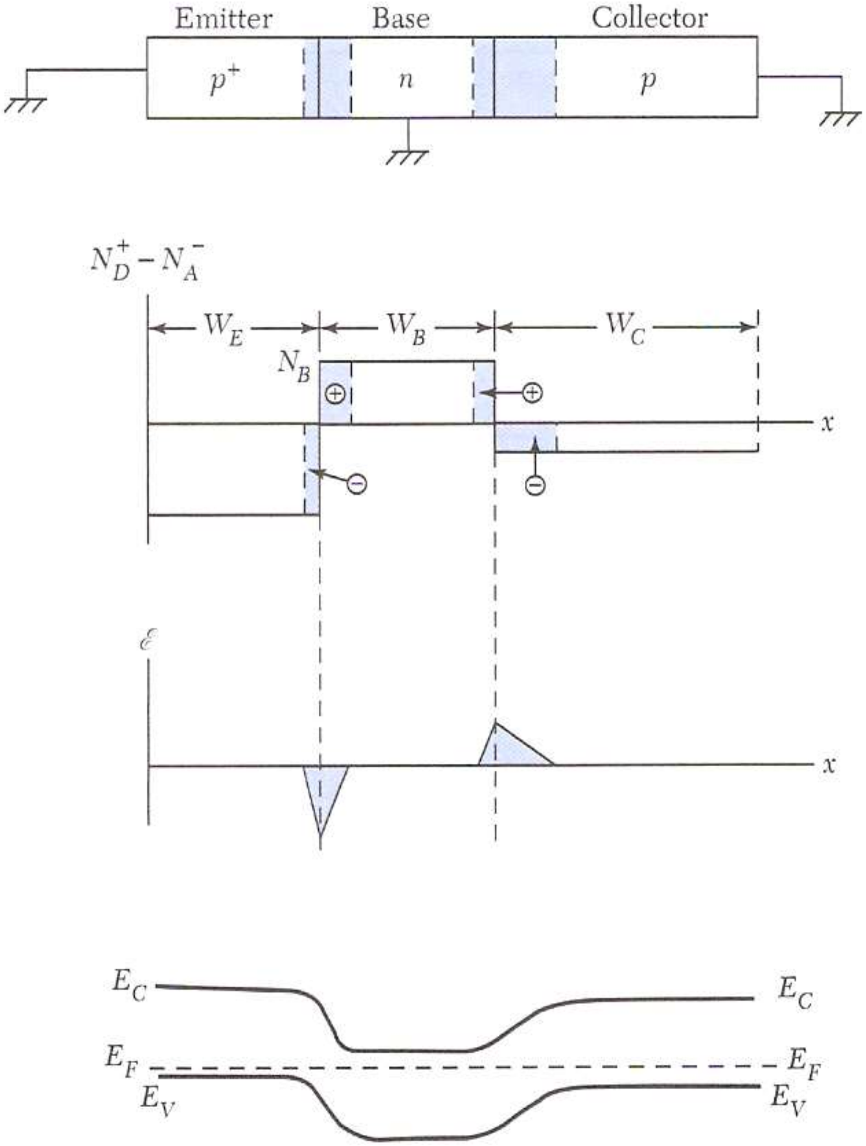
$E_g = 1.12$ eV $W = |x_n| + |x_p| = 1.05$ µm $x_p =$ -0.527 µm $x_n = 0.527$ µm $V_{bi} = 0.618$ V $n_i = 6.41\text{e}{+}9\ \text{cm}^{-3}$

$D_p = 12.4\ \text{cm}^2/\text{s}$ $D_n = 34.9\ \text{cm}^2/\text{s}$ $L_p = 11.1$ µm $L_n = 18.7$ µm $n_{p_0} = 4.10\text{e}{+}4\ \text{cm}^{-3}$ $p_{n_0} = 4.10\text{e}{+}4\ \text{cm}^{-3}$

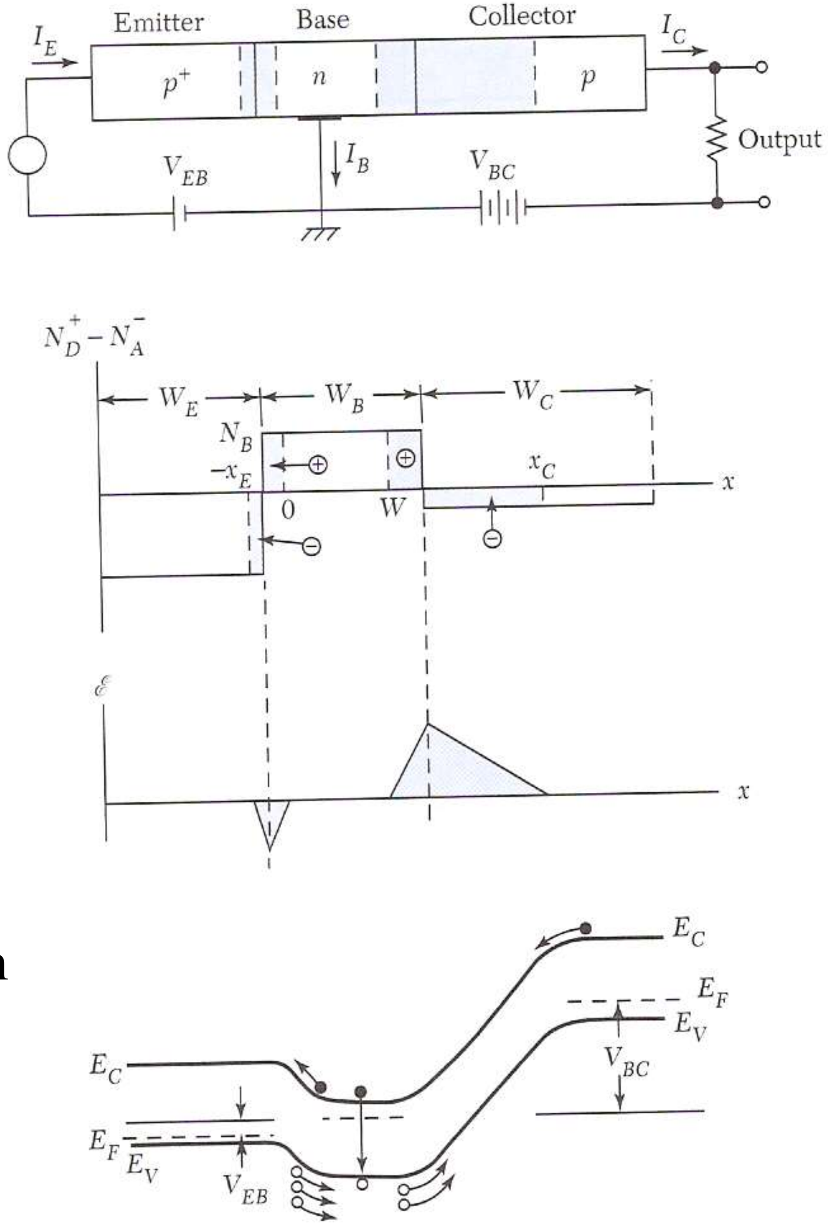
$A_n = -5.35\text{e}{+}8\ \text{cm}^{-3}$ $B_n = 6.62\text{e}{+}8\ \text{cm}^{-3}$ $A_p = 4.24\text{e}{+}8\ \text{cm}^{-3}$ $B_p = -2.96\text{e}{+}8\ \text{cm}^{-3}$

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

pnp transistor, no bias



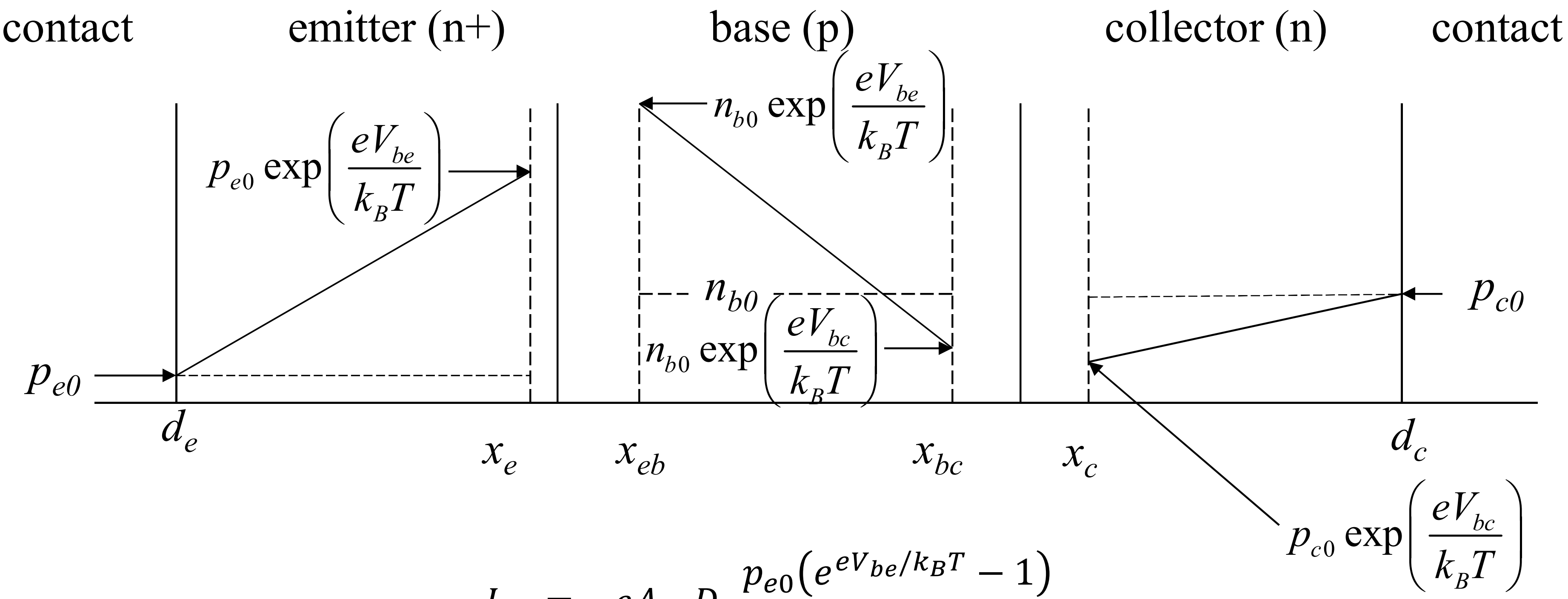
pnp transistor, forward active bias



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.

