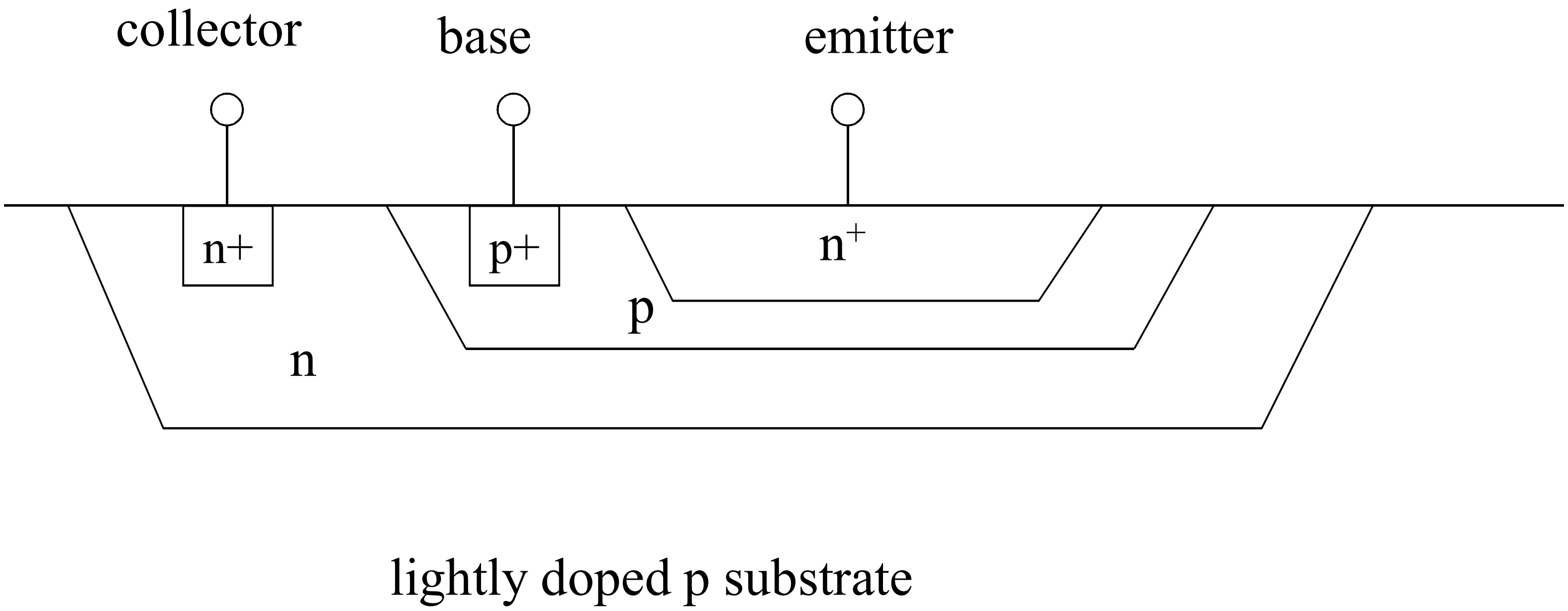
Bipolar transistors

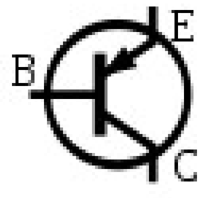
bipolar transistors

npn transistor

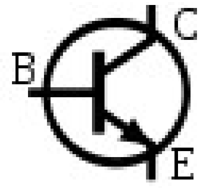


Used in front-end high-frequency receivers (mobile telephones).

bipolar transistors



PNP



NPN

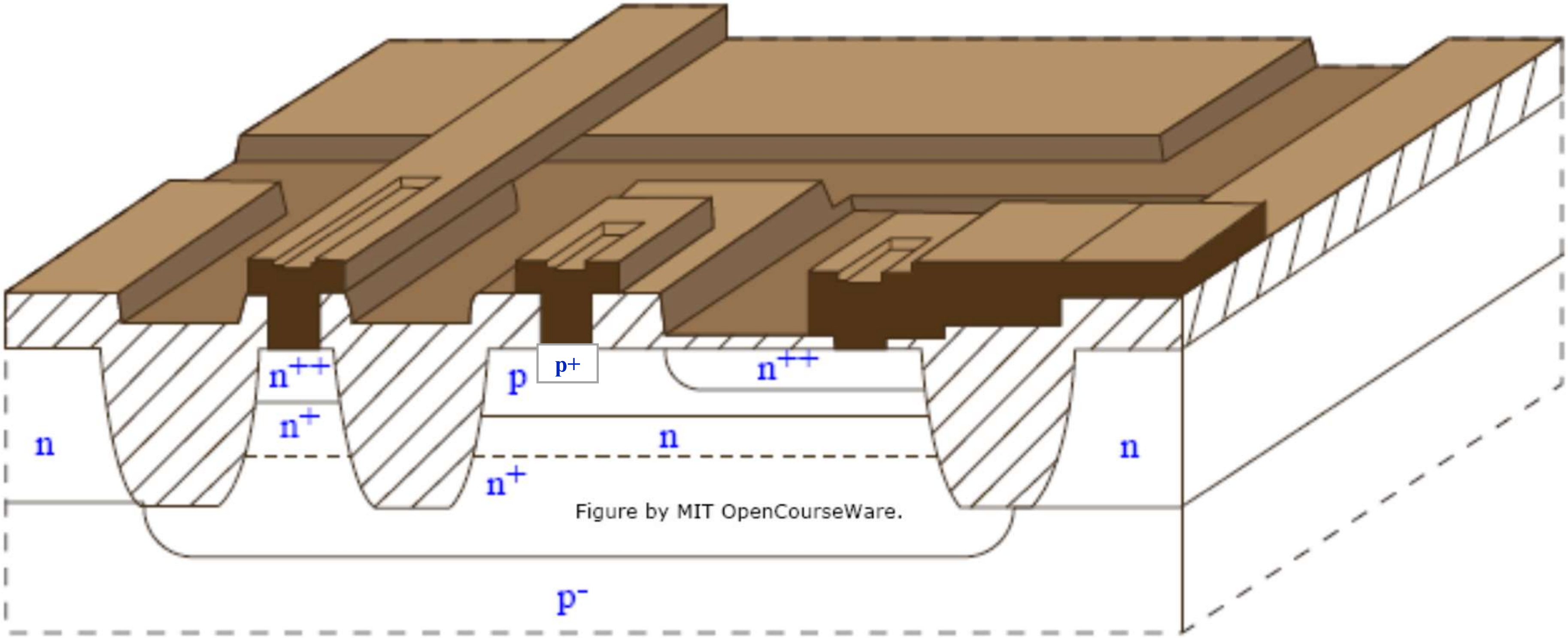
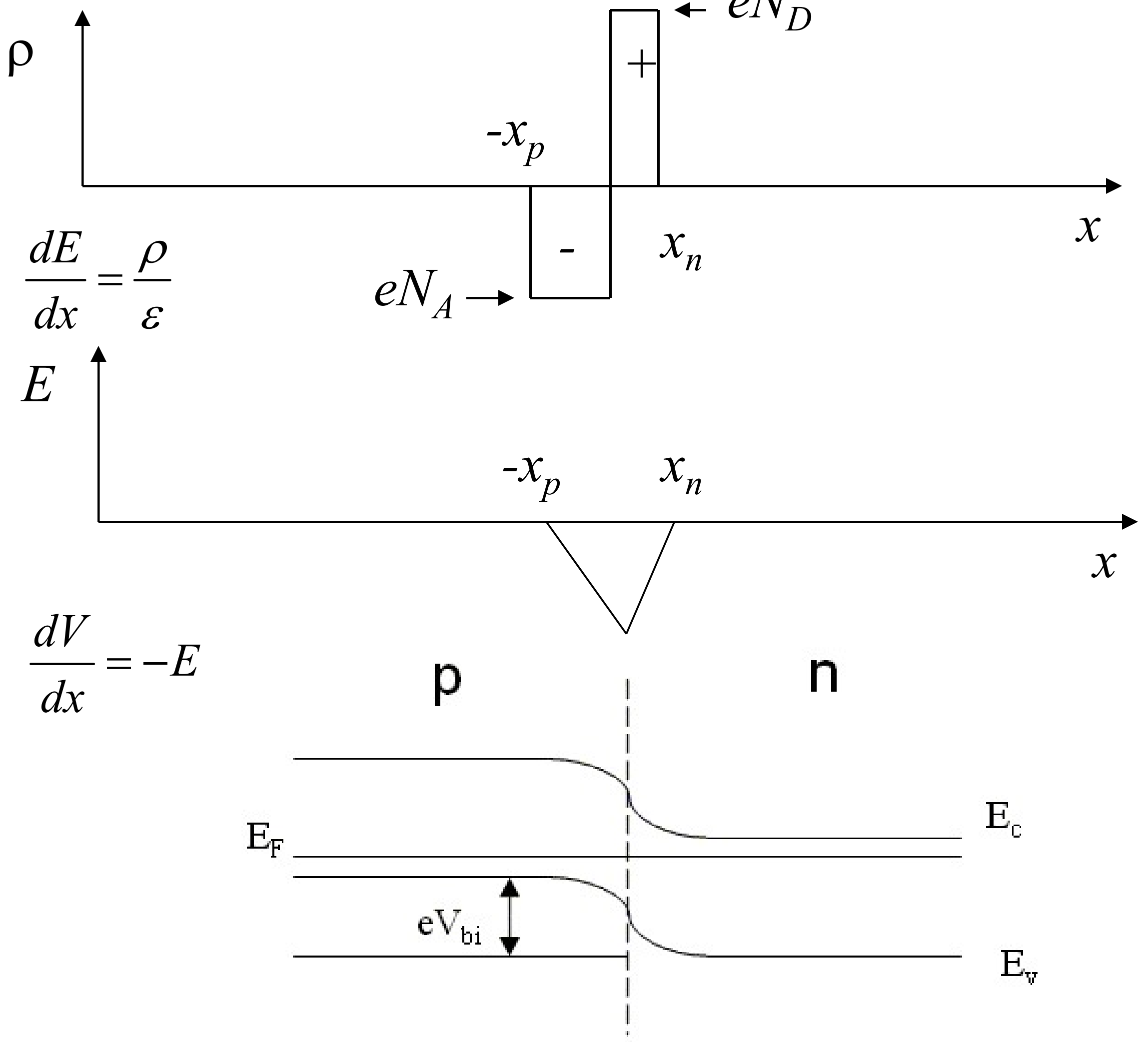


