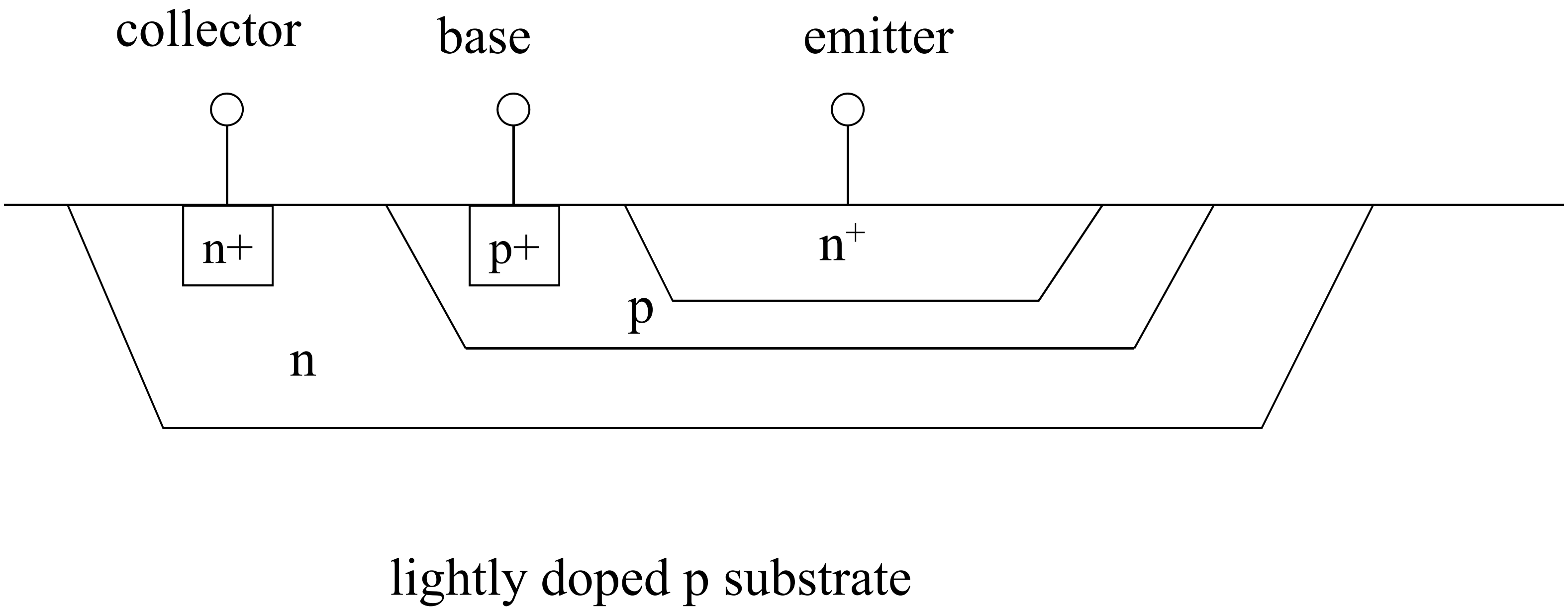
13. Bipolar transistors

Jan. 16, 2019

bipolar transistors

npn transistor



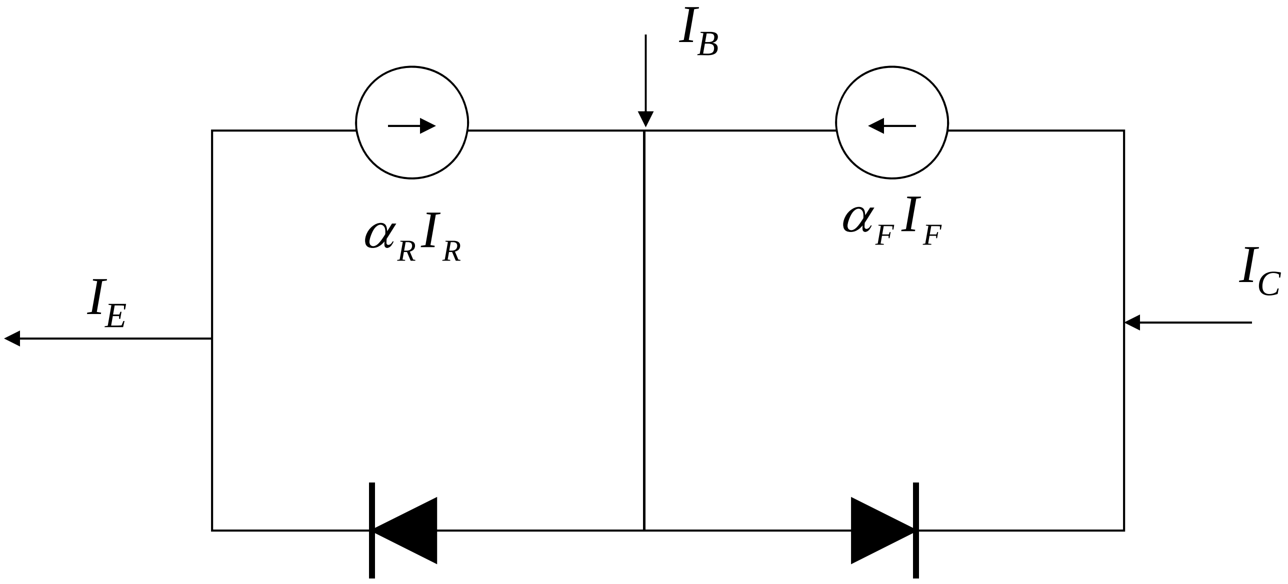
Used in front-end high-frequency receivers (mobile telephones), low input impedance amplifier.

Ebers-Moll model

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

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

$$I_B = I_E - I_C$$



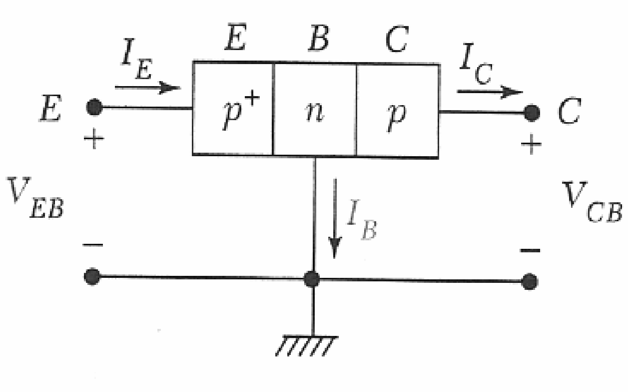
$$I_F = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) \qquad I_R = I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

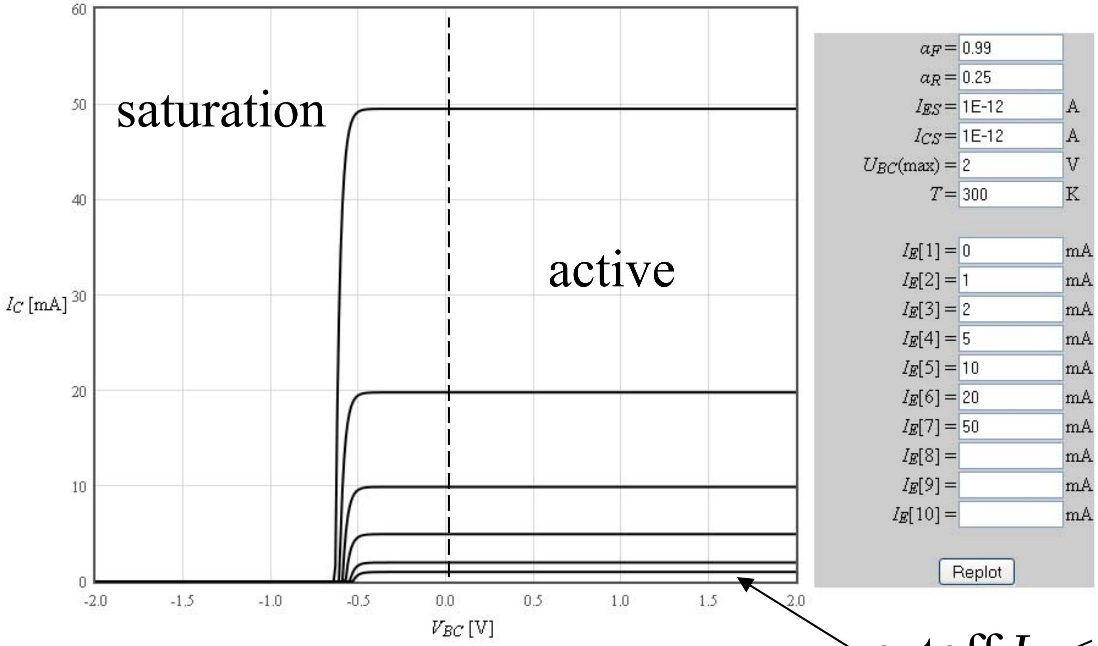
Common base configuration

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

solve for V_{be}

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





$\alpha_F =$ 0.99
$\alpha_R =$ 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