Minority carrier concentration



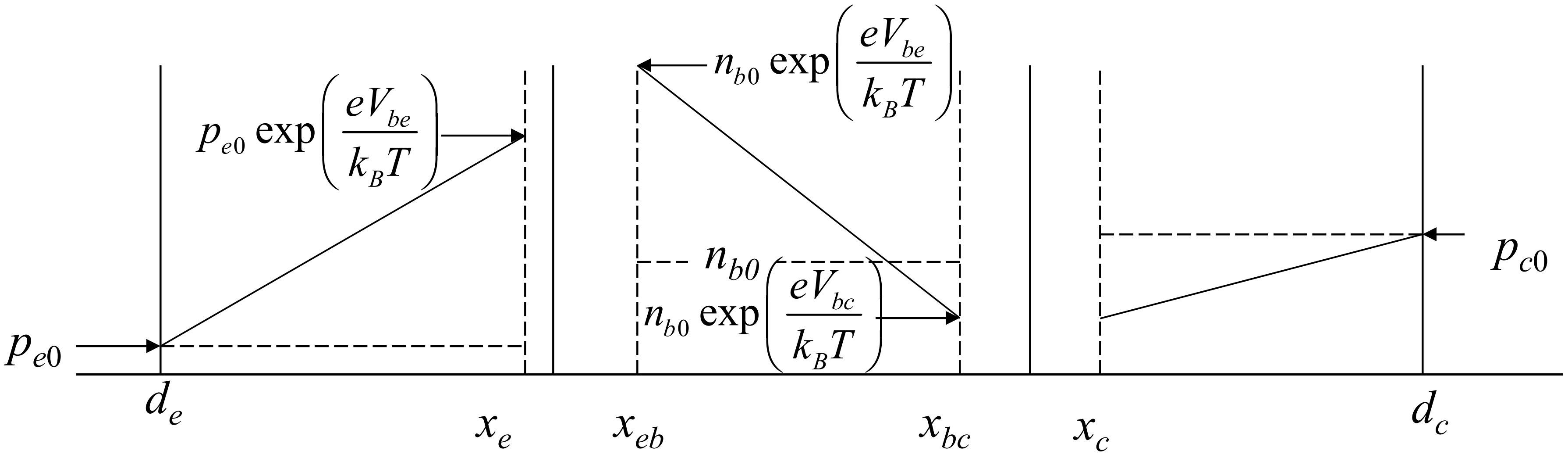
$$I_{Ep} = -eA_{be}D_p\frac{p_{e0}\left(e^{eV_{be}/k_BT} - 1\right)}{x_e - d_e}$$

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

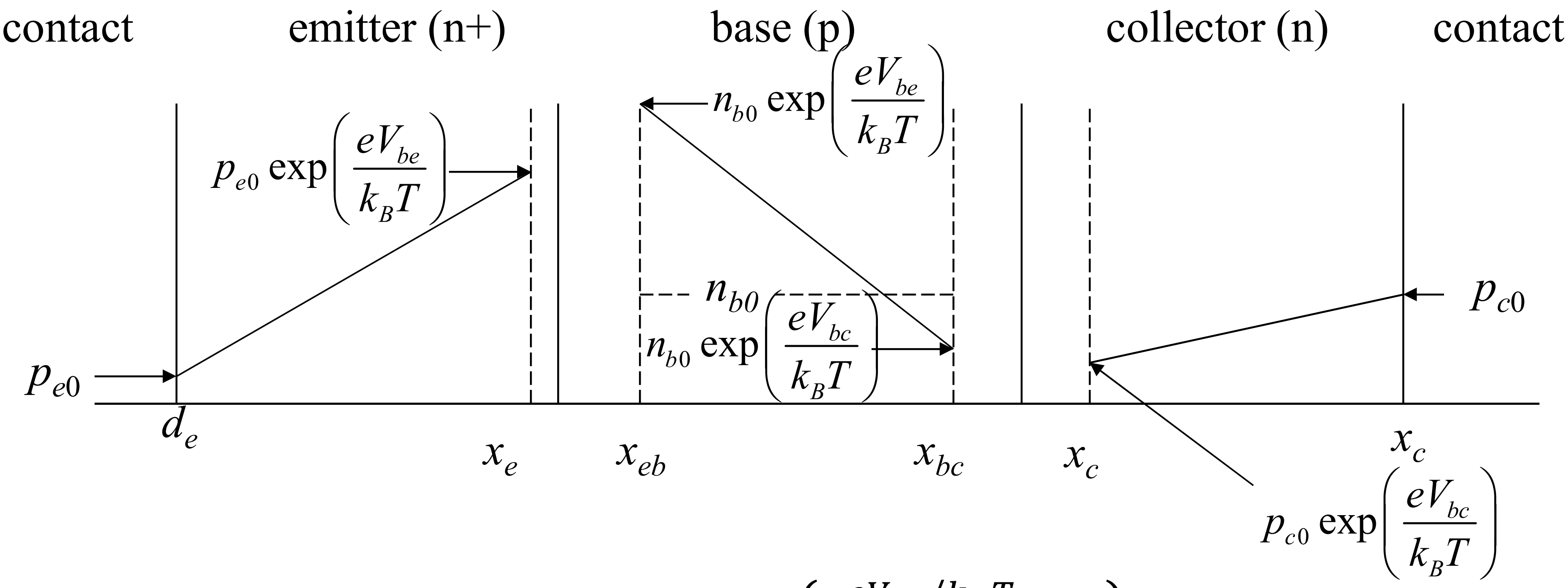
Emitter current

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

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



Collector current



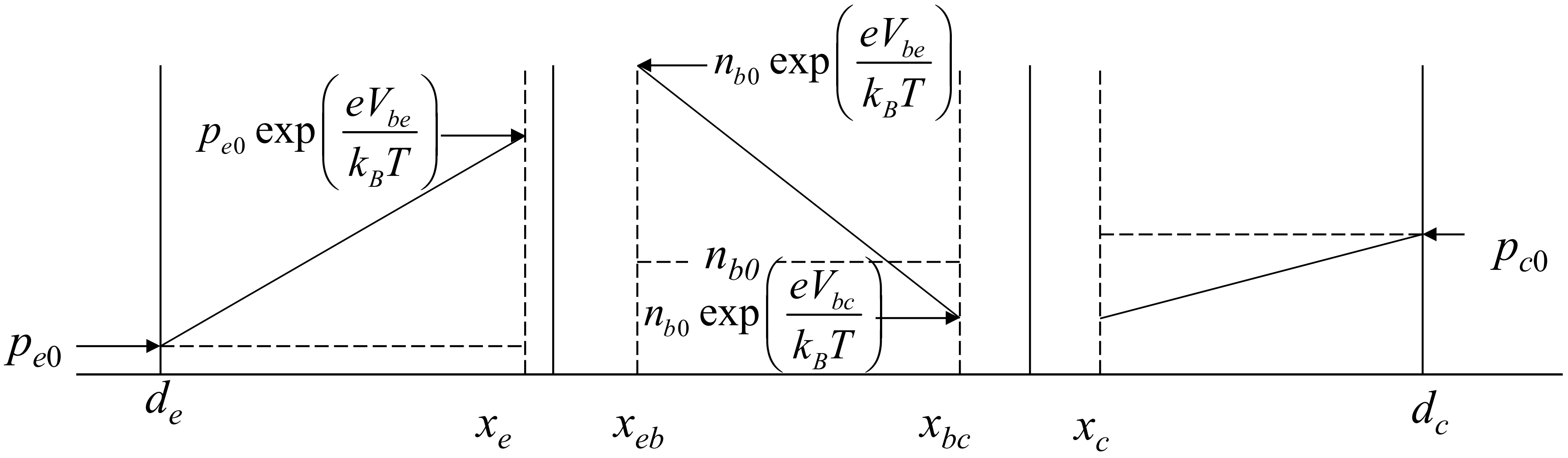
$$I_{cp} = -eA_{bc}D_p \frac{p_{c0}\left(e^{eV_{bc}/k_BT} - 1\right)}{d_c - x_c}$$