Figure by MIT OpenCourseWare.

Oxide isolated integrated BJT - a modern process

abrupt junction



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

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

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

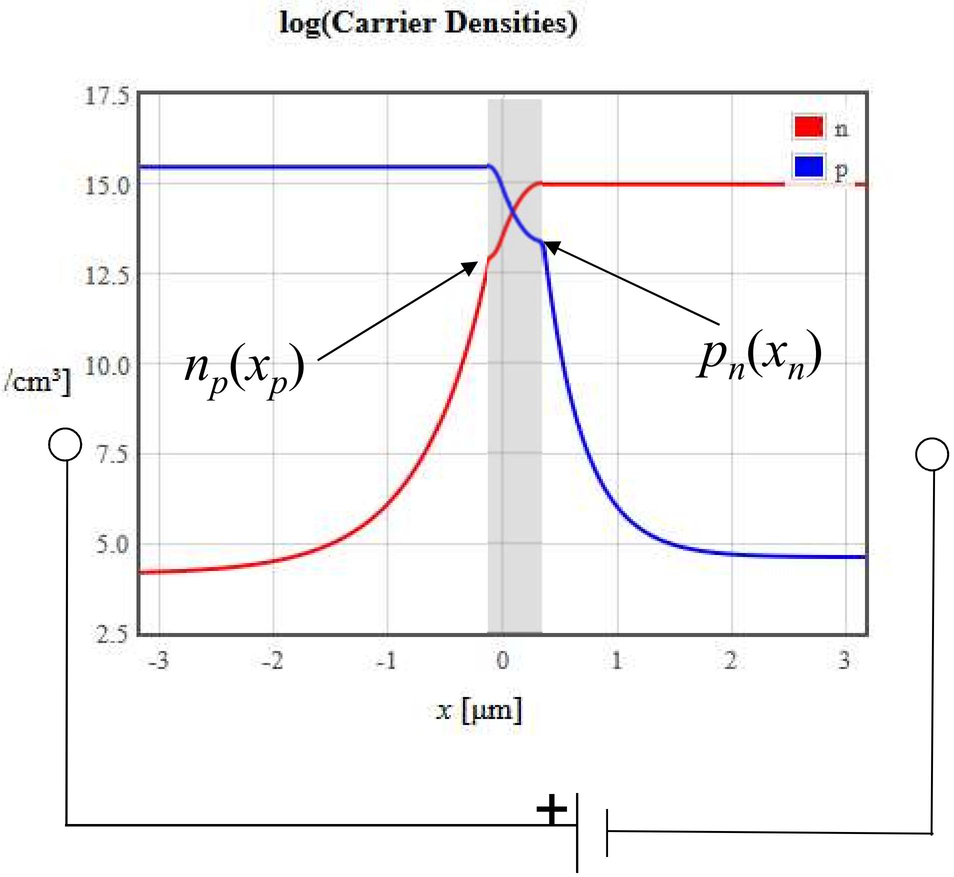
$$E = -\frac{eN_A}{\varepsilon}\left(x + x_p\right) \qquad -x_p > x > 0$$