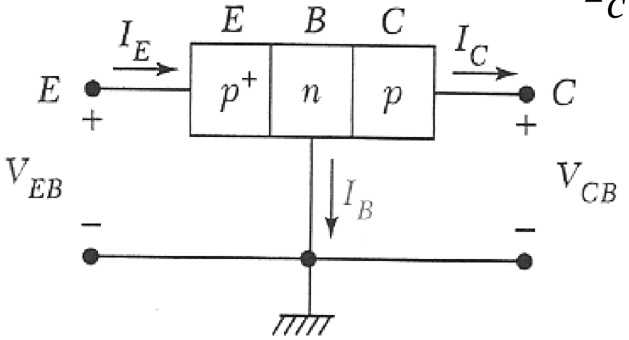
saturation

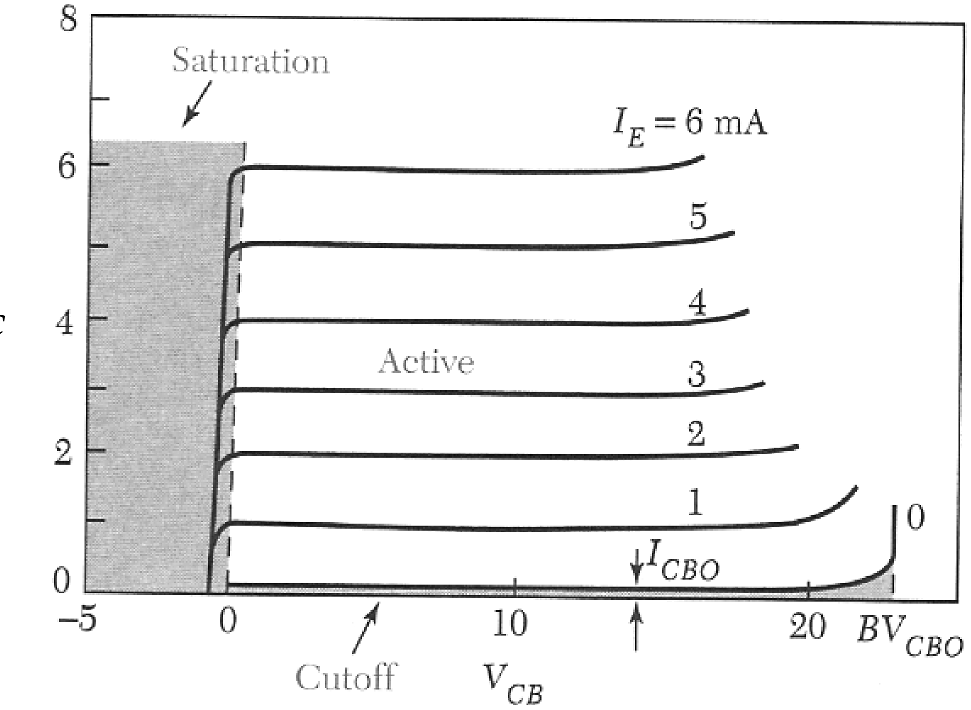
active

cutoff $I_E < 0$

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

Common base configuration





$I_C \sim I_E$ buffer circuit: the output current is constant over a wide range of output voltages

Ebers - Moll Model

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

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

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

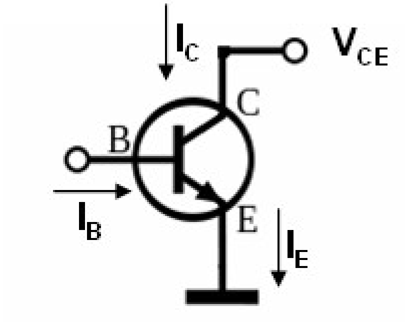
$$I_{CS} = \left[\frac{eA_{bc} D_p p_{c0}}{x_c - W_c} + \frac{eA_{bc} D_n n_{b0}}{W_{bc} - W_{be}} \right]$$

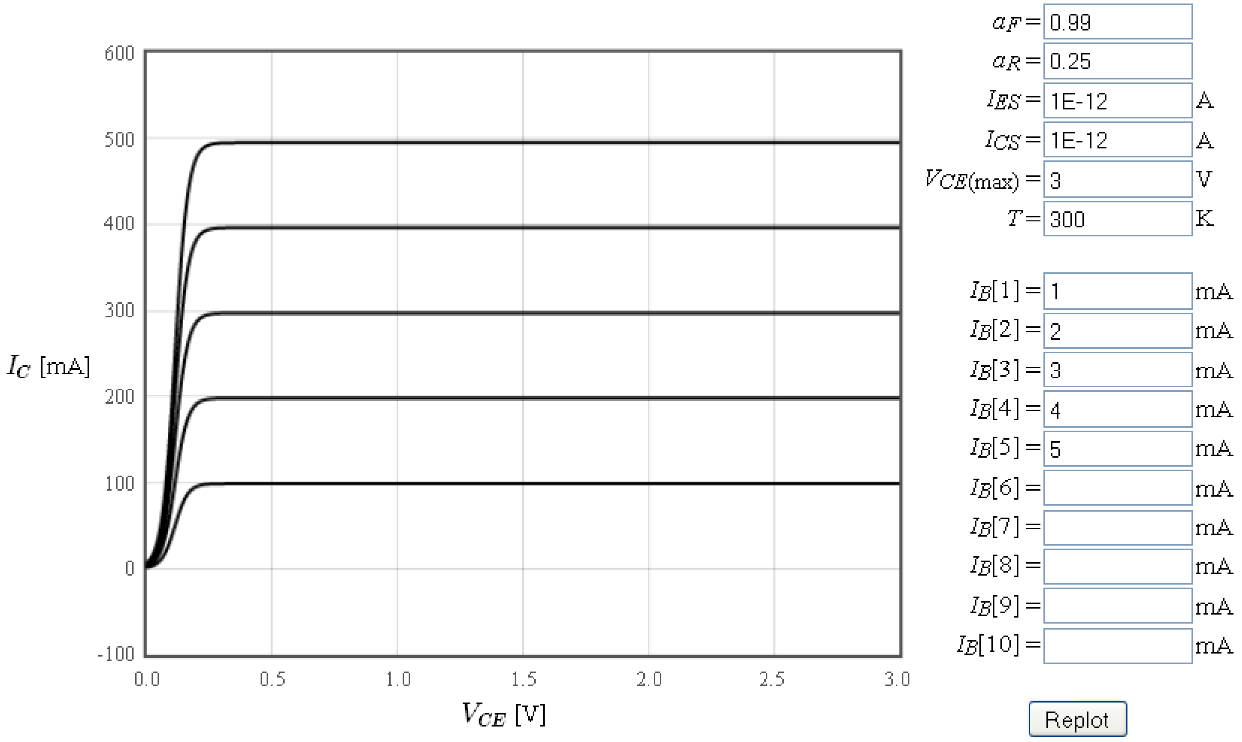
Common emitter configuration

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

$$I_B = I_E - I_C$$

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





$\alpha_F =$ 0.99

$\alpha_R =$ 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

Current amplification factor

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

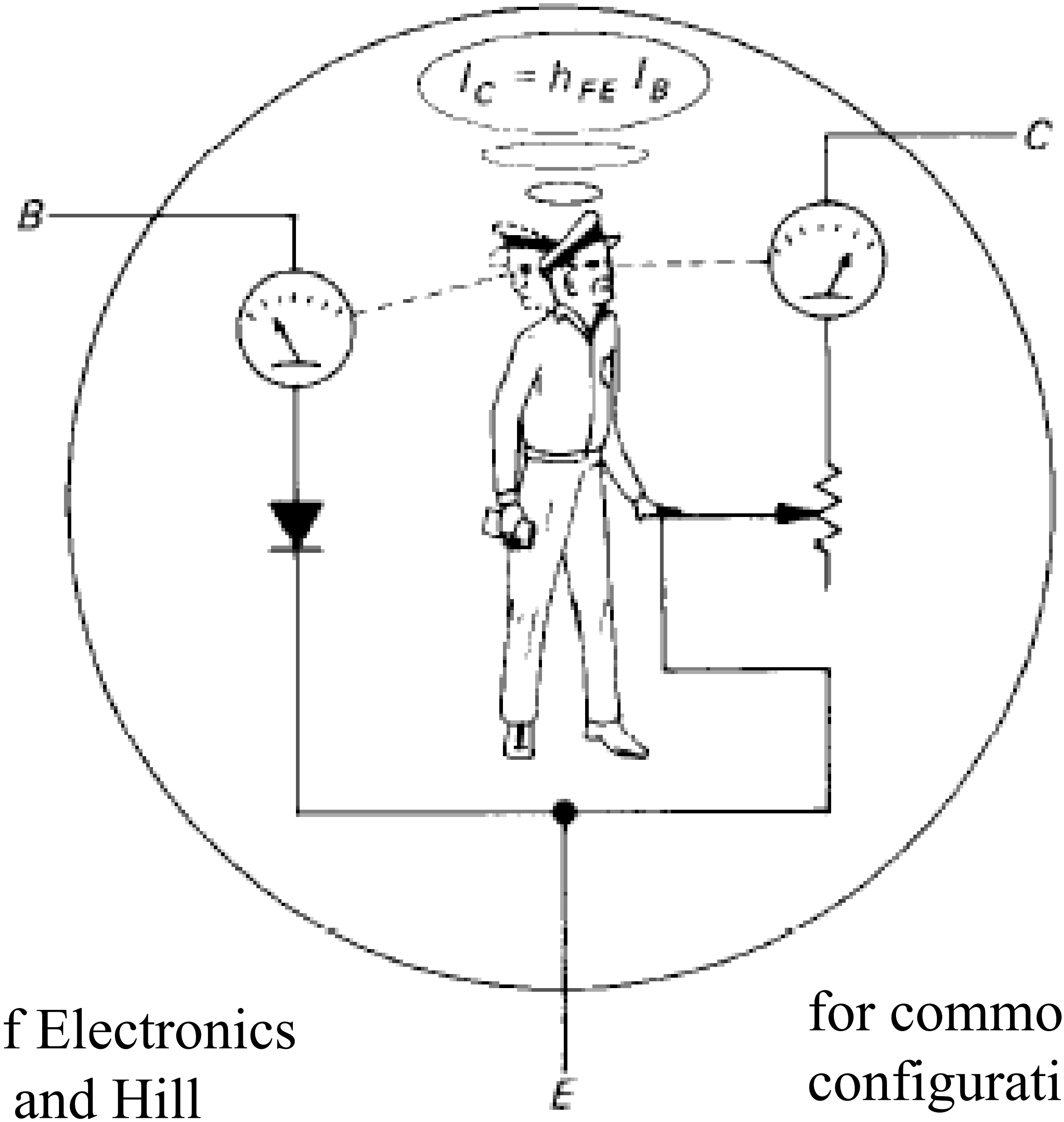
$$I_B = I_E - I_C$$

$$I_C = \alpha I_E$$

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

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

$\beta \sim 50$ - 500



The Art of Electronics
Horowitz and Hill

for common emitter
configuration

“Transistor man”