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

Collector current

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

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

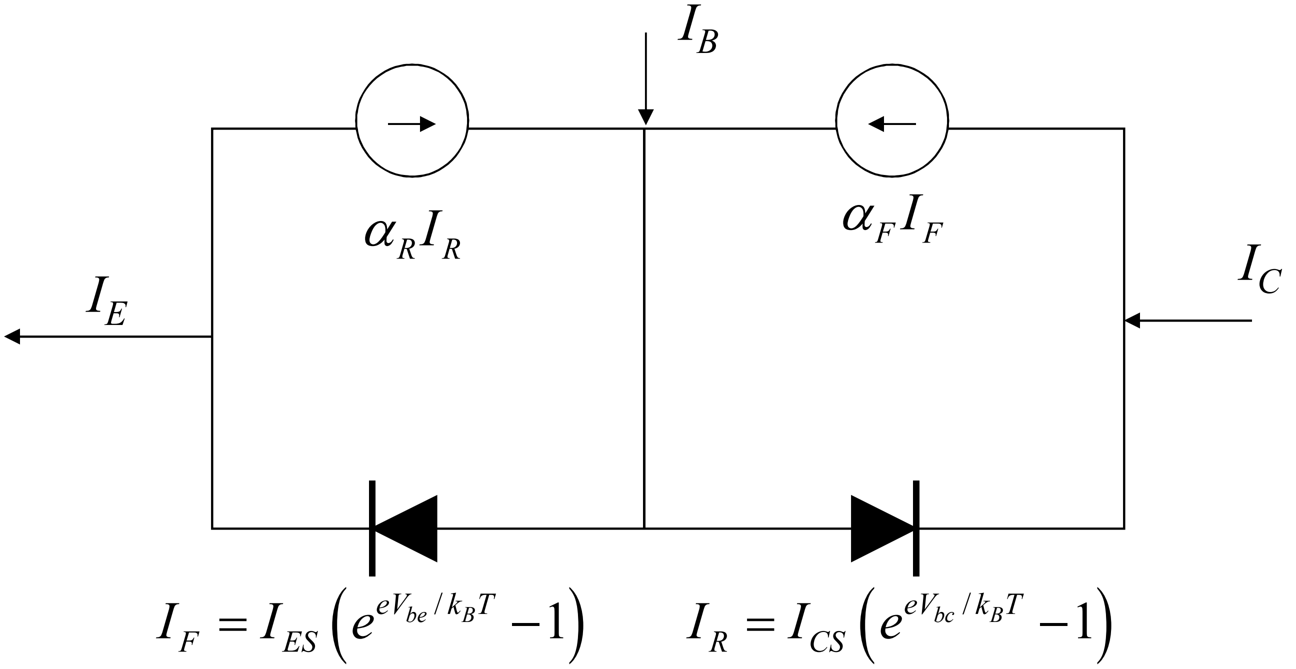


Ebers-Moll model

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

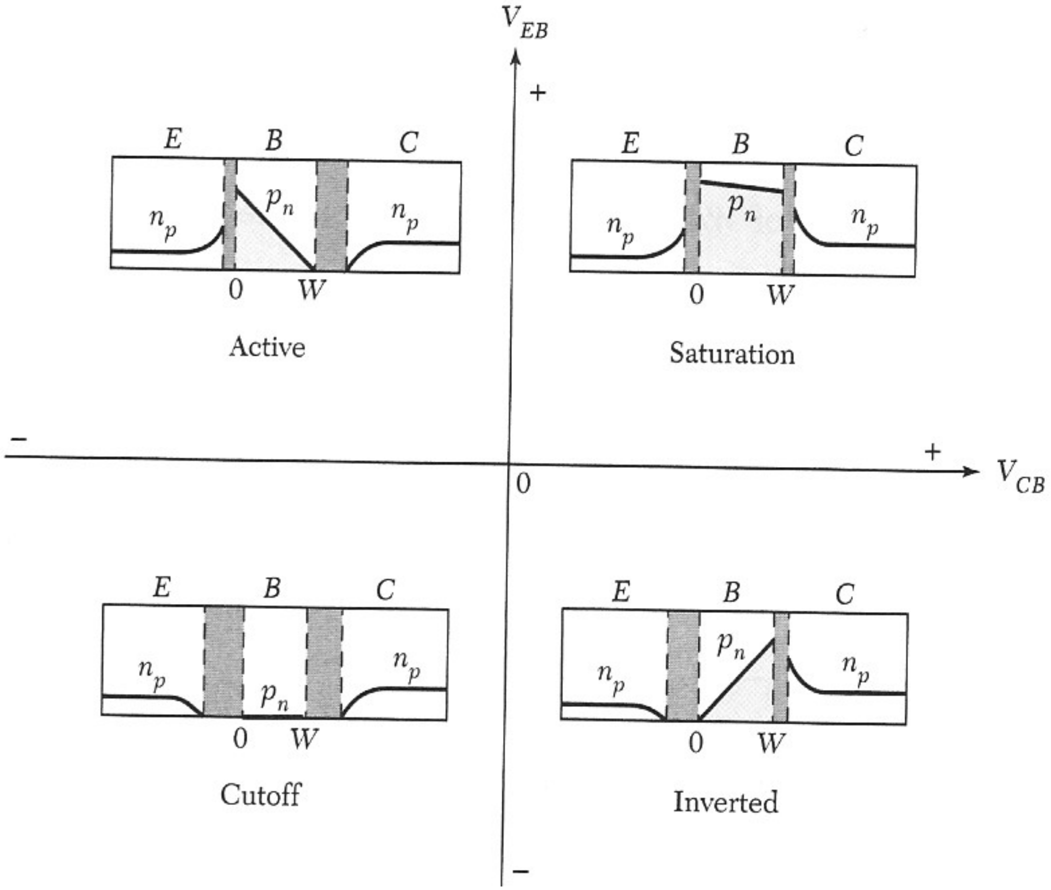
$$I_C = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$



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**

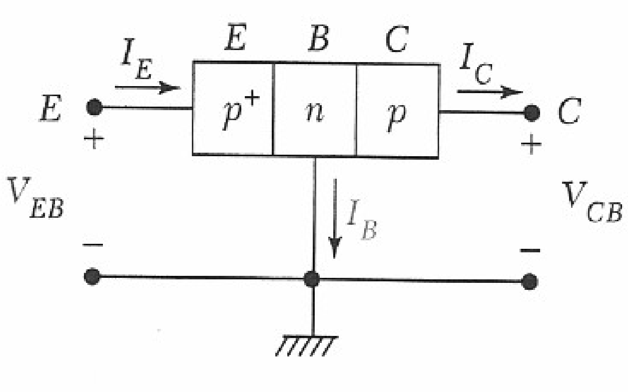


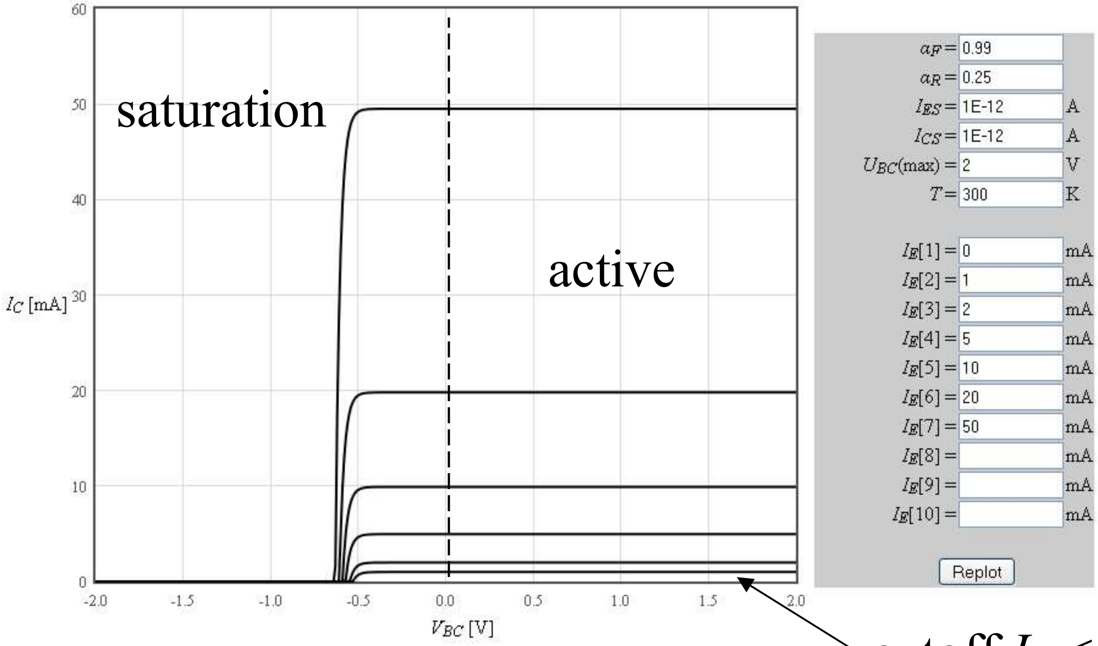
Common base configuration

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

solve for V_{be}

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





α_F = 0.99
α_R = 0.25
I_{ES} = 1E-12 A
I_{CS} = 1E-12 A
U_{BC}(max) = 2 V
T = 300 K

$I_E[1]$ = 0 mA
$I_E[2]$ = 1 mA
$I_E[3]$ = 2 mA
$I_E[4]$ = 5 mA
$I_E[5]$ = 10 mA
$I_E[6]$ = 20 mA
$I_E[7]$ = 50 mA
$I_E[8]$ = mA
$I_E[9]$ = mA
$I_E[10]$ = mA

saturation

active

cutoff $I_E < 0$

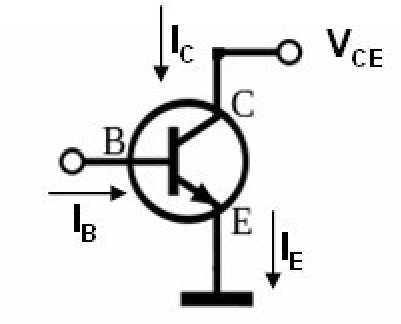
http://lamp.tu-graz.ac.at/~hadley/psd/L13/commonbase/pnp_current.html