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

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

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

Forward bias, V > 0



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

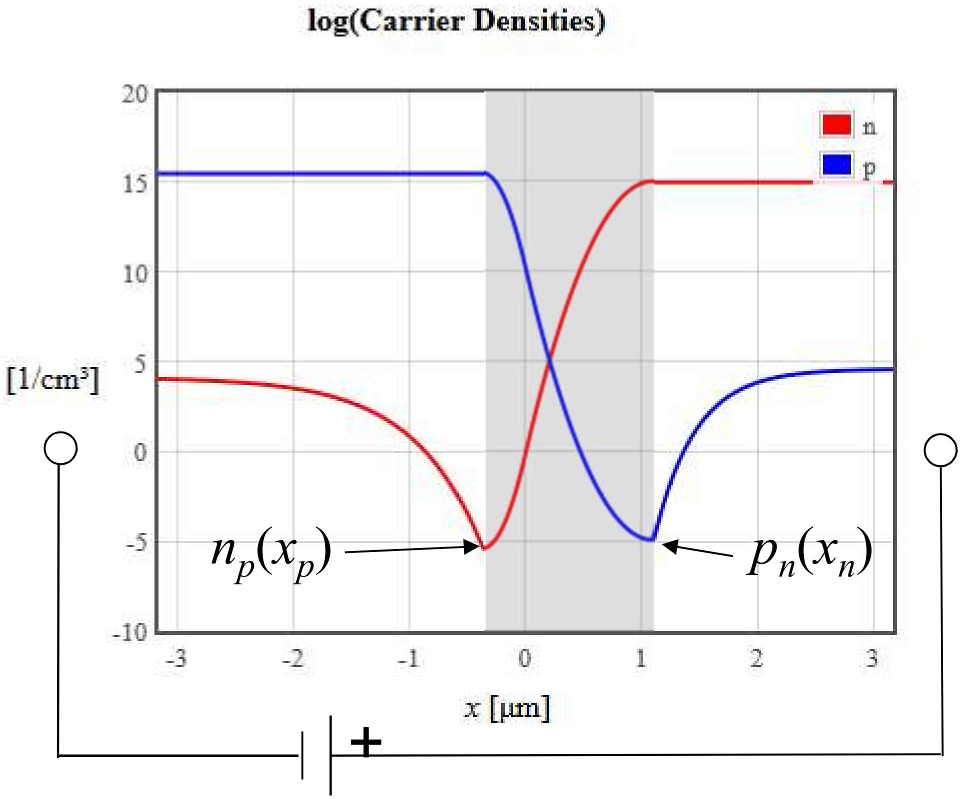
$$n_p(x_p) = n_{p0} \exp\left(\frac{eV}{k_B T}\right)$$