Transconductance

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

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

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:

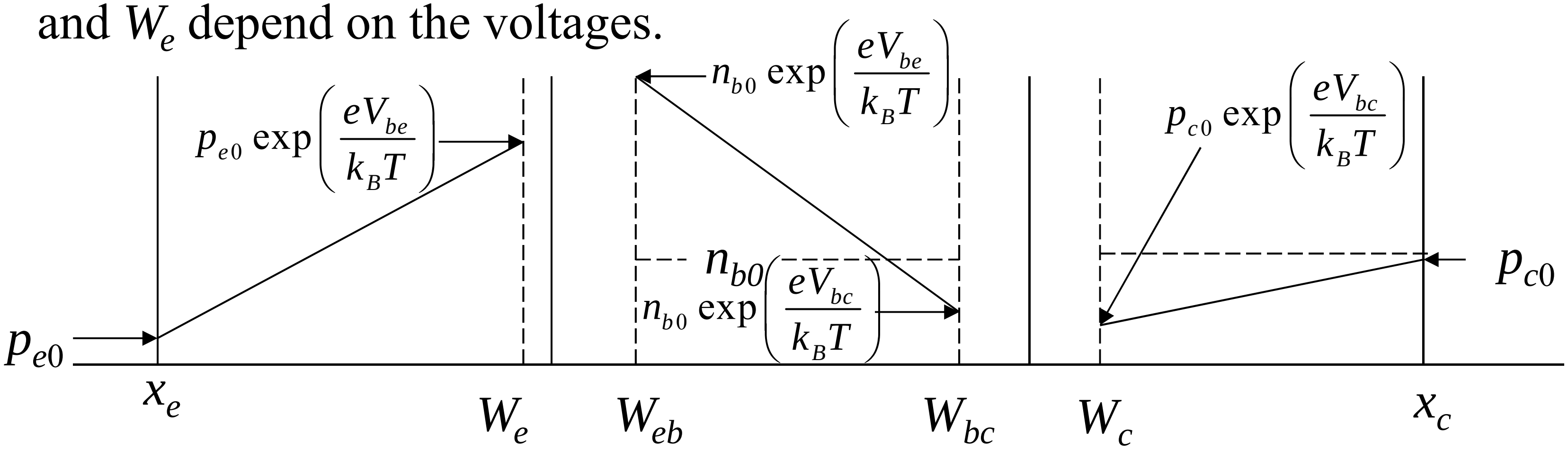
$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

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

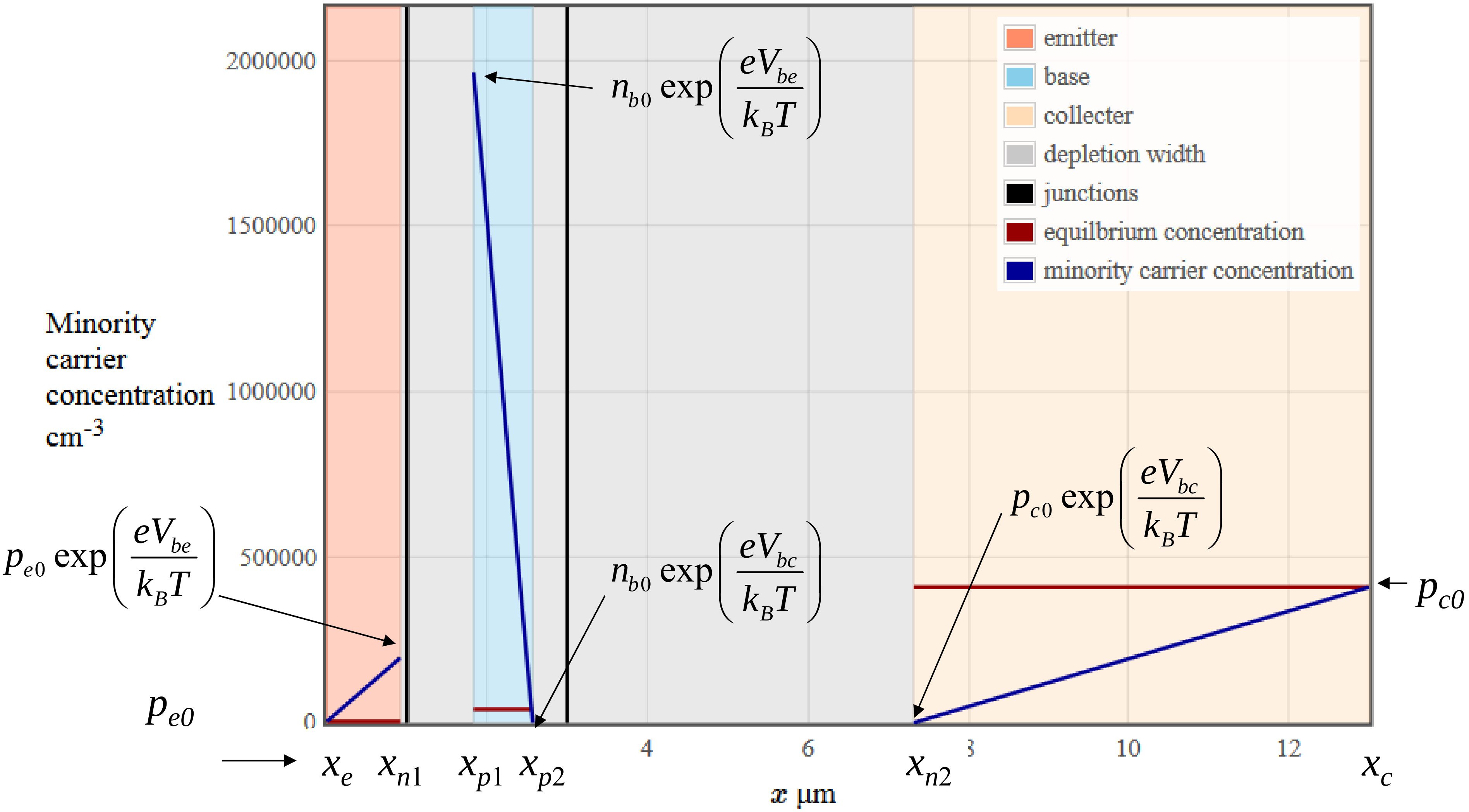
$$I_B = I_E - I_C$$

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

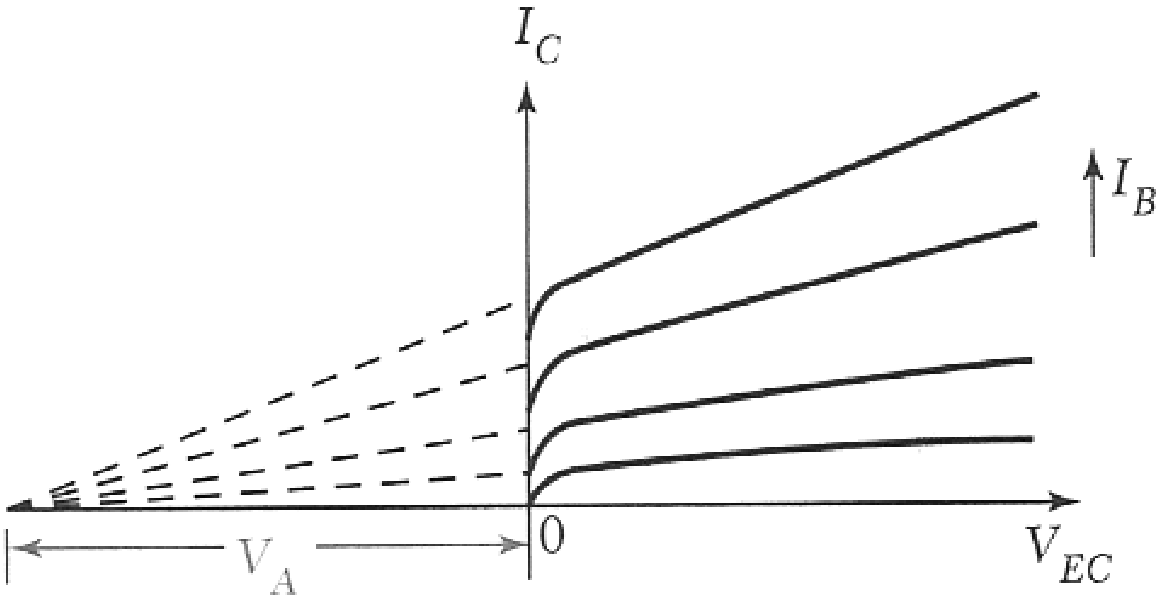
I_{ES} and I_{CS} are treated as constants but the depletion widths W_{bc}, W_{be}, W_c, and W_e depend on the voltages.