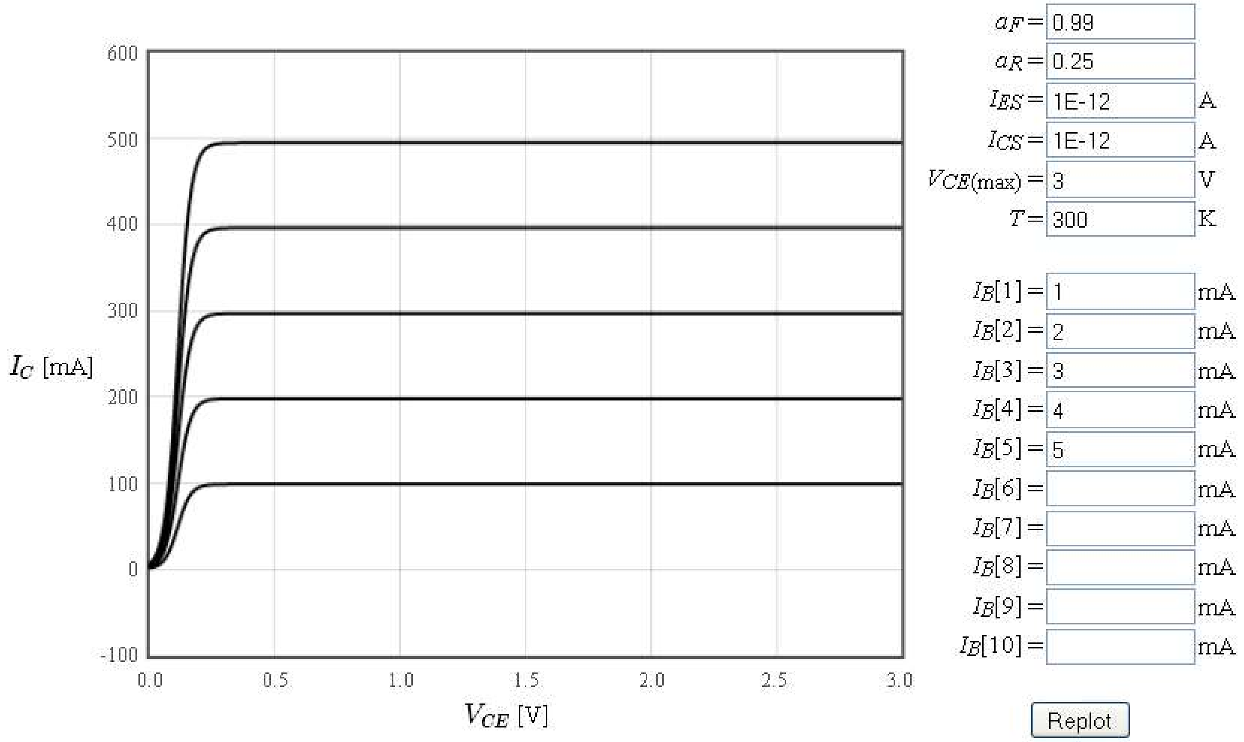
Common emitter configuration

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

$$I_B = I_E - I_C$$

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





a_F = 0.99

a_R = 0.25

I_{ES} = 1E-12 A

I_{CS} = 1E-12 A

V_{CE}(max) = 3 V

T = 300 K

$I_B[1]$ = 1 mA

$I_B[2]$ = 2 mA

$I_B[3]$ = 3 mA

$I_B[4]$ = 4 mA

$I_B[5]$ = 5 mA

$I_B[6]$ = mA

$I_B[7]$ = mA

$I_B[8]$ = mA

$I_B[9]$ = mA

$I_B[10]$ = mA

current amplification ~100

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

Emitter efficiency

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

for npn

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

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

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

neutral base width

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

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

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

α ~ 1 for a good BJT

Current amplification factor

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

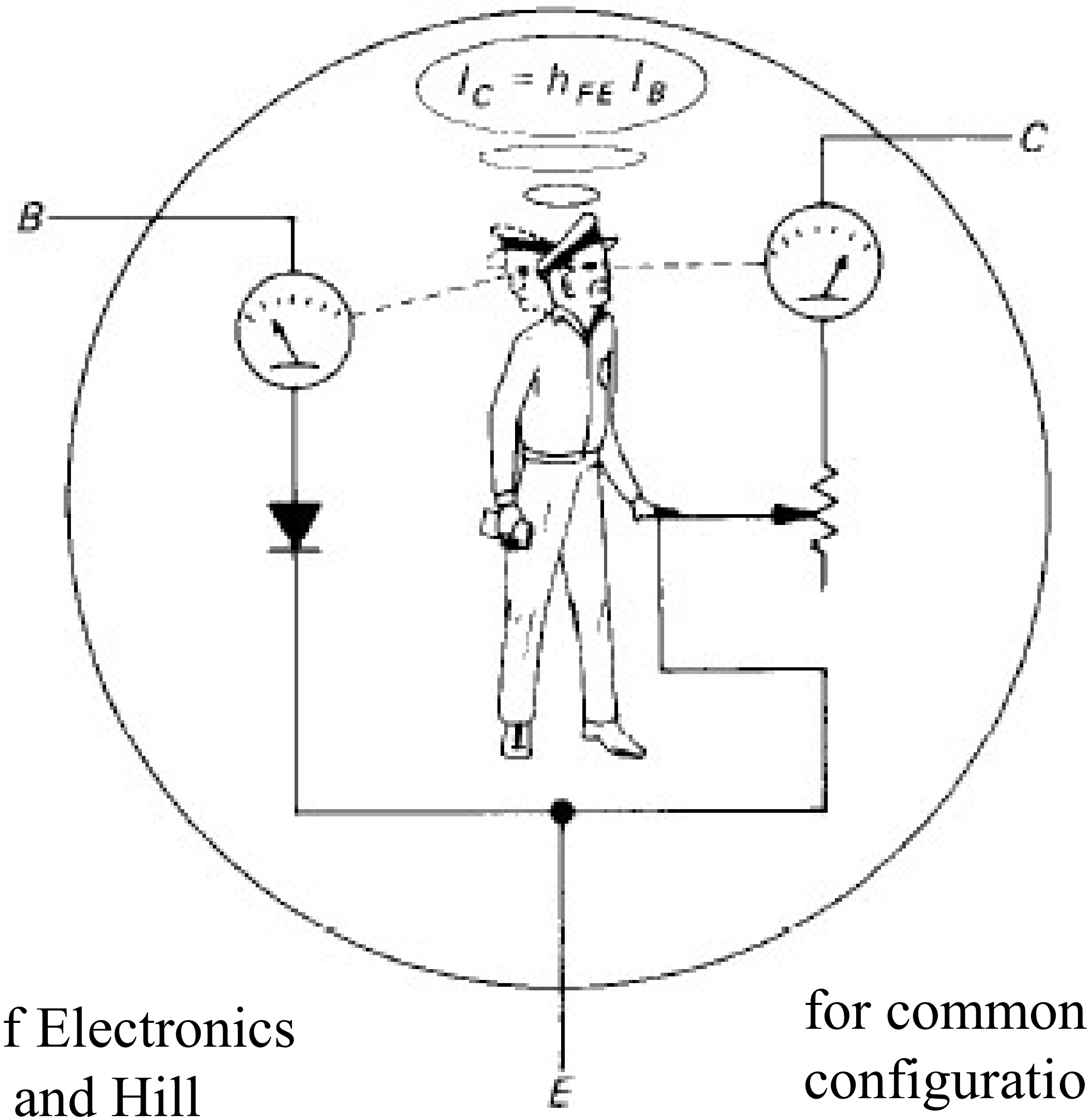
$$I_B = I_E - I_C$$

$$I_C = \alpha I_E$$

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

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

$\beta \sim 50 - 500$



“Transistor man”

The Art of Electronics
Horowitz and Hill

for common emitter
configuration

Transconductance

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

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

The 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:

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

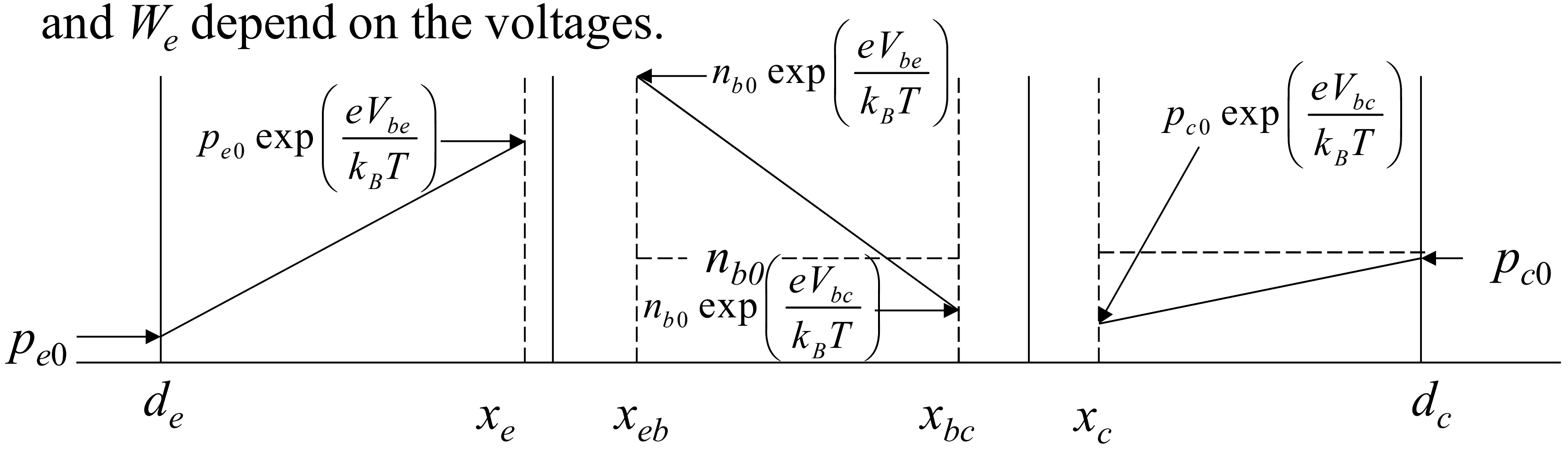
$$I_c = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT}-1\right)-I_{CS}\left(e^{eV_{bc}/k_BT}-1\right)$$

$$I_B = I_E - I_C$$

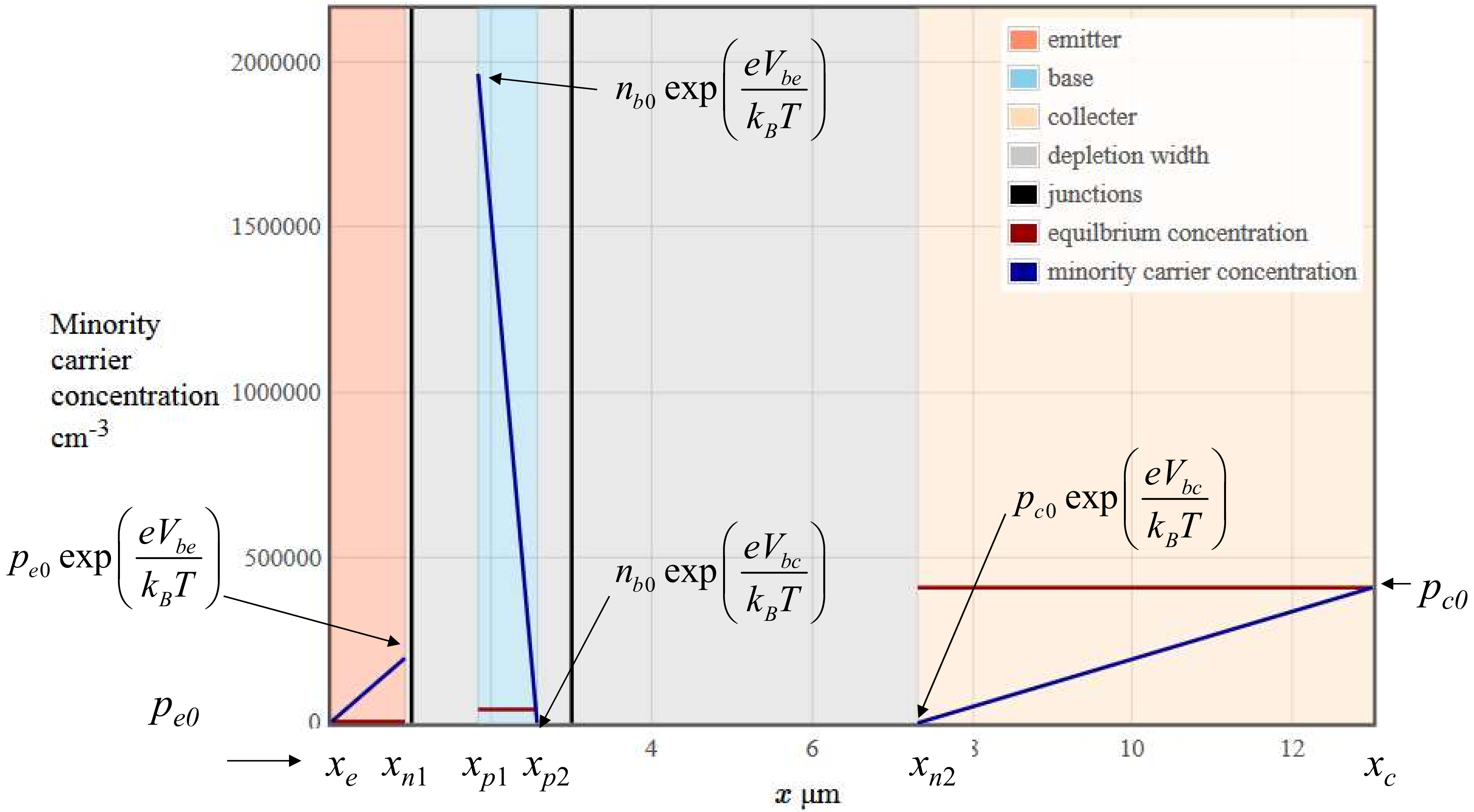
$$I_{ES} = \left[\frac{eA_{be}D_p p_{e0}}{x_{eb}-d_e}+\frac{eA_{be}D_n n_{b0}}{x_{bc}-d_{be}}\right]$$