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

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

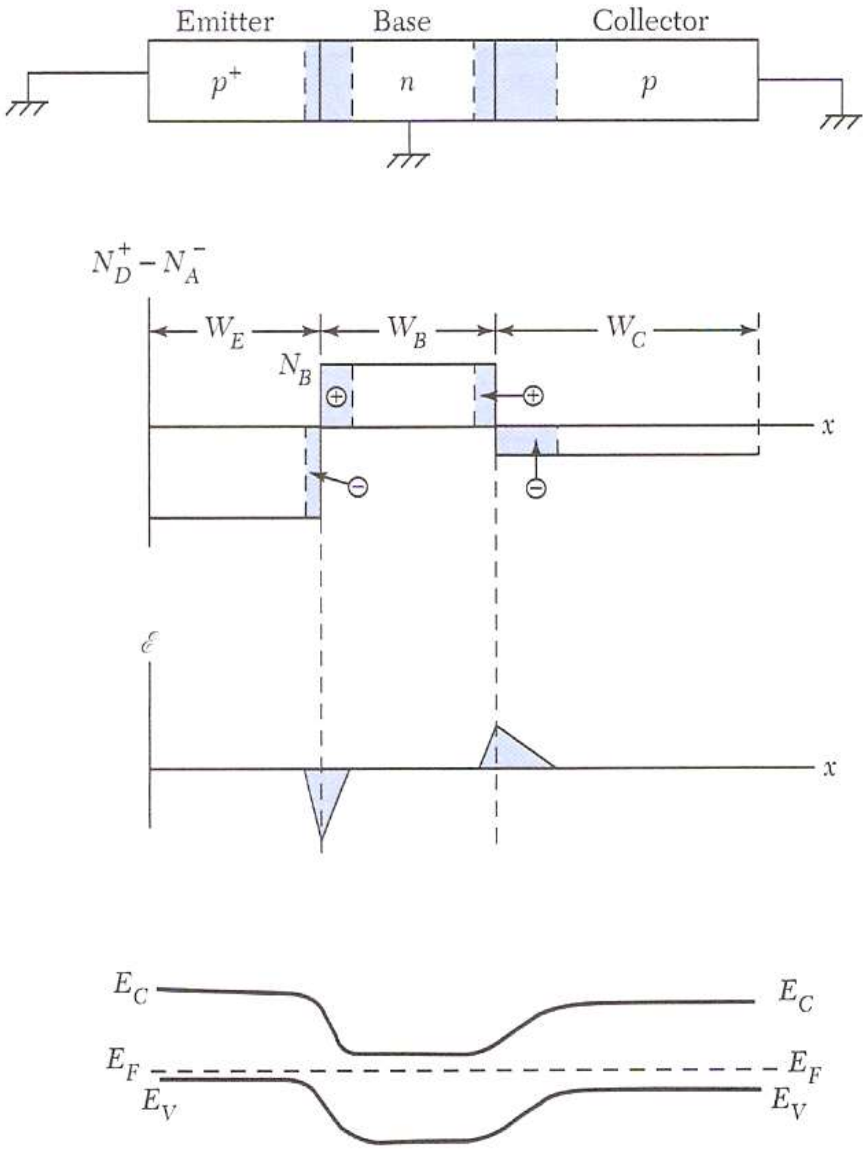


$$n_p(x_p) = n_{p0} \exp\left(\frac{eV}{k_B T}\right)$$

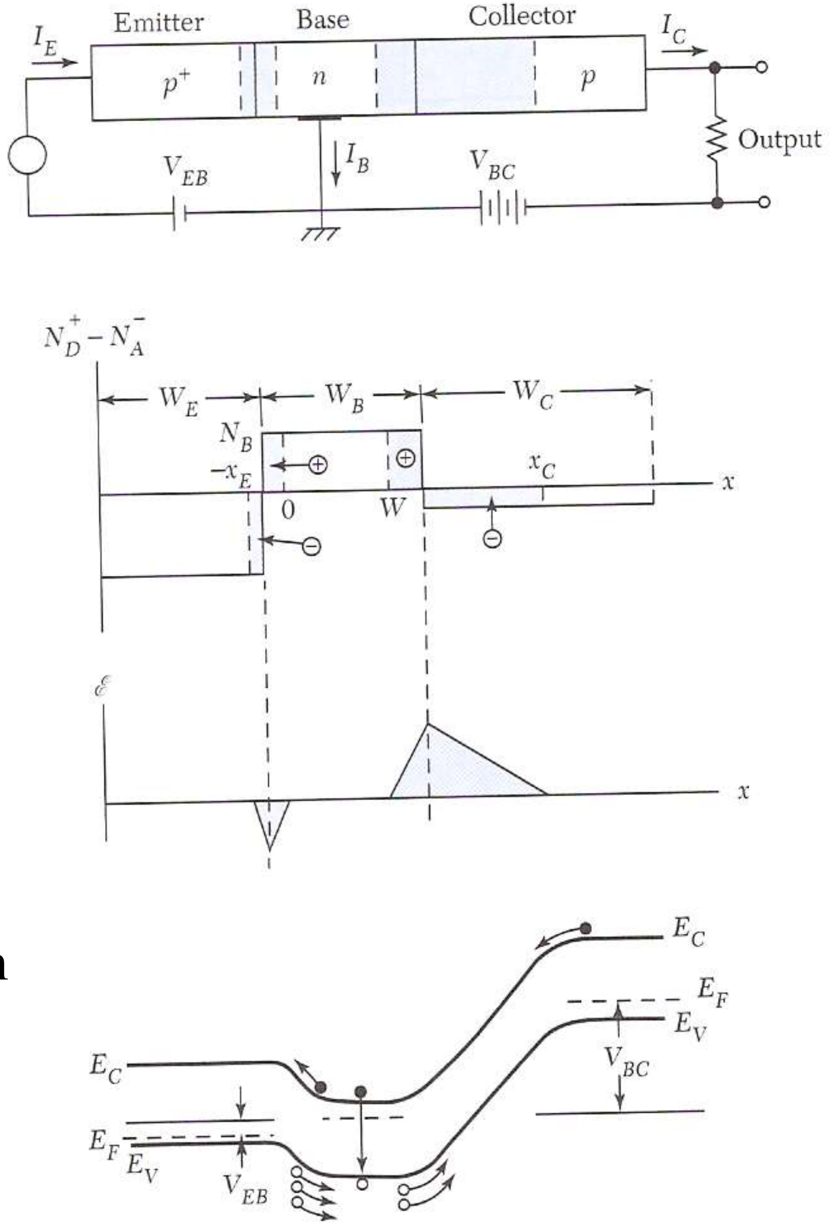
$$p_n(x_n) = p_{n0} \exp\left(\frac{eV}{k_B T}\right)$$

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



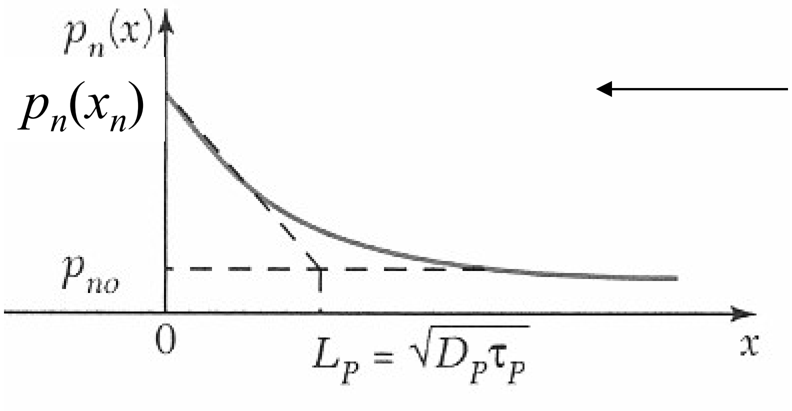
pnp transistor, forward active bias



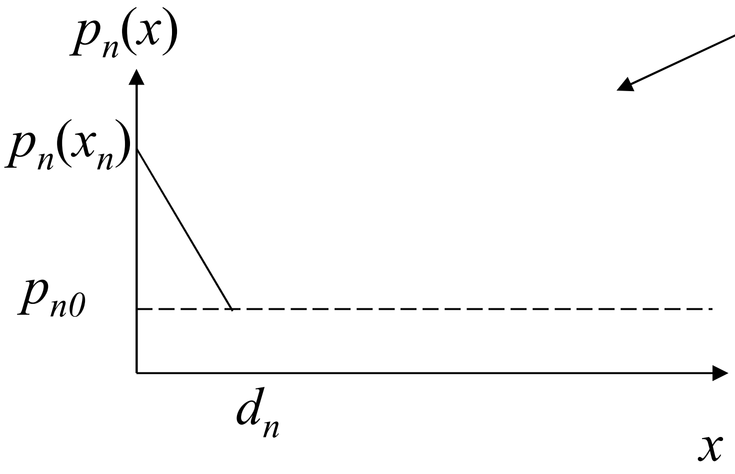
Always dissipate power due to the forward bias