Minority carrier concentration



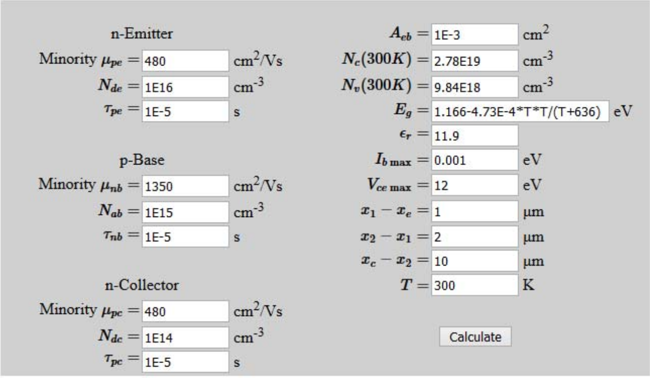
Early effect



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



n-Emitter

Minority μ_{pe} = 480 cm^2/Vs

N_{de} = 1E16 cm^{-3}

τ_{pe} = 1E-5 s

p-Base

Minority μ_{nb} = 1350 cm^2/Vs

N_{ab} = 1E15 cm^{-3}

τ_{nb} = 1E-5 s

n-Collector

Minority μ_{pc} = 480 cm^2/Vs

N_{dc} = 1E14 cm^{-3}

τ_{pc} = 1E-5 s

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

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

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

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

ϵ_r = 11.9

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

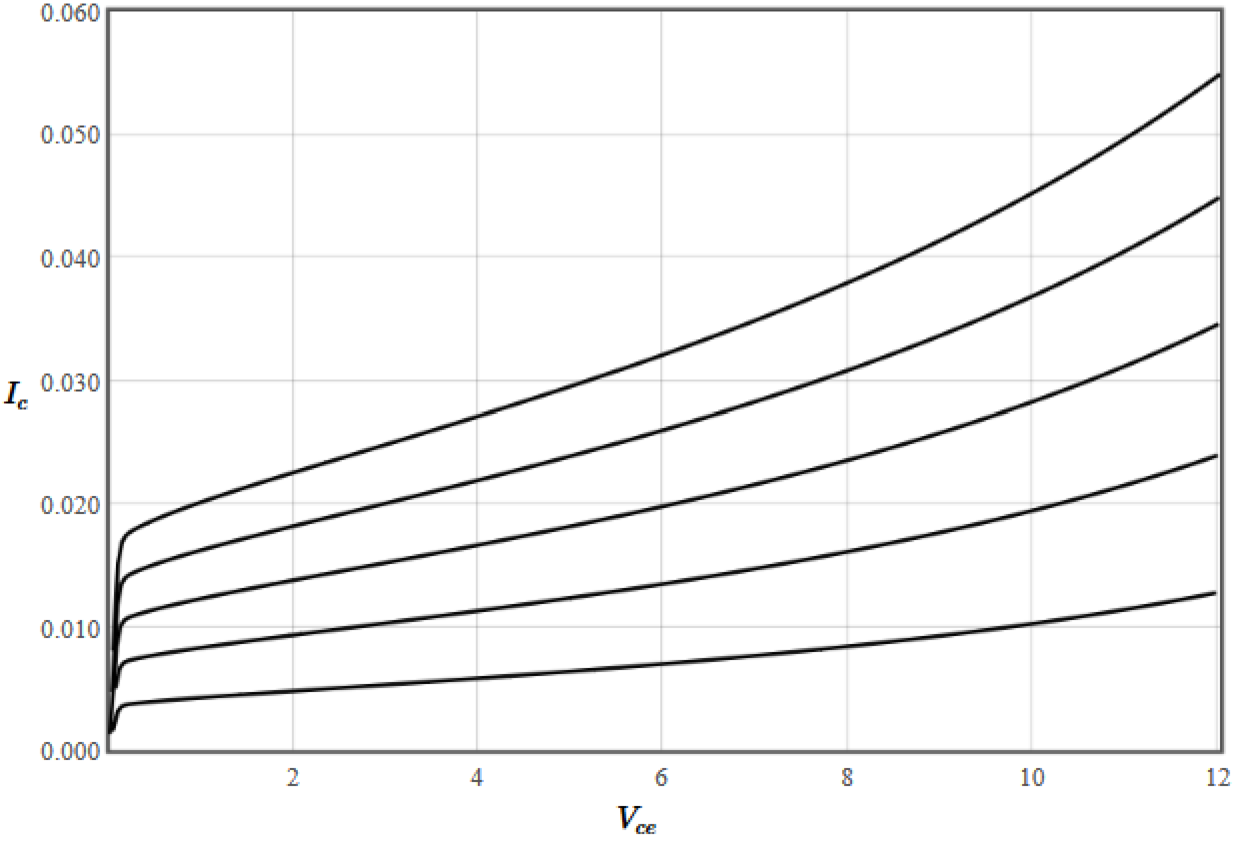
$V_{ce\,\max}$ = 12 eV

$x_1 - x_e$ = 1 µm