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

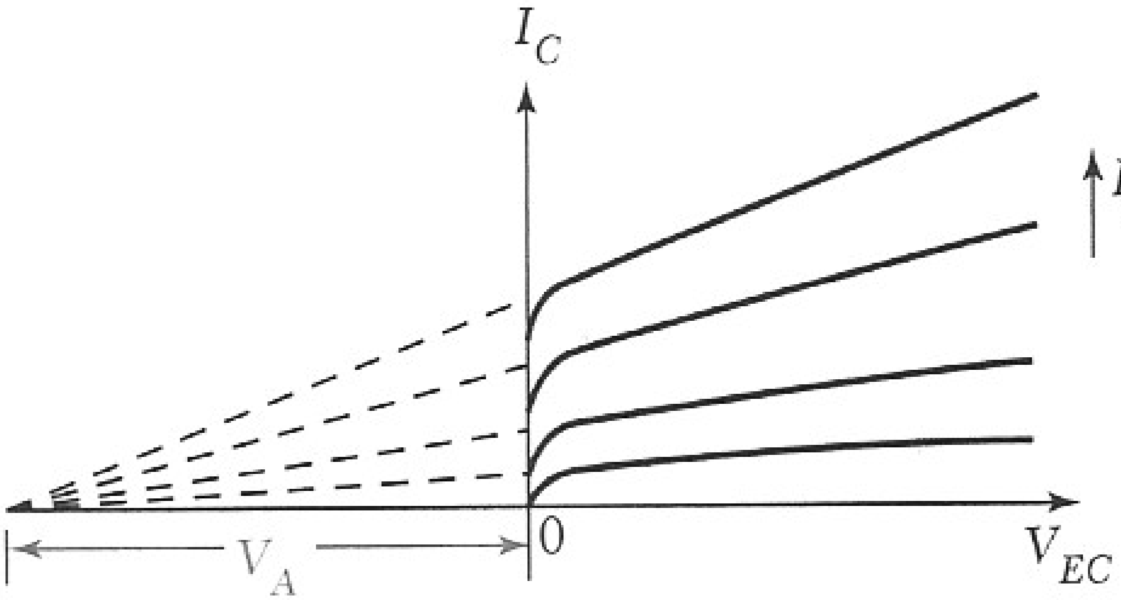
I_{ES} and I_{CS} are treated as constants but the depletion widths W_{bc}, W_{be}, W_c, and W_e depend on the voltages.



Minority carrier concentration



Early effect

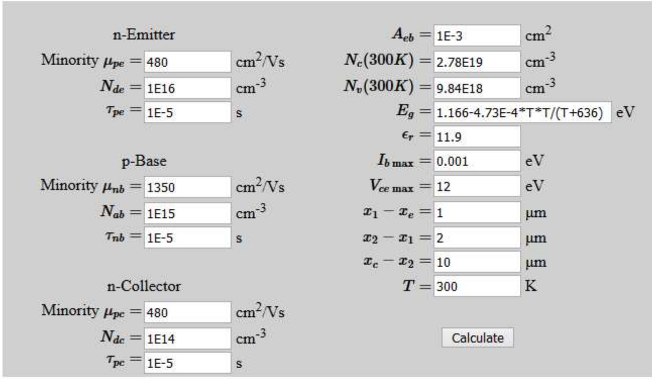


Common emitter configuration
Base width modulation: smaller width increases the diffusion current and increases the gain.