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

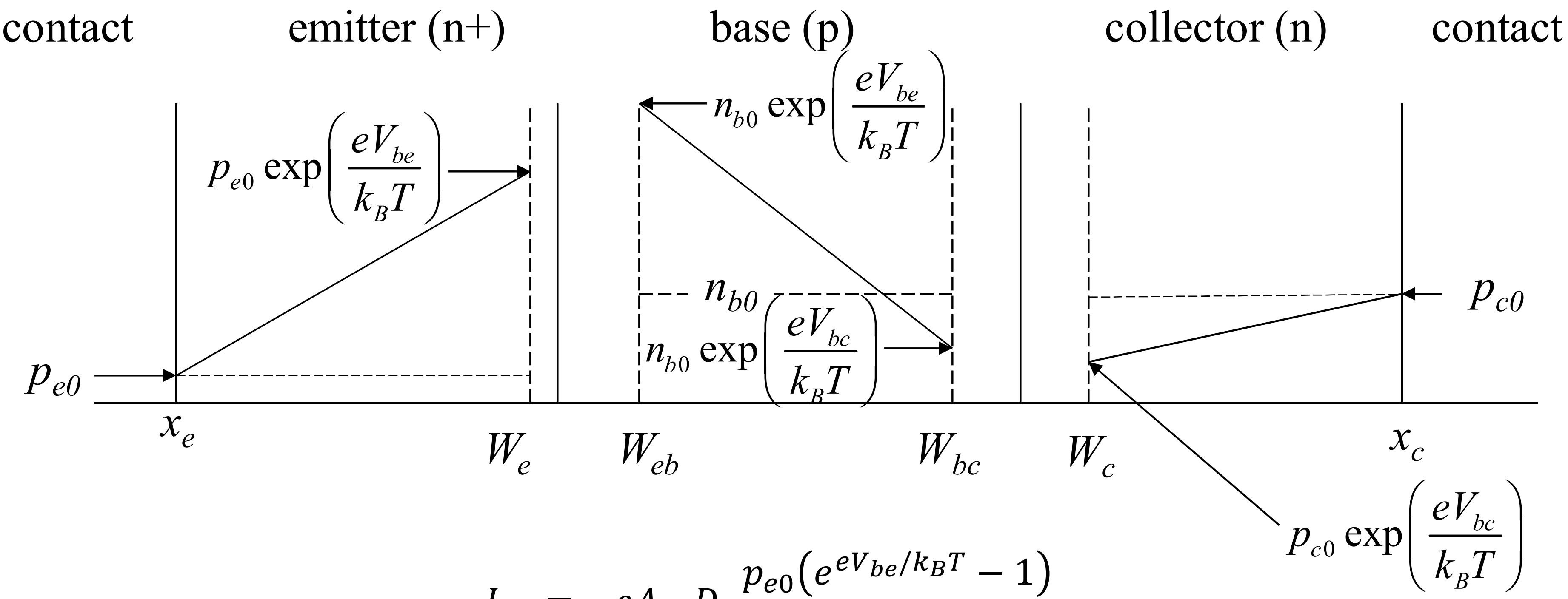
$d_n << L_p$

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

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

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

Minority carrier concentration



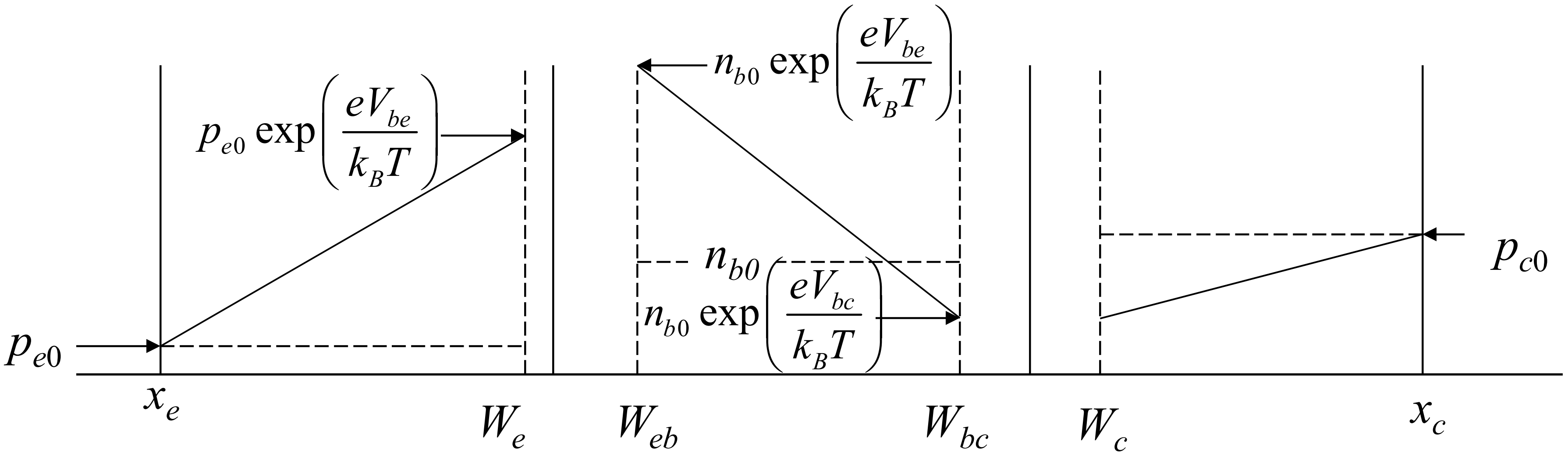
$$I_{Ep} = -eA_{be}D_p \frac{p_{e0}\left(e^{eV_{be}/k_BT} - 1\right)}{W_e - x_e}$$

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

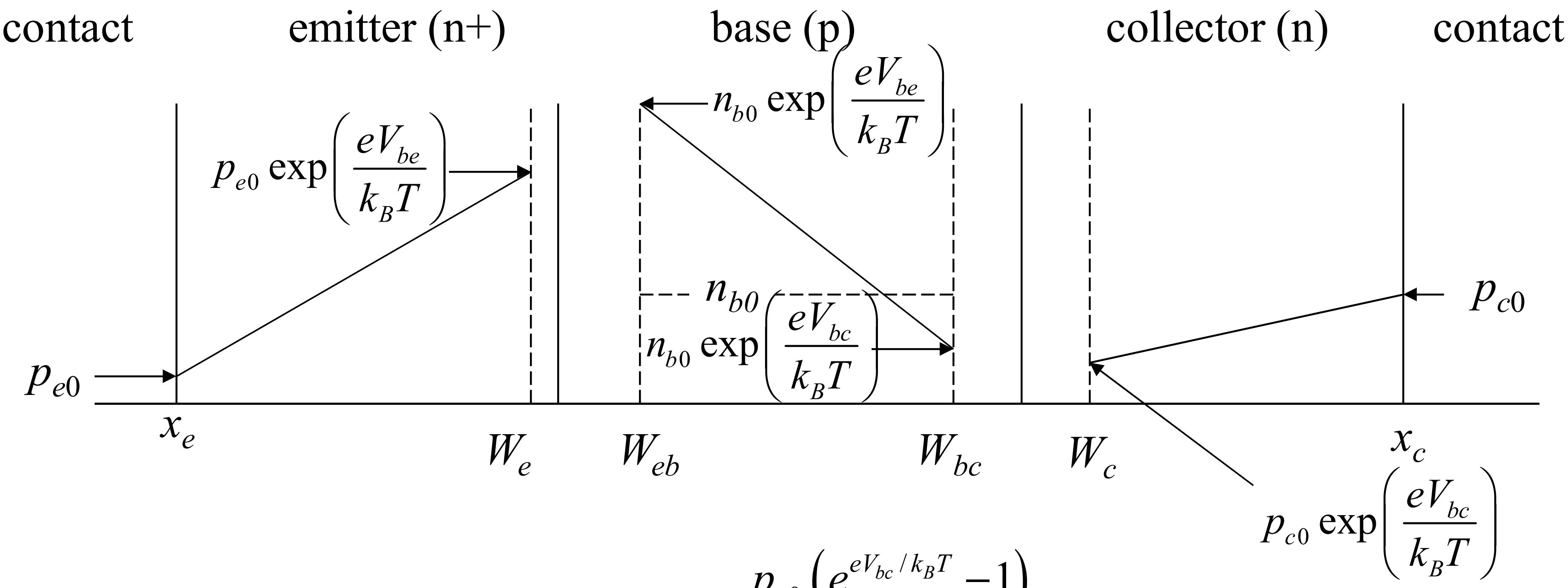
Emitter current

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

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



Collector current



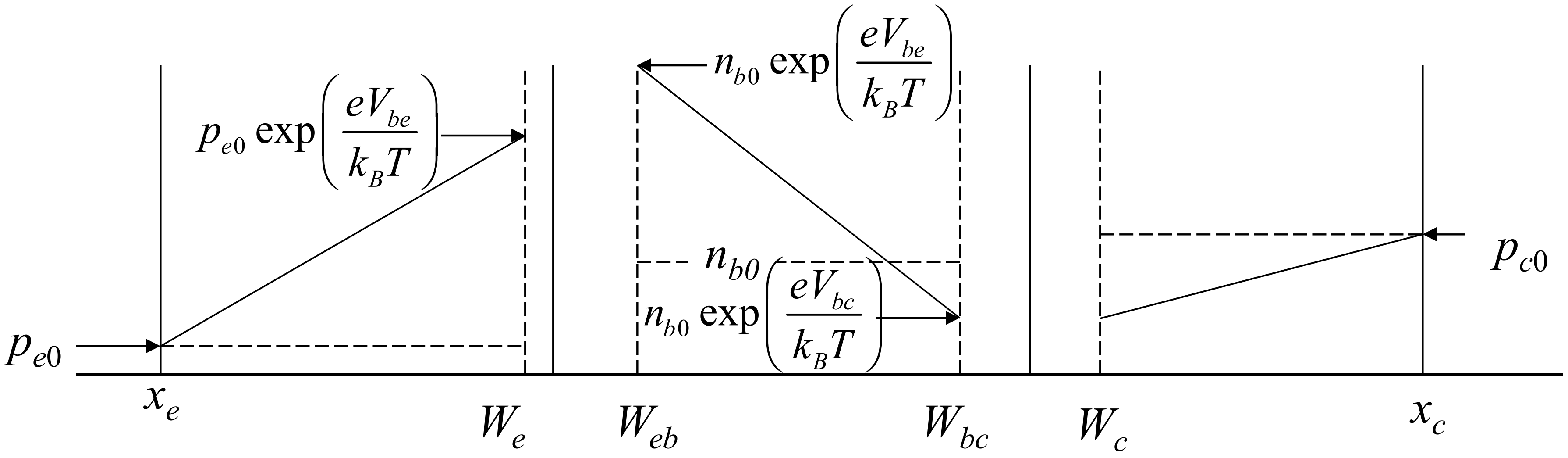
$$I_{cp} = -eA_{bc}D_p \frac{p_{c0}\left(e^{eV_{bc}/k_BT}-1\right)}{x_c - W_c}$$