$x_2 - x_1$ = 2 µm

$x_c - x_2$ = 10 µm

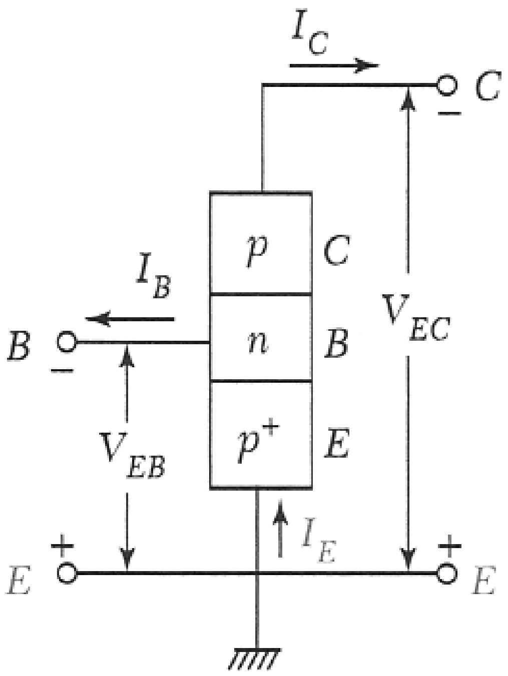
T = 300 K

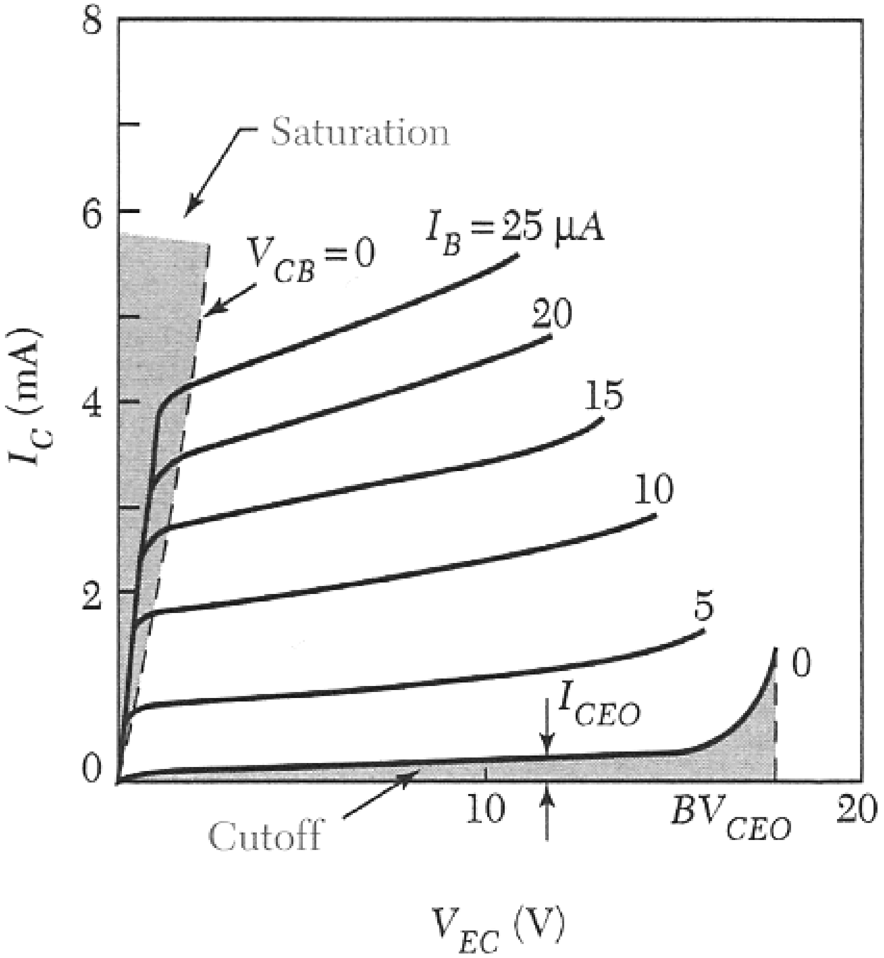


$$I_C \sim \beta I_B$$

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

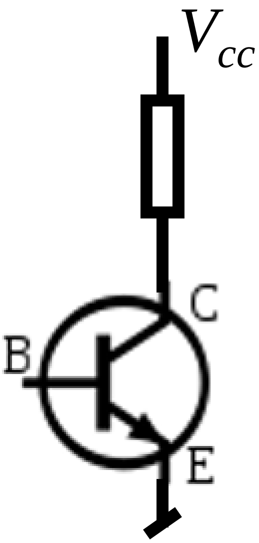
Common emitter configuration

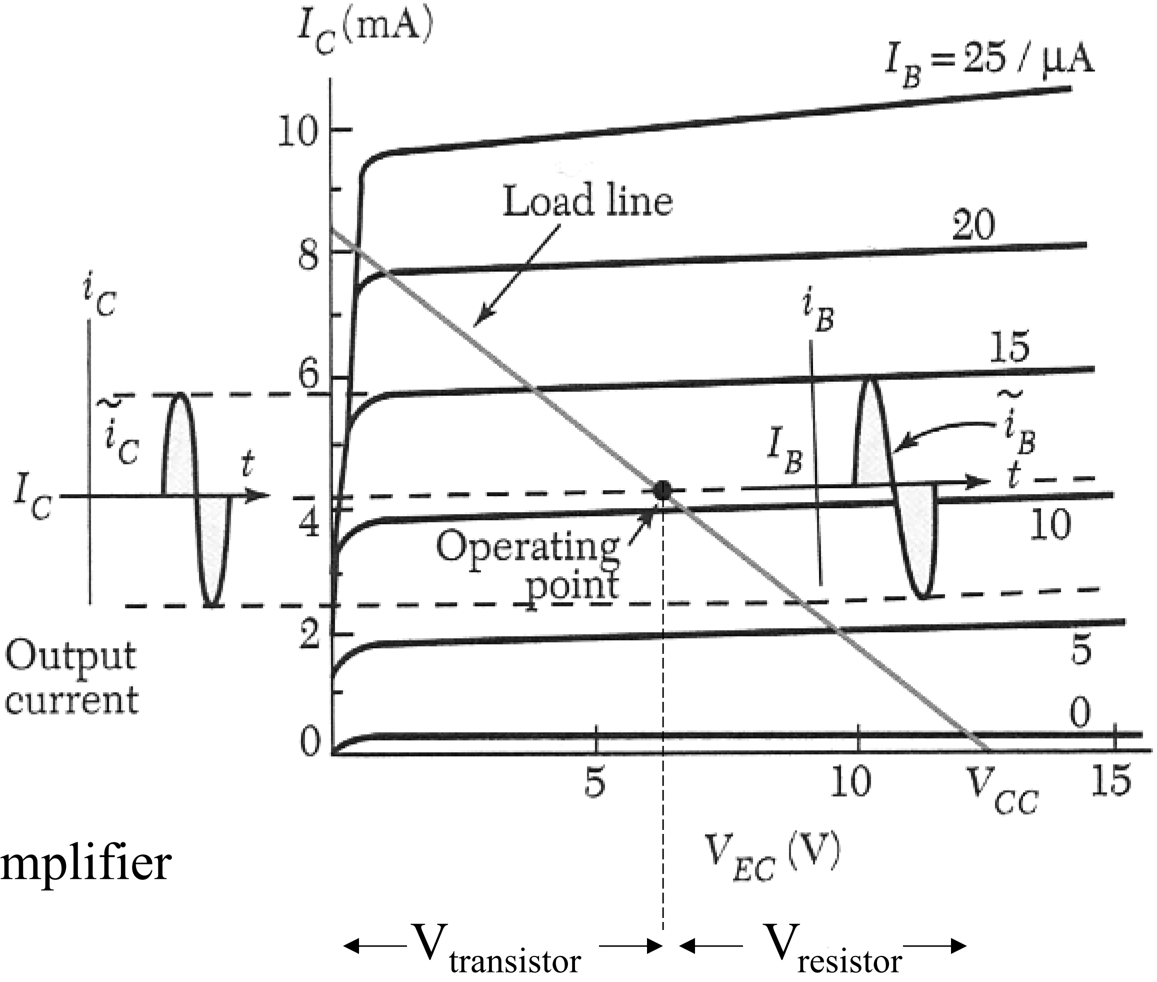




$I_C \sim \beta I_B$ amplifier

Small signal response

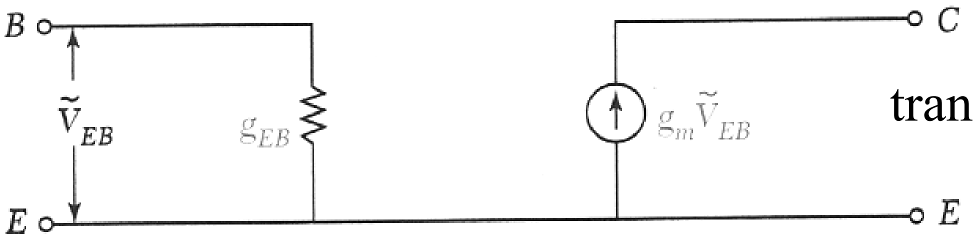




Low input impedance amplifier

Small signal response

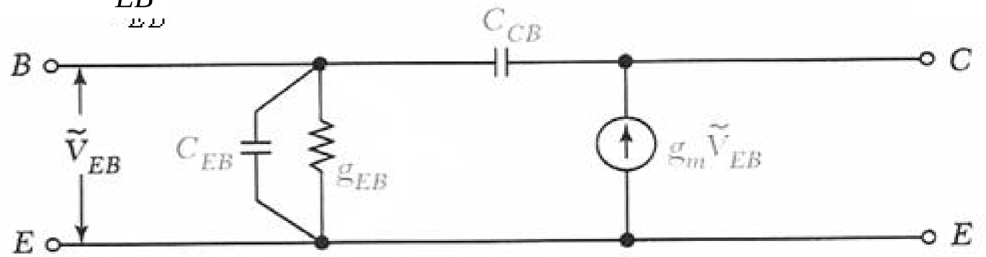
$$\tilde{i}_c = \beta \tilde{i}_B = \beta g_{EB} \tilde{v}_{EB}$$

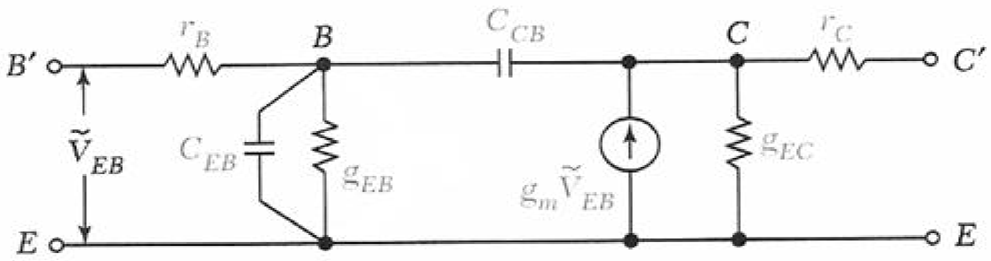


transistor man

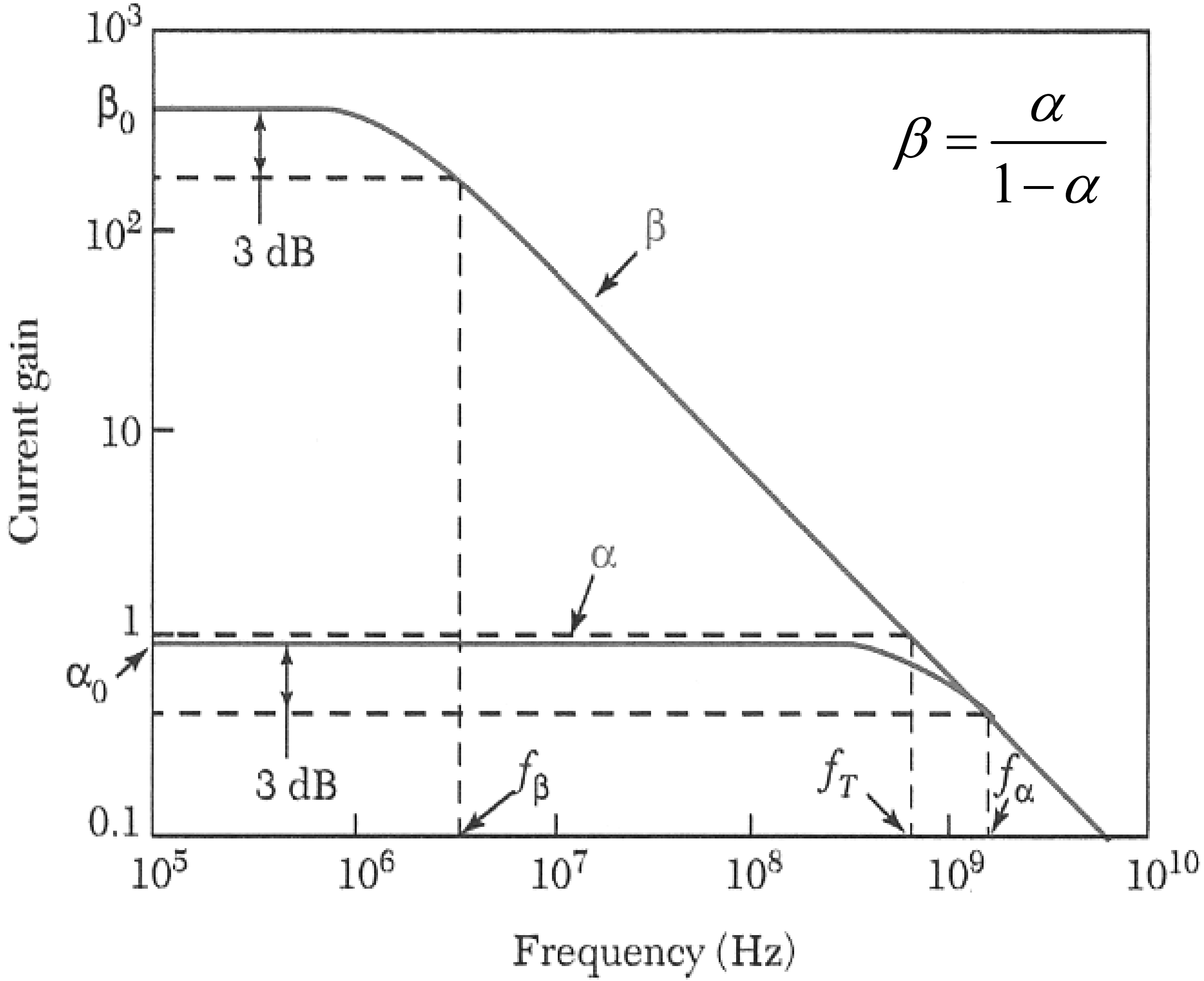
input conductance: $g_{EB} = \dfrac{\tilde{i}_B}{\tilde{v}_{EB}}$