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

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

NPN common emitter configuration



n-Emitter

Minority $\mu_{pe} =$ 480 $\mathrm{cm^2/Vs}$

$N_{de} =$ 1E16 $\mathrm{cm^{-3}}$

$\tau_{pe} =$ 1E-5 s

p-Base

Minority $\mu_{nb} =$ 1350 $\mathrm{cm^2/Vs}$

$N_{ab} =$ 1E15 $\mathrm{cm^{-3}}$

$\tau_{nb} =$ 1E-5 s

n-Collector

Minority $\mu_{pc} =$ 480 $\mathrm{cm^2/Vs}$

$N_{dc} =$ 1E14 $\mathrm{cm^{-3}}$

$\tau_{pc} =$ 1E-5 s

$A_{eb} =$ 1E-3 $\mathrm{cm^2}$

$N_c(300K) =$ 2.78E19 $\mathrm{cm^{-3}}$

$N_v(300K) =$ 9.84E18 $\mathrm{cm^{-3}}$

$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$\epsilon_r =$ 11.9

$I_{b\,\max} =$ 0.001 eV

$V_{ce\,\max} =$ 12 eV

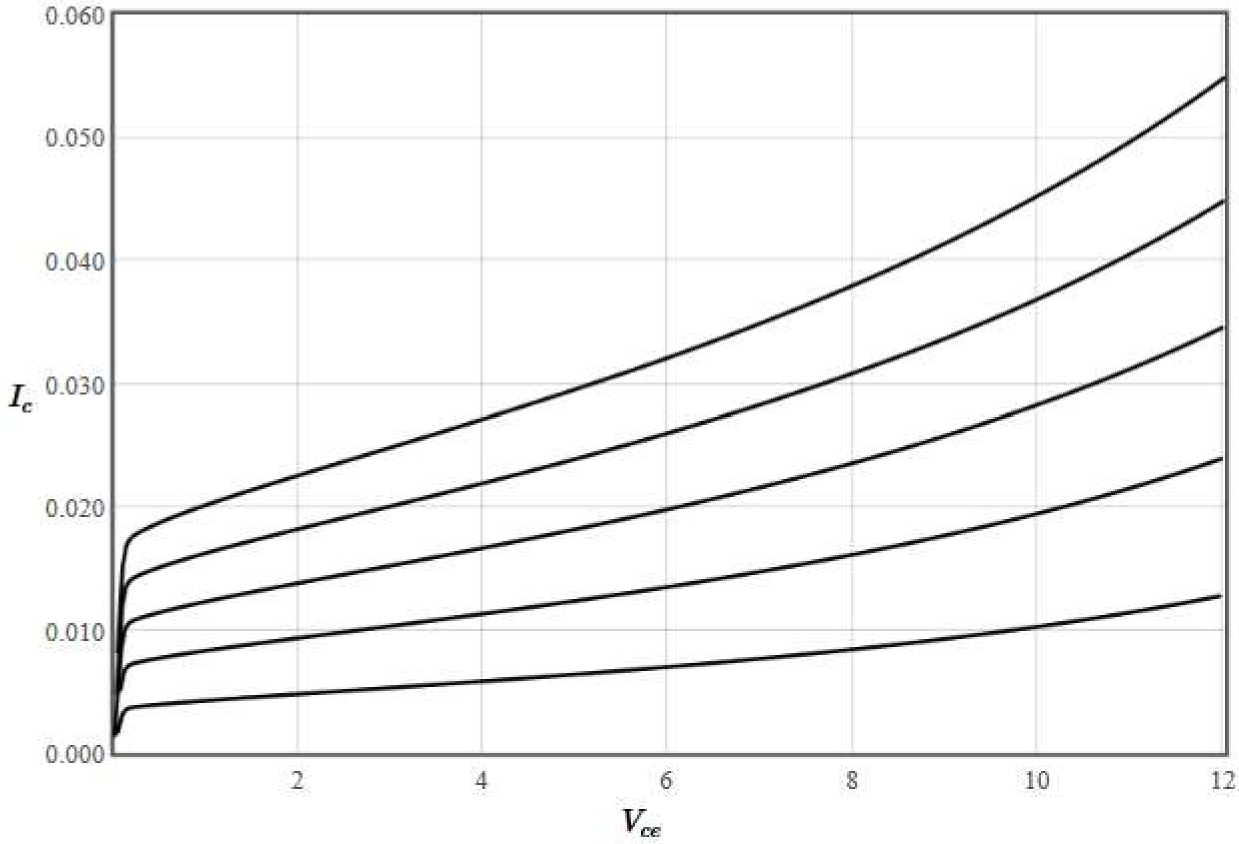
$x_1 - x_e =$ 1 µm

$x_2 - x_1 =$ 2 µm

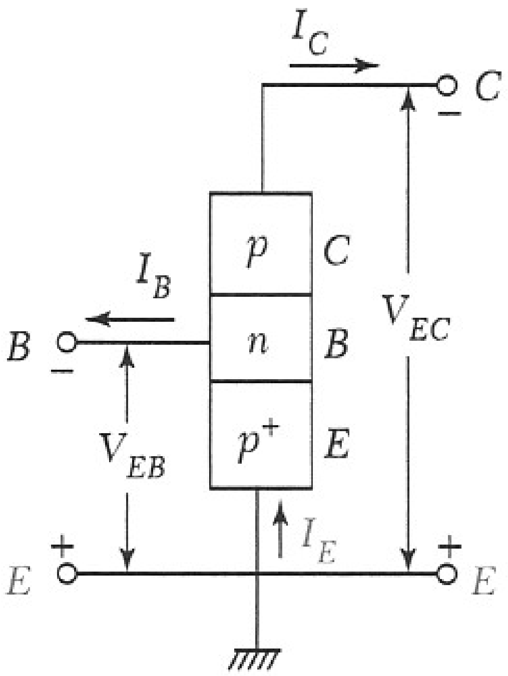
$x_c - x_2 =$ 10 µm

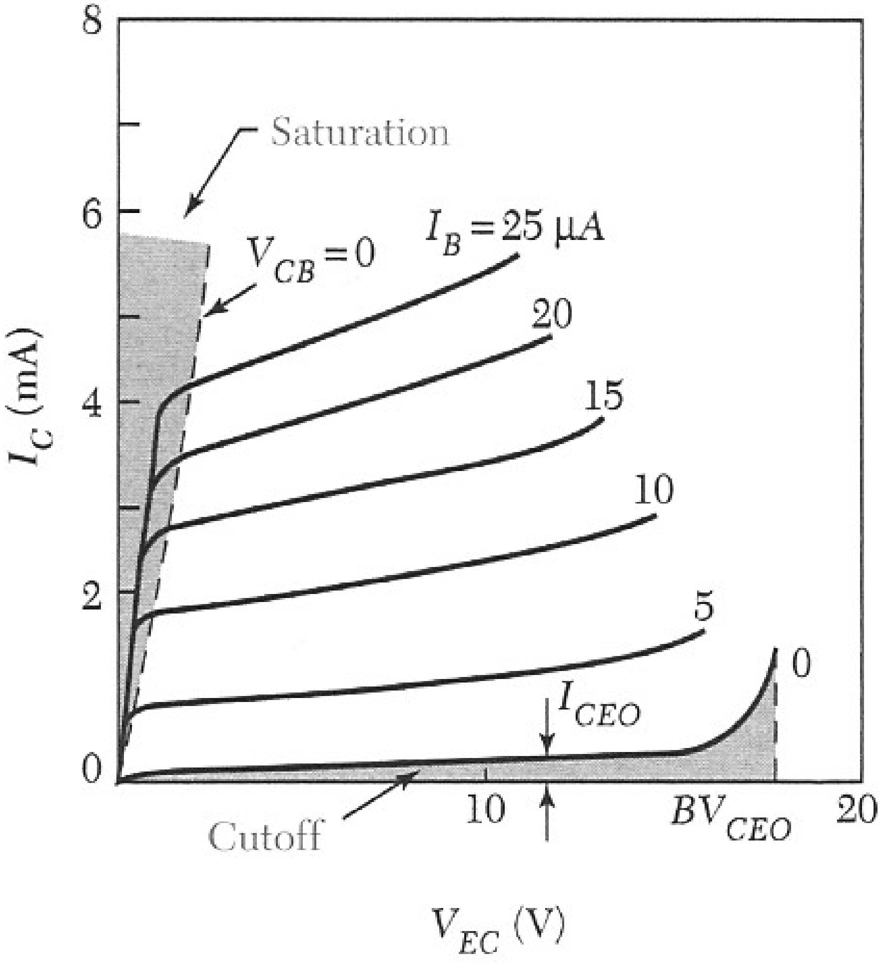
$T =$ 300 K

$$I_C \sim \beta I_B$$



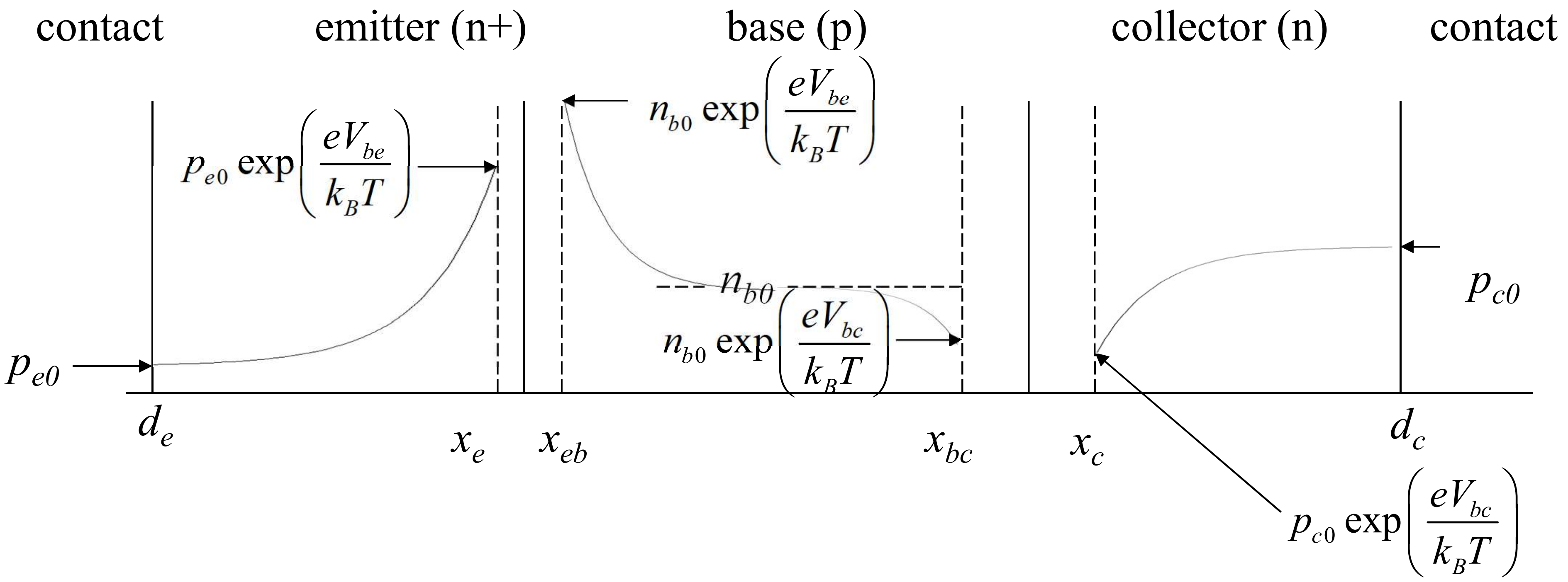
Common emitter configuration



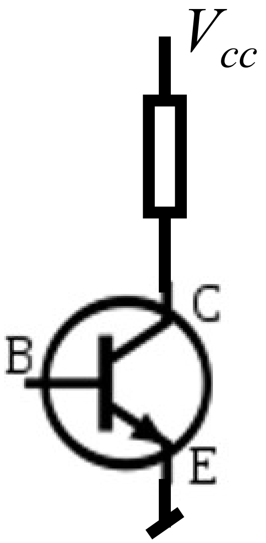


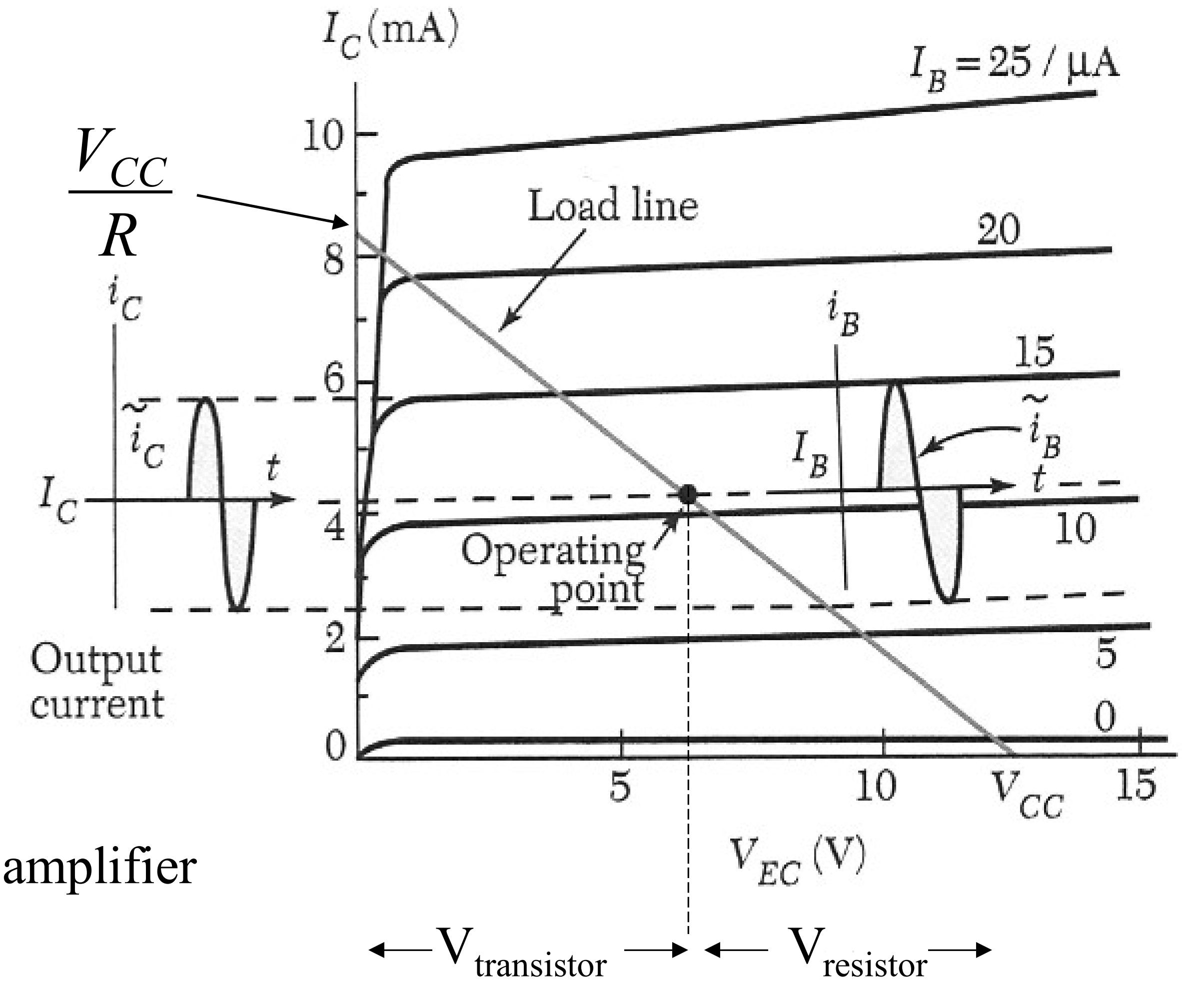
$I_C \sim \beta I_B$ amplifier

Not an npn transistor



Small signal response

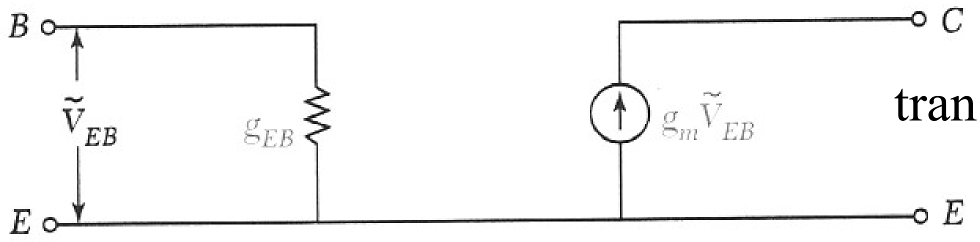




Low input impedance amplifier

Small signal response

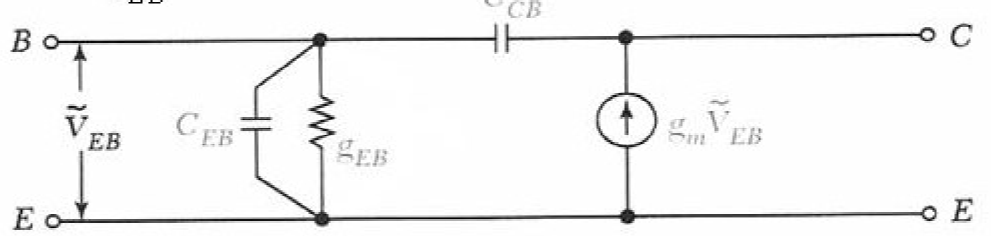
$$\tilde{i}_c = \beta \tilde{i}_B = \beta g_{EB} \tilde{v}_{EB}$$