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

Collector current

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

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

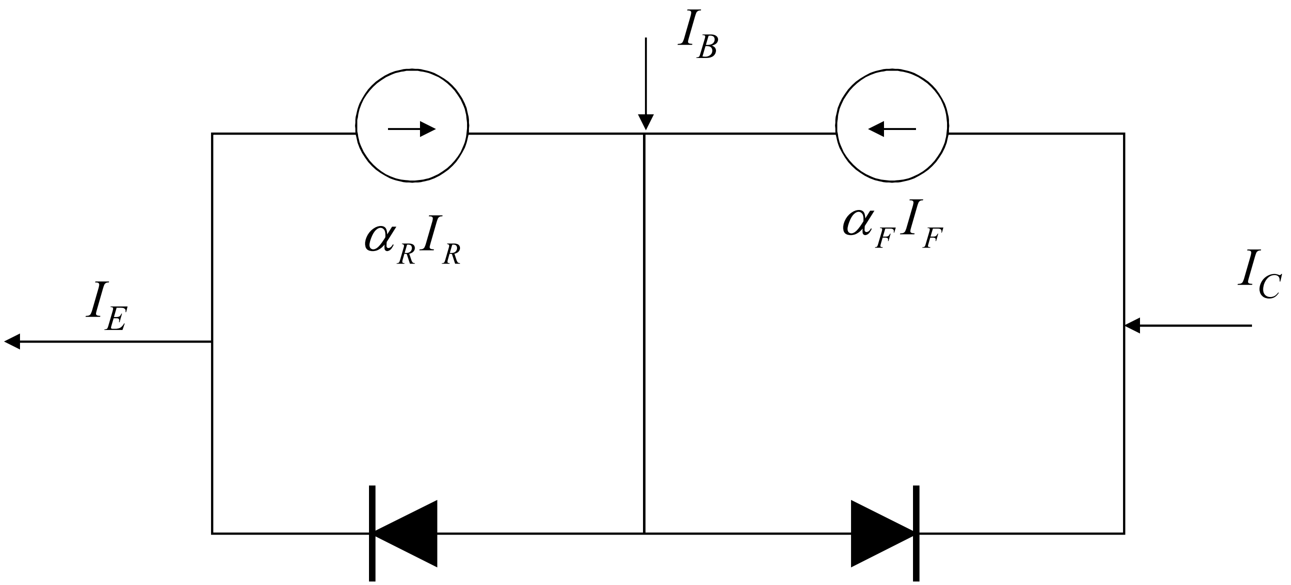


Ebers-Moll model

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

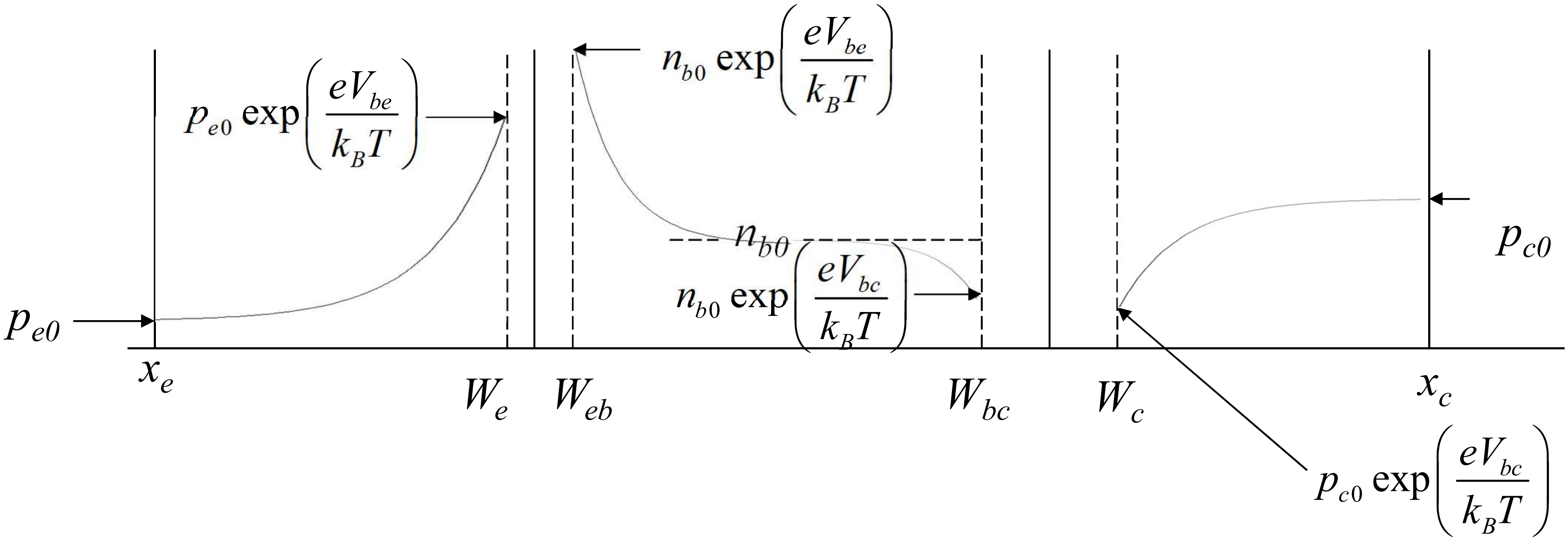
$$I_C = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$