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





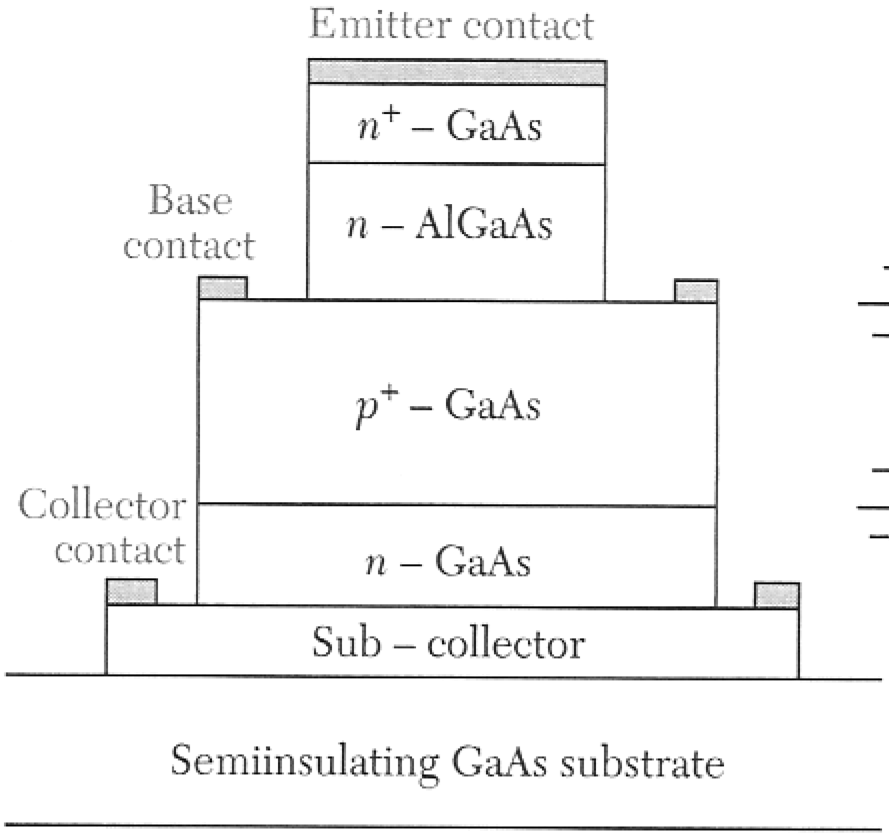
Small signal response

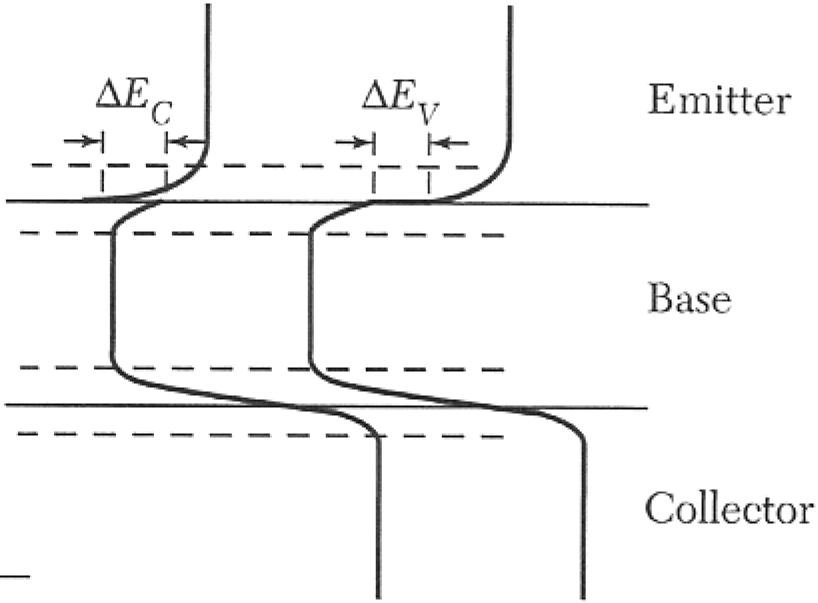


$$\beta = \frac{\alpha}{1-\alpha}$$

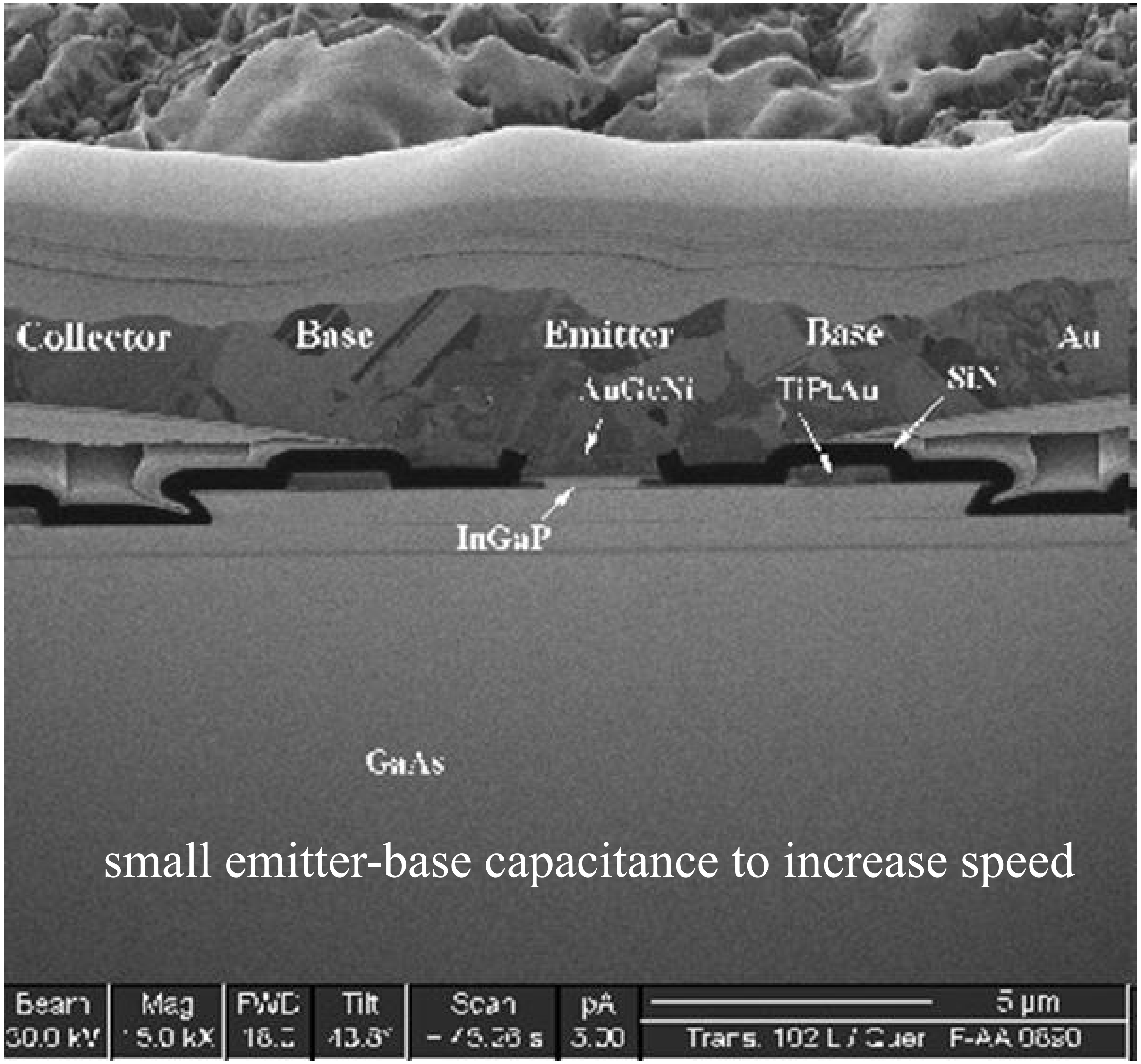
$$f_\beta = (1-\alpha_0)\, f_\alpha \qquad f_T = \alpha_0 f_\alpha$$

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?