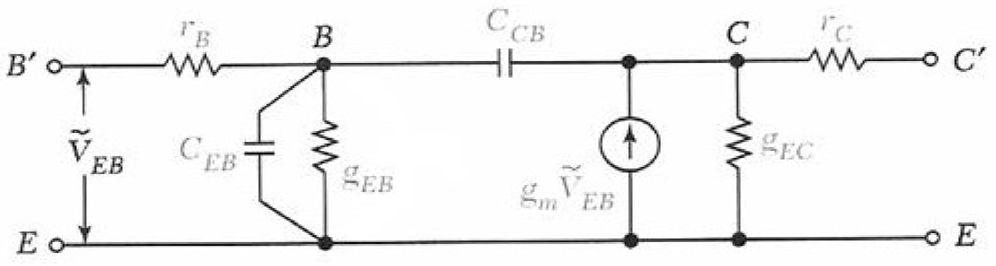


transistor man

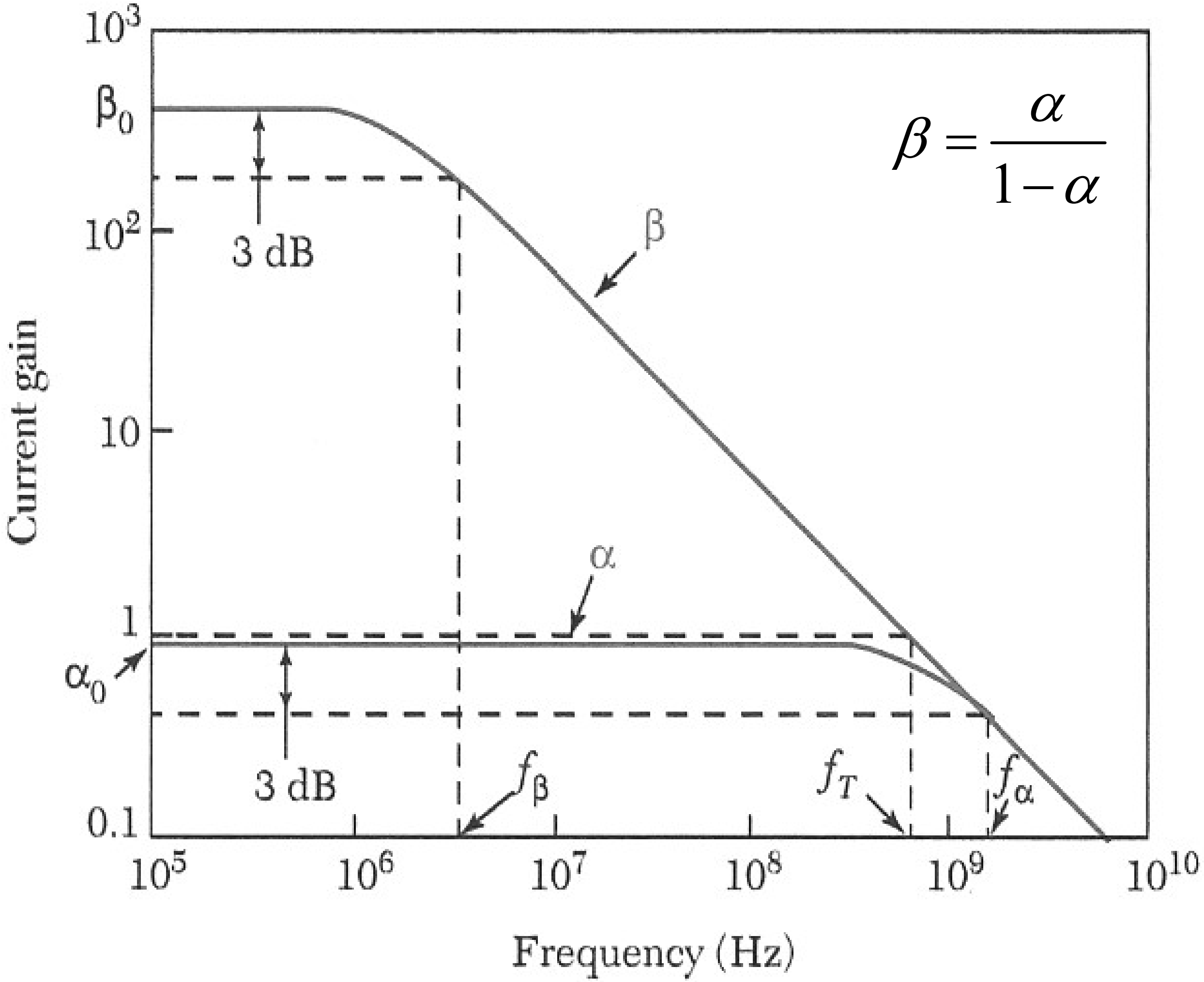
input conductance: $g_{EB} = \frac{\tilde{i}_B}{\tilde{v}_{EB}}$

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





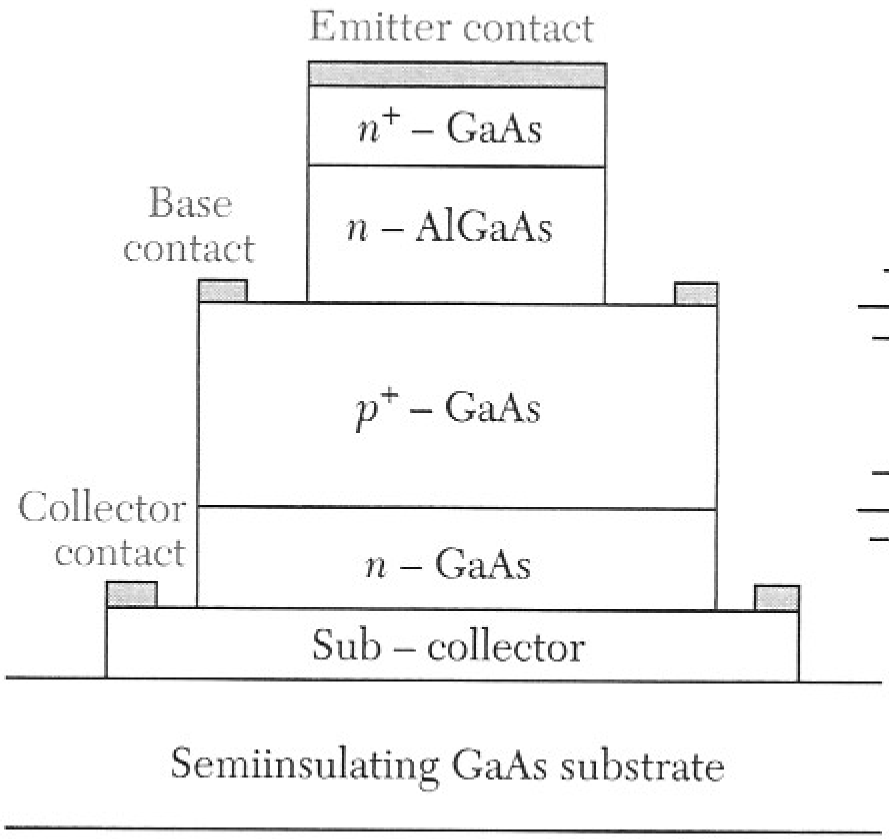
Small signal response

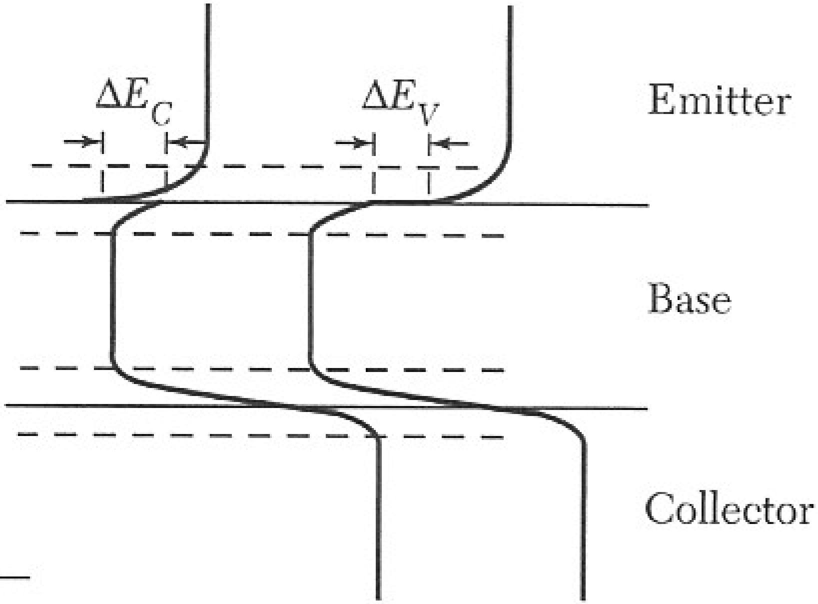


$$\beta = \frac{\alpha}{1-\alpha}$$

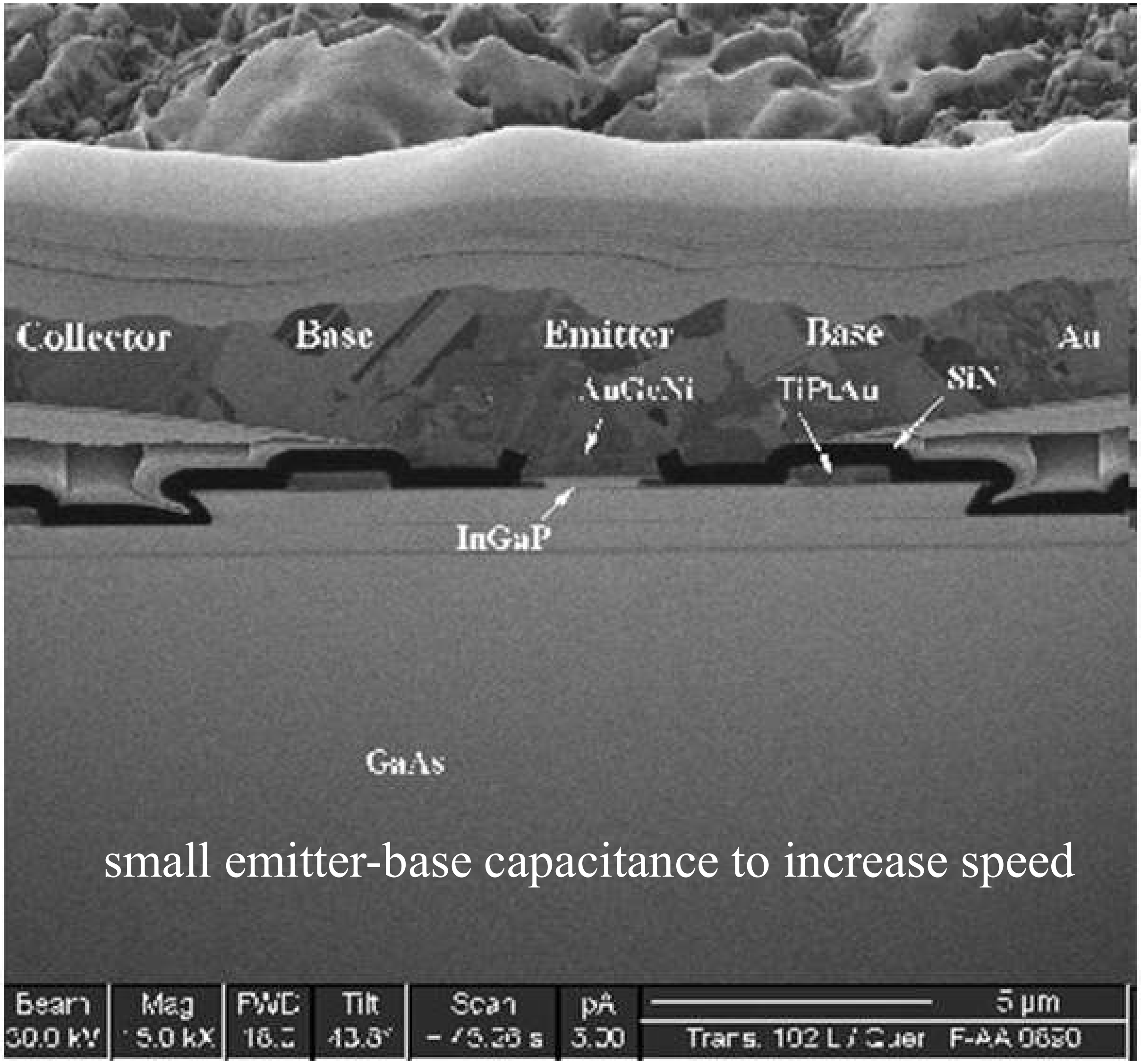
$$f_\beta = \left(1-\alpha_0\right) f_\alpha \qquad f_T = \alpha_0 f_\alpha$$