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

Not an npn transistor



contact

emitter (n+)

base (p)

collector (n)

contact

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

$n_{b0} \exp\left(\frac{eV_{be}}{k_B T}\right)$

n_{b0}

$n_{b0} \exp\left(\frac{eV_{bc}}{k_B T}\right)$

p_{c0}

p_{e0}

x_e

W_e

W_{eb}

W_{bc}

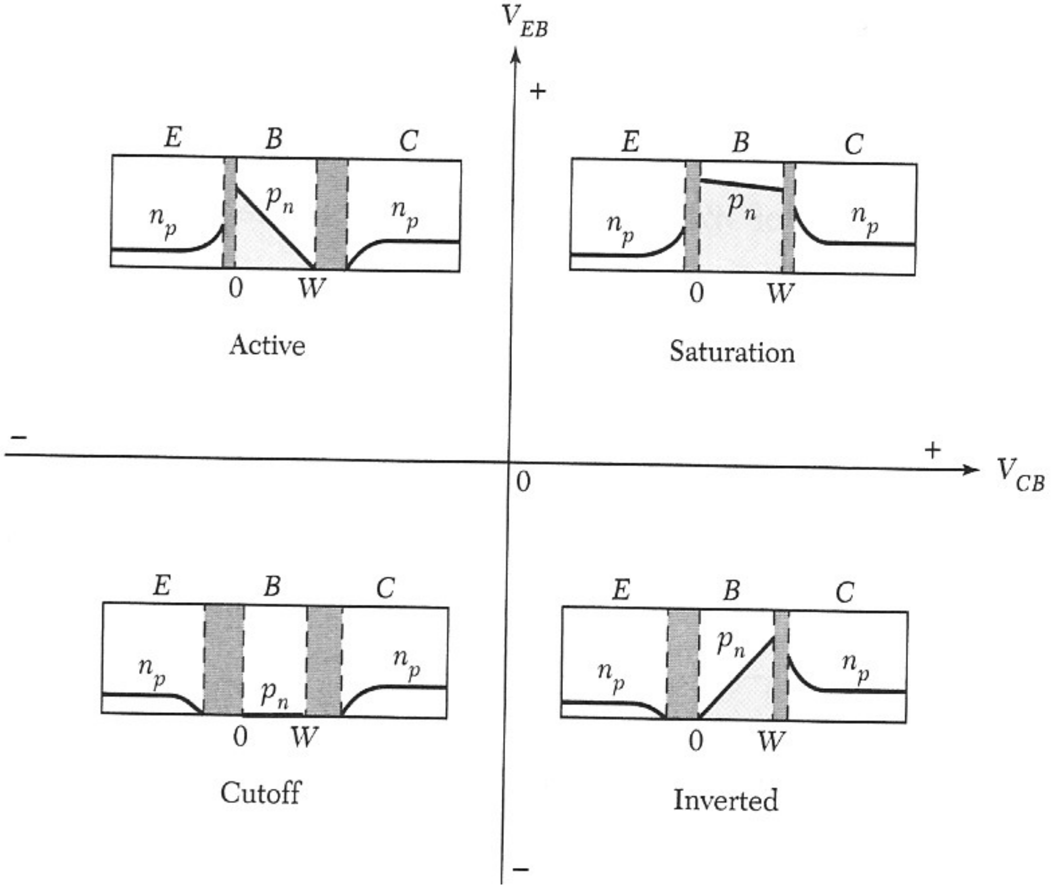
W_c

x_c

$p_{c0} \exp\left(\frac{eV_{bc}}{k_B T}\right)$

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**



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 $n_{b0} >> p_{e0}$

neutral base width

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

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

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

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

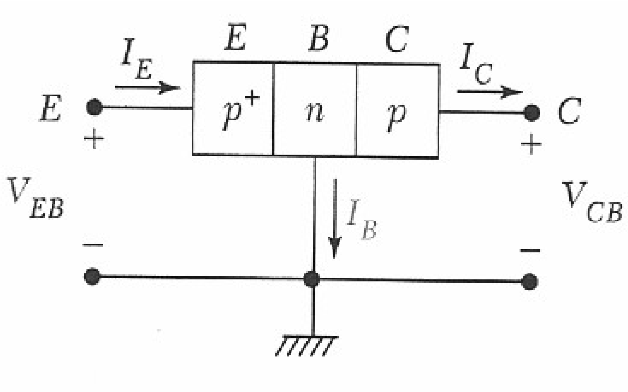
α ~ 1 for a good BJT

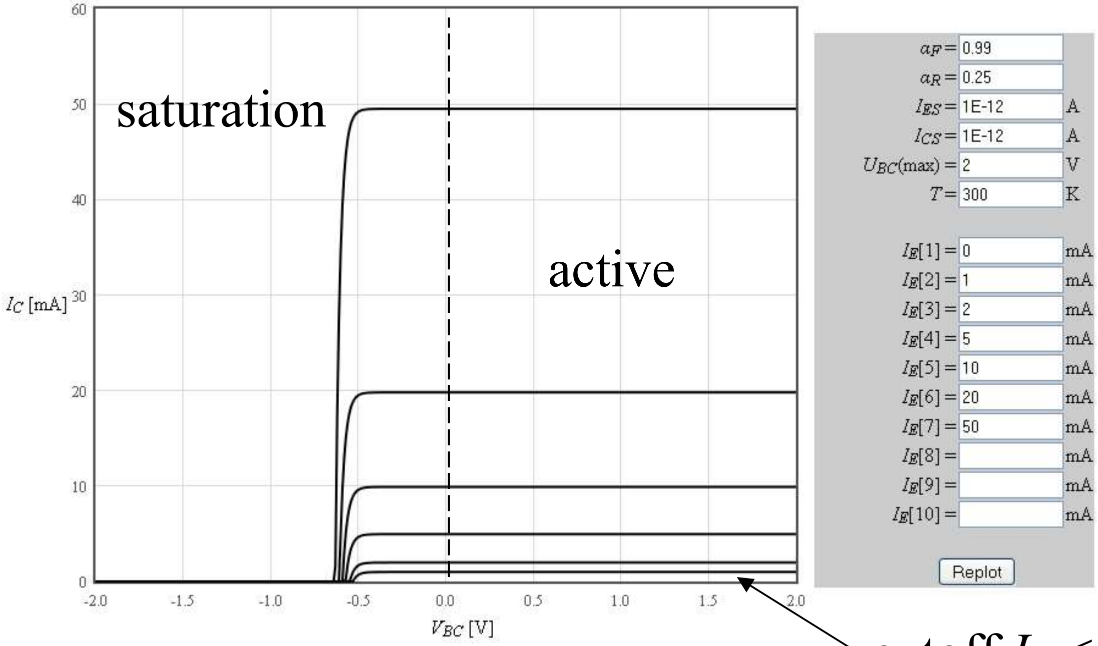
Common base configuration

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

solve for V_{be}