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

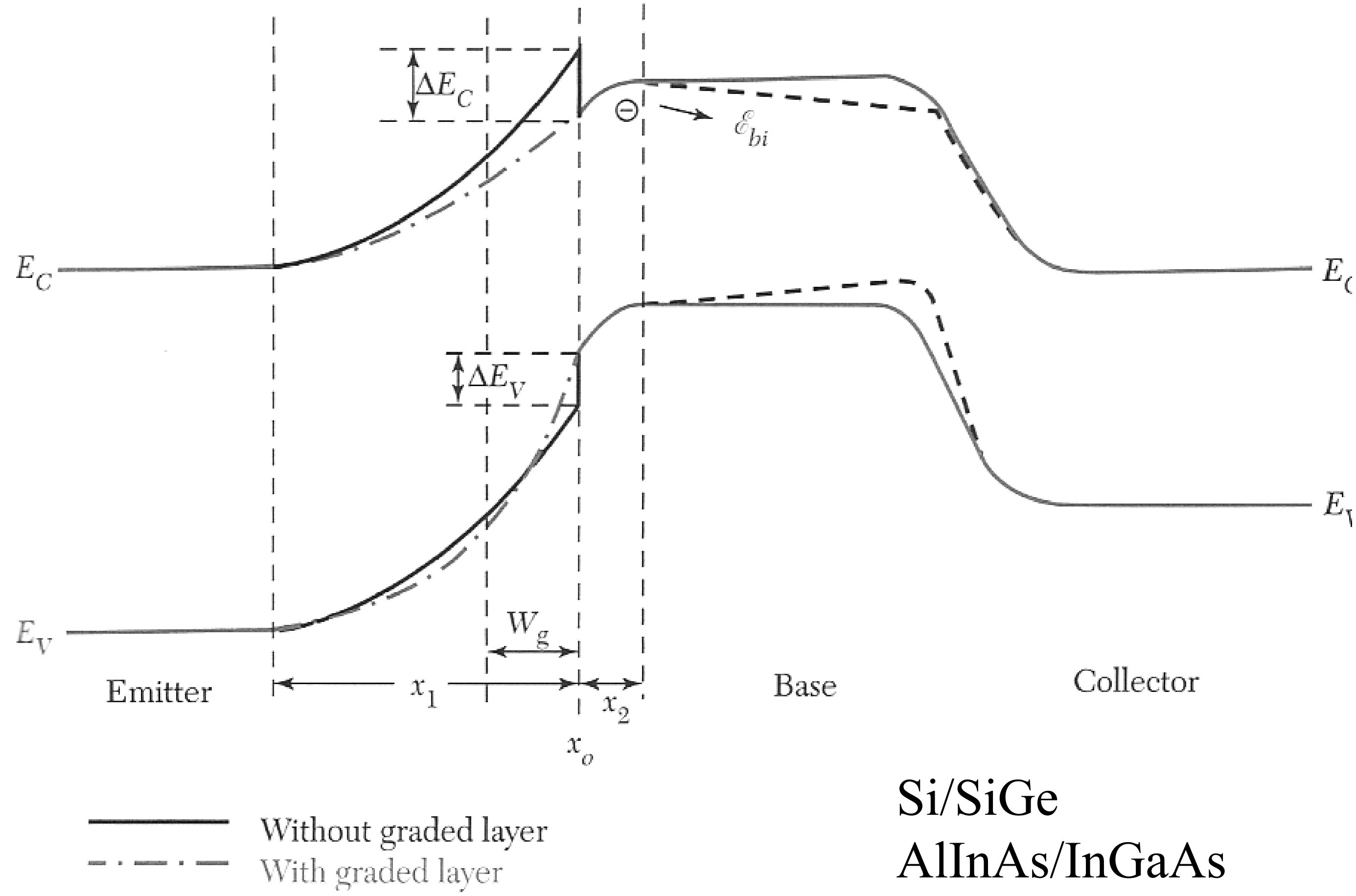
HBT

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

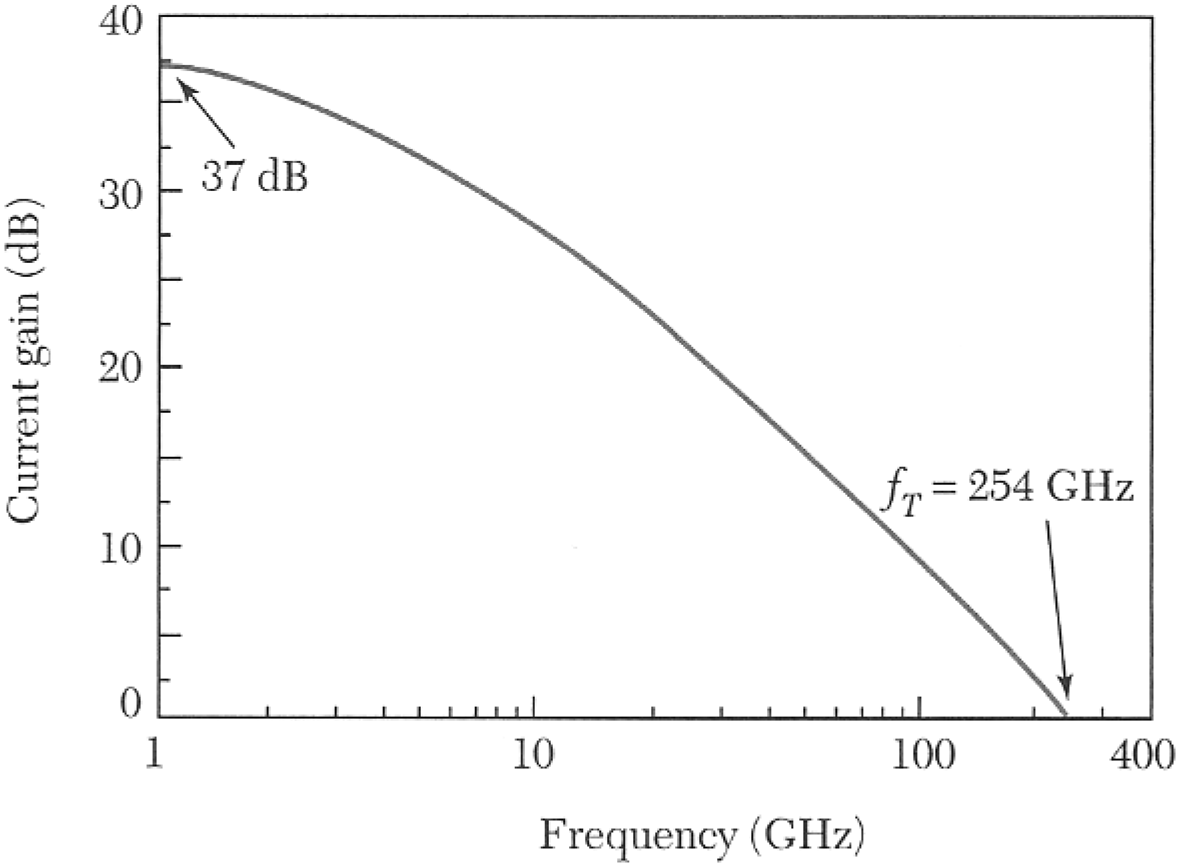
HBT current gain



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

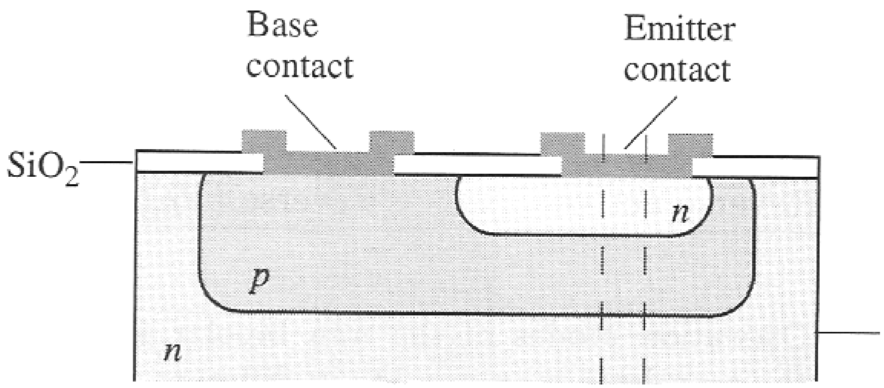
Electronics: $L << \lambda$ $f <\sim 10$ GHz

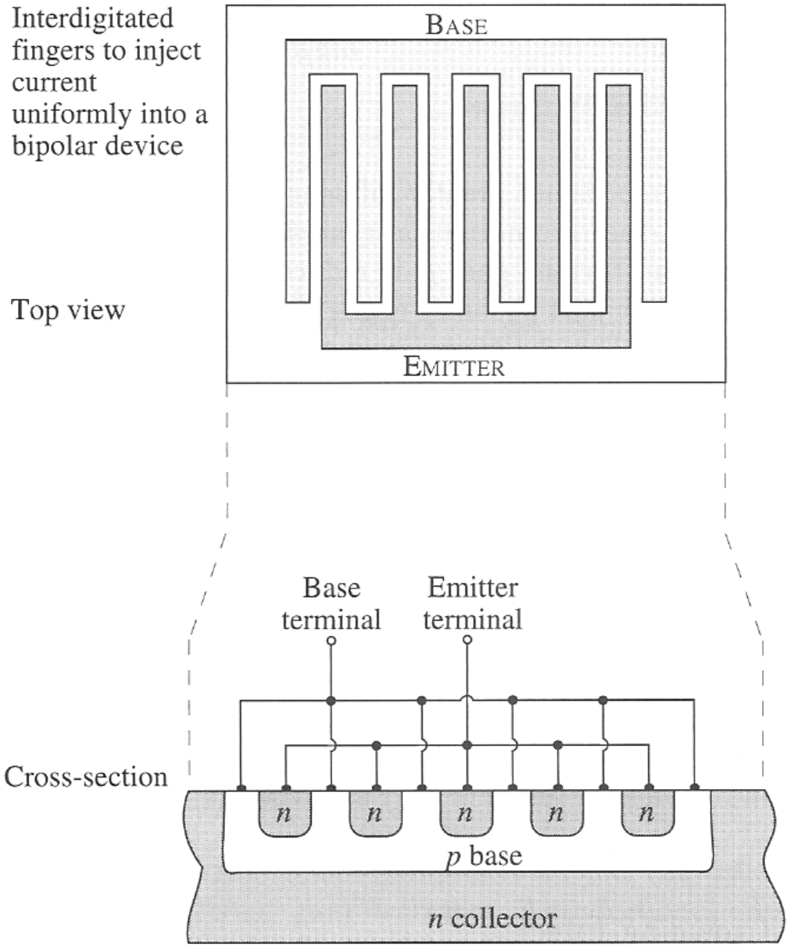
Microwave: $\lambda < L$ $10\text{ GHz} < f < 1\text{ THz}$

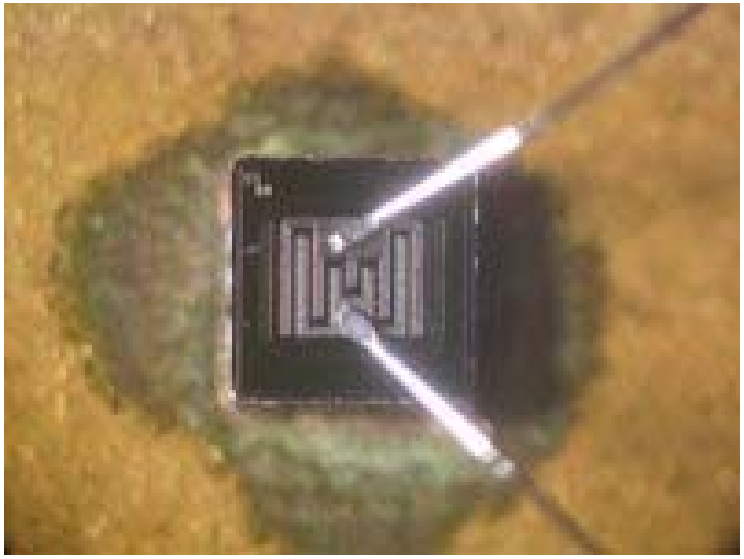
TeraHertz: $\lambda << L$ $1\text{ THz} < f < 100\text{ THz}$

Optics: $\lambda << L$ 100 THz

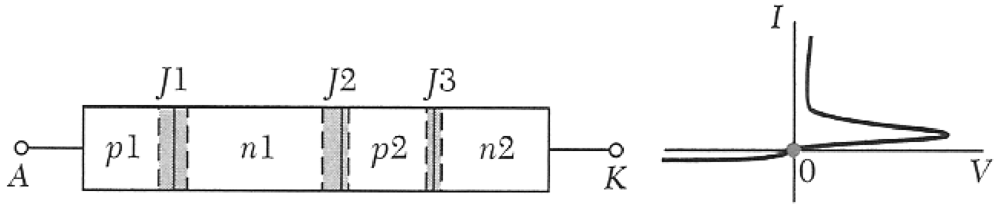
Interdigitated contacts in power transistors