Heterojunction bipolar transistors





Heterojunction bipolar transistor



small emitter-base capacitance to increase speed

HBT current gain

$$I_C = \beta I_B$$

$$\beta = \frac{\alpha}{1-\alpha} \approx \frac{n_{B0}}{p_{E0}} \qquad \text{(npn)}$$

Higher doping in the emitter makes the minority carrier concentration lower in the emitter.

$$n_{B0} = \frac{n_i^2}{N_A} = \frac{N_C N_V \exp(-E_{gB}/k_B T)}{N_A}$$

$$p_{E0} = \frac{n_i^2}{N_D} = \frac{N'_C N'_V \exp(-E_{gE}/k_B T)}{N_D}$$

If the emitter and the base have different band gaps

$$\beta = \frac{N_E}{N_B} \frac{N_c N_v}{N'_c N'_v} \exp\left(\frac{\Delta E_g}{k_B T}\right) \sim 100000$$

HBT current gain

A HBT has an emitter bandgap of 1.62 and a base bandgap of 1.42.
A BJT has an emitter bandgap of 1.42 and a base bandgap of 1.42.
Both have an emitter doping of 10^{18} cm^{-3} and a base doping of 10^{15}cm^{-3}.
How much larger is the gain in the HBT?

$$\frac{\beta(\mathrm{HBT})}{\beta(\mathrm{BJT})} = \exp\left(\frac{\Delta E_g}{k_B T}\right) = \exp\left(\frac{1.62 - 1.42}{0.0259}\right) = 2257$$

Heavy doping narrows the bandgap so if in a normal transistor the bandgap is smaller in the emitter.

HBT

Trade off gain for higher speed

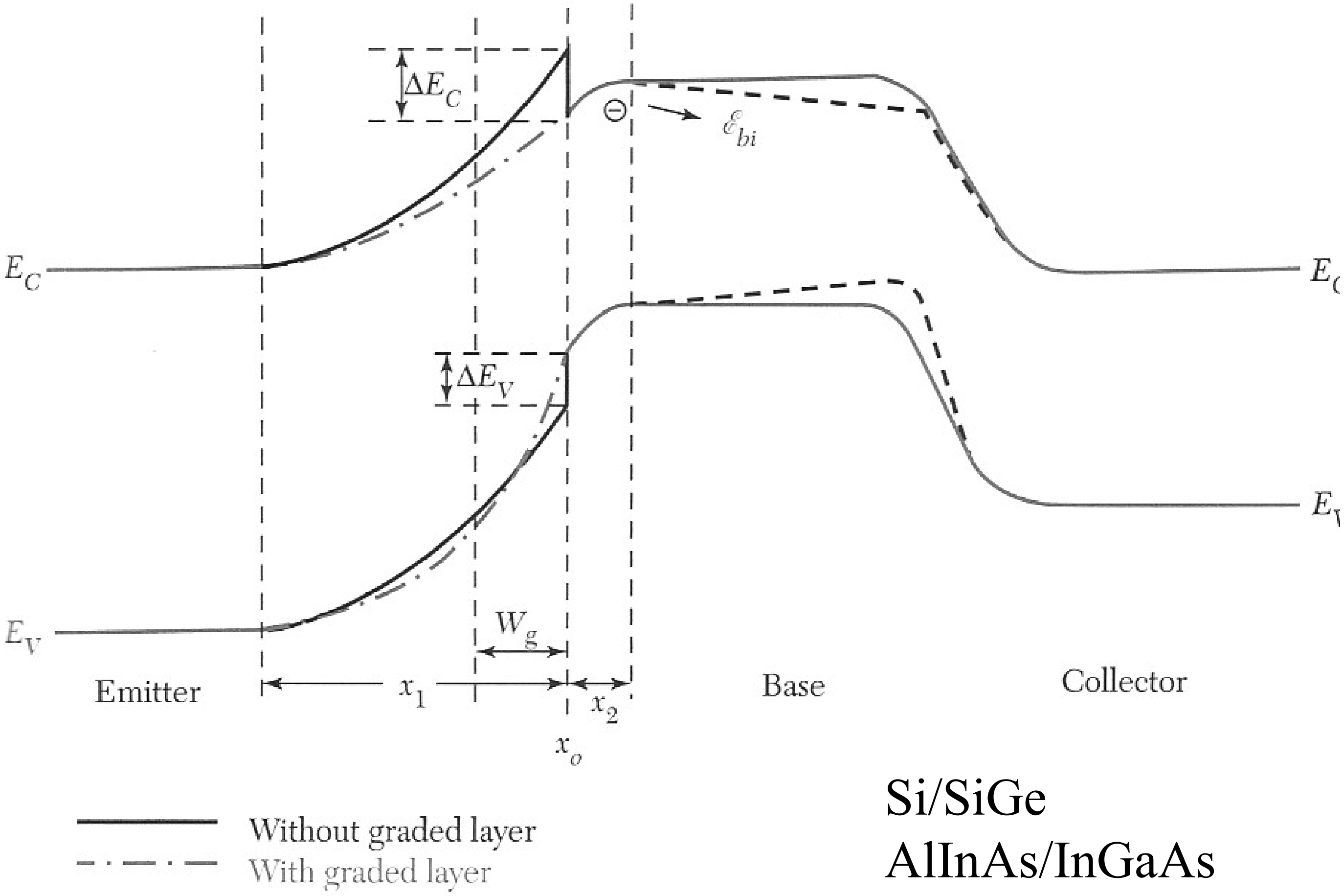
Higher base doping

- lower base resistance
- reduced Early effect
- less trouble with punch through
- base can be made thinner -> faster transistors

Because of higher base doping, a higher collector doping is possible without punch through

- lower collector resistance

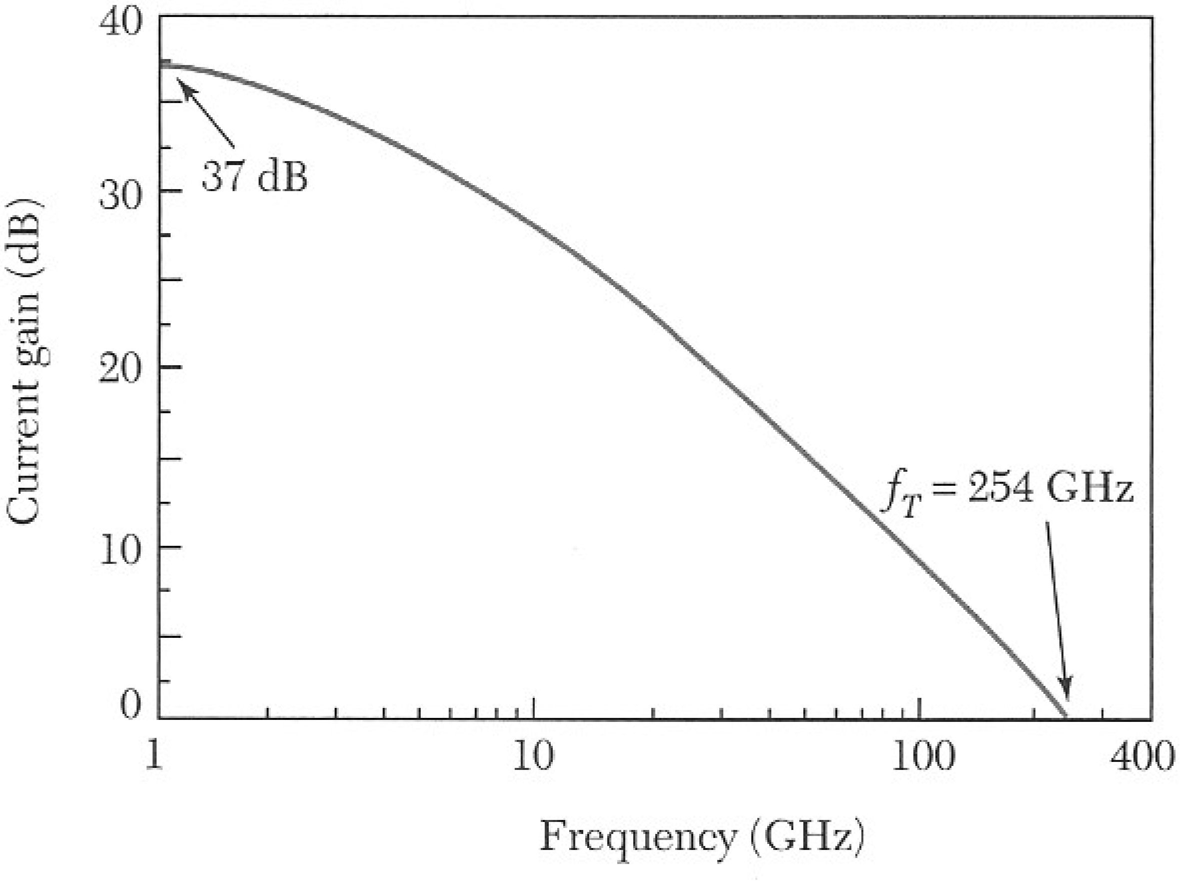
HBT current gain



Si/SiGe
AlInAs/InGaAs

band discontinuity reduces emitter efficiency
Graded layer emitter and base improve performance

Heterojunction bipolar transistors



Fastest InP/InGaAs HBT's have an f_T of 710 GHz.

Higher doping in the base allows for a thinner base without punch through and lower base resistance and thus higher frequency operation

Microwave engineering

Electronics: $L << \lambda$ $f <\sim 10$ GHz

Microwave: $\lambda < L$ 10 GHz $< f <$ 1 THz

TeraHertz: $\lambda << L$ 1 THz $< f <$ 100 THz

Optics: $\lambda << L$ 100 THz