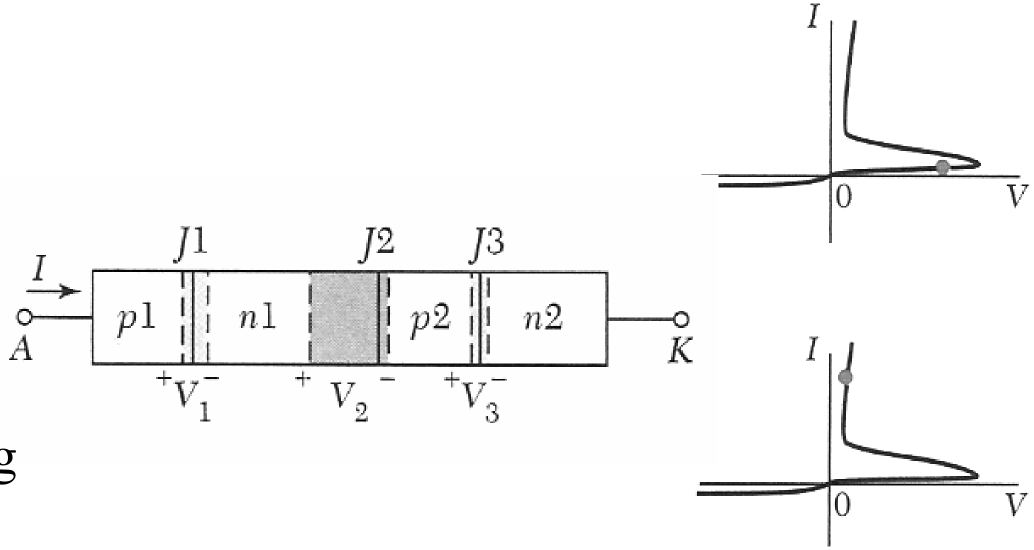

Interdigitated fingers to inject current uniformly into a bipolar device



Thyristors

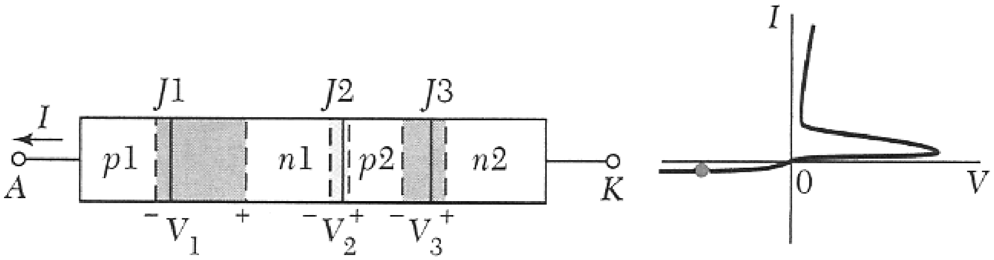


Forward blocking

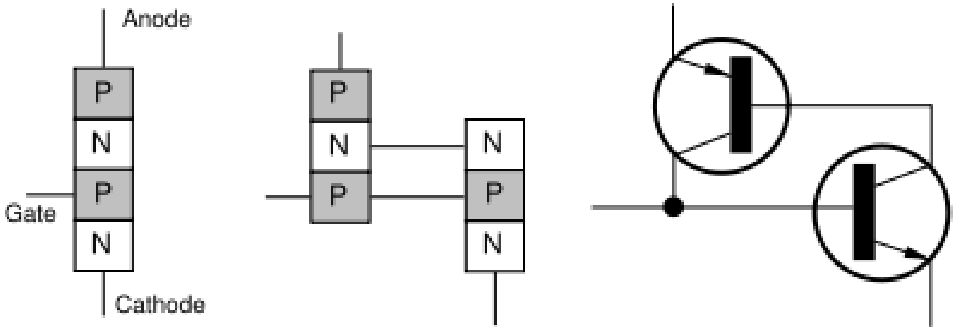


Forward conducting

Reverse blocking



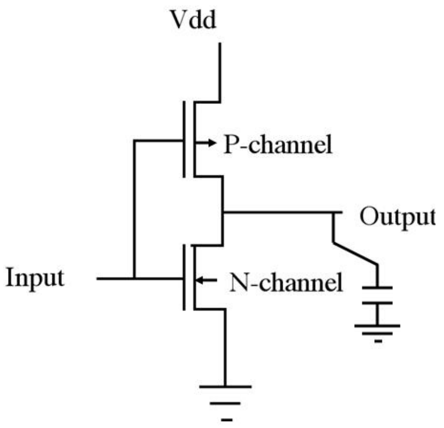
Thyristors

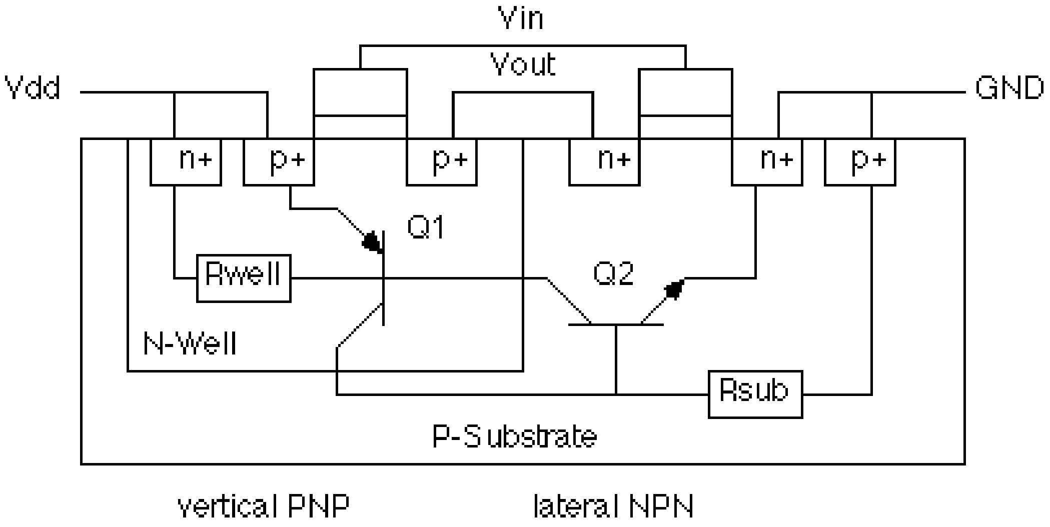


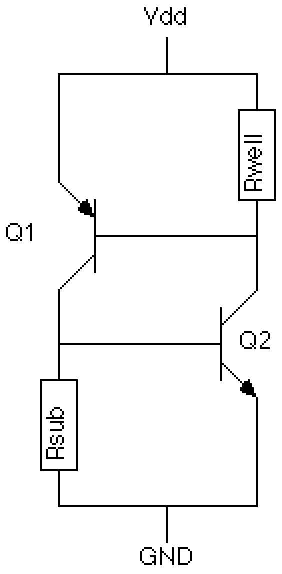
$\beta_1 * \beta_2 > 1$

Used for switching high currents or voltages

Latch-up



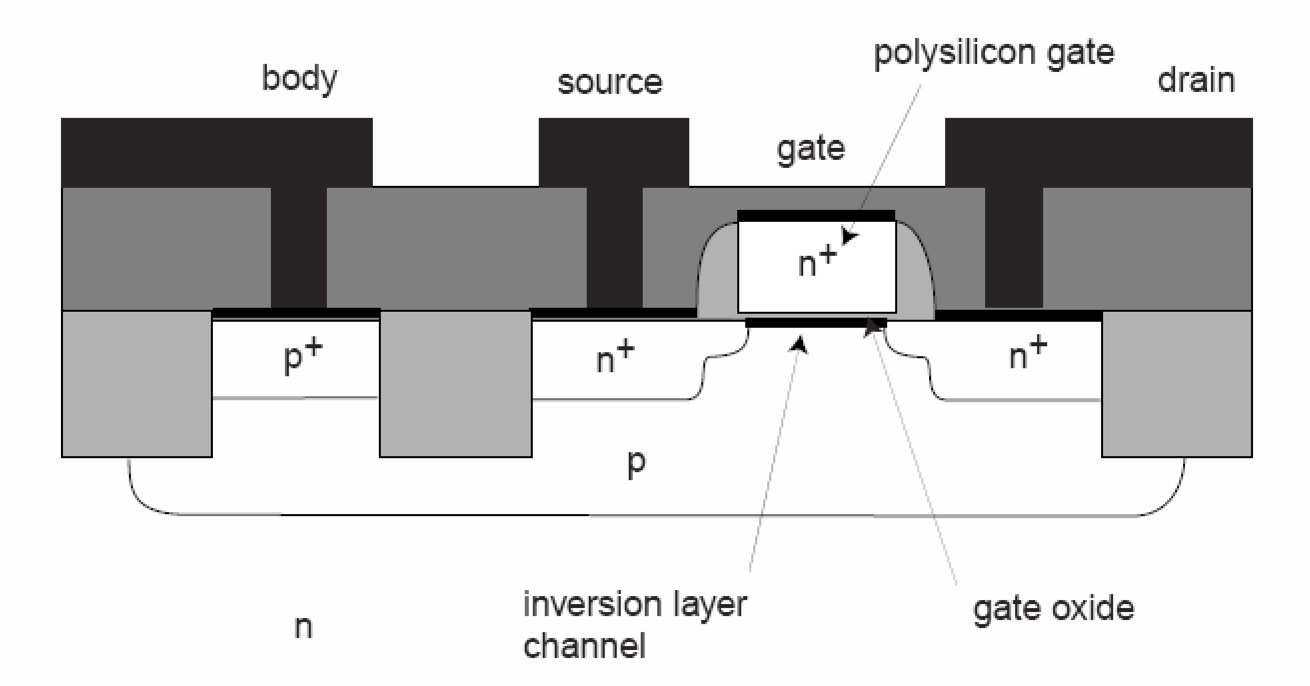




Both BJT's conduct, creating a low resistance path between V_{dd} and GND. The product of the gains of the two transistors in the feedback loop, is greater than one. The result of latchup is at the minimum a circuit malfunction, and in the worst case, the destruction of the device.

http://www.ece.drexel.edu/courses/ECE-E431/latch-up/latch-up.html

Subthreshold current



If the p-concentration in the channel is low, electrons emitted into the channel by the forward biased junction diffuse across the channel without recombining.