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





saturation

active

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

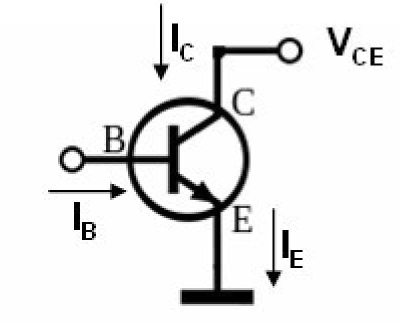
cutoff $I_E < 0$

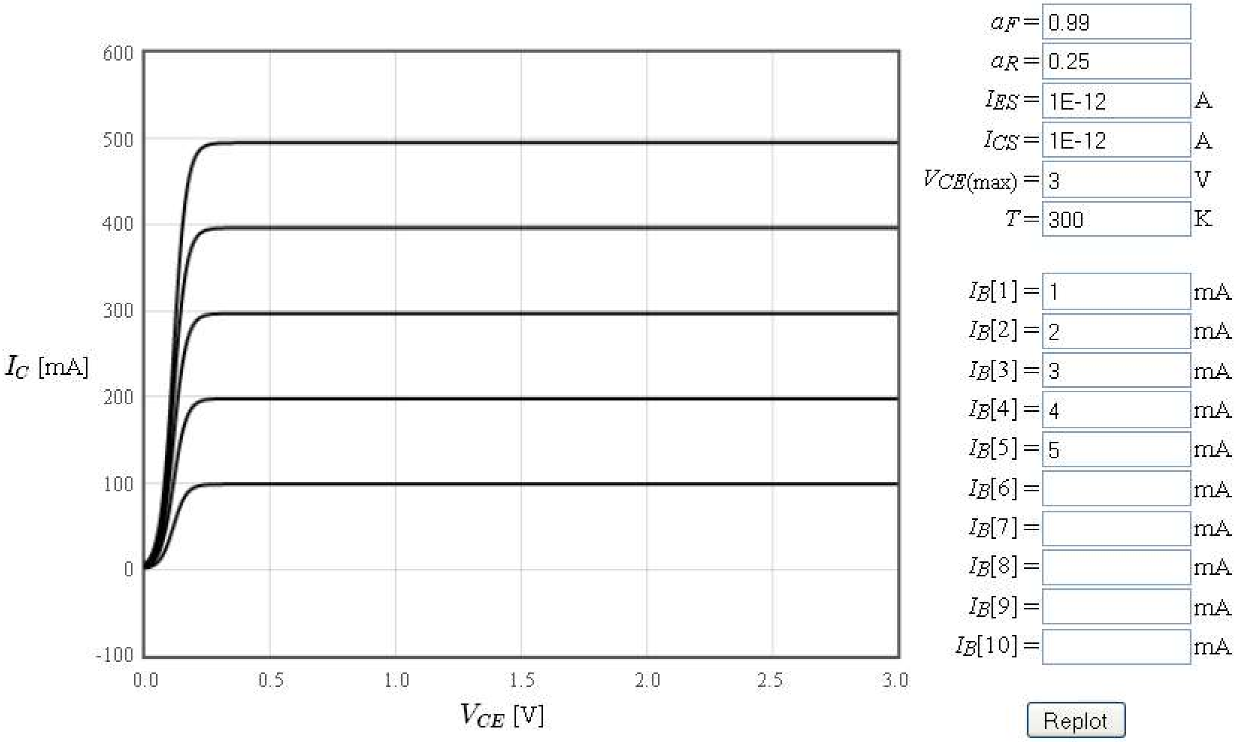
http://lamp.tu-graz.ac.at/~hadley/psd/L13/commonbase/pnp_current.html

Common emitter configuration

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

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





α_F = 0.99

α_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

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

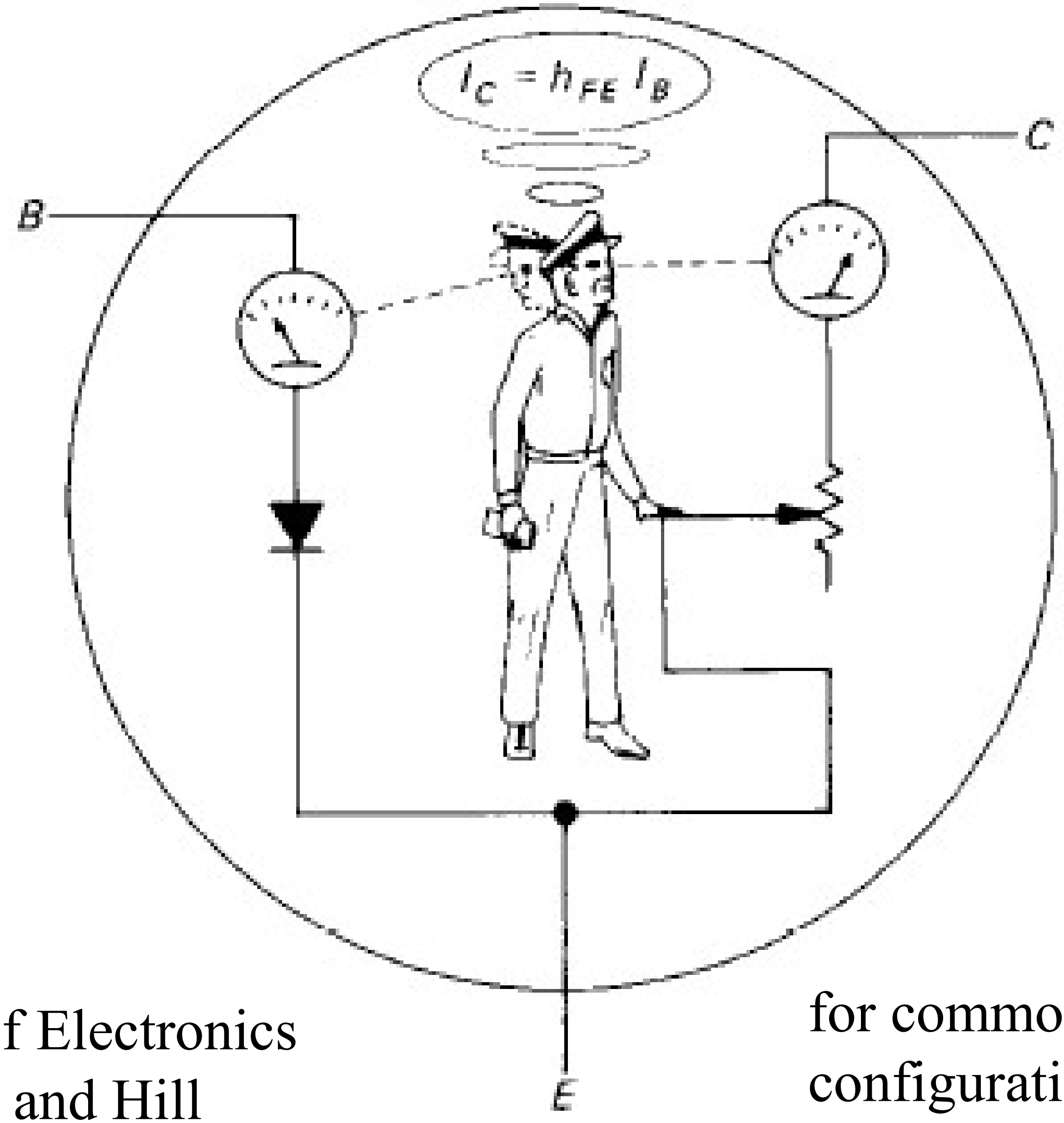
$$I_B = I_E - I_C$$

$$I_C = \alpha I_E$$

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

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

$\beta \sim 50 - 500$



“Transistor man”

The Art of Electronics
Horowitz and Hill

for common emitter
configuration

Transconductance

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

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

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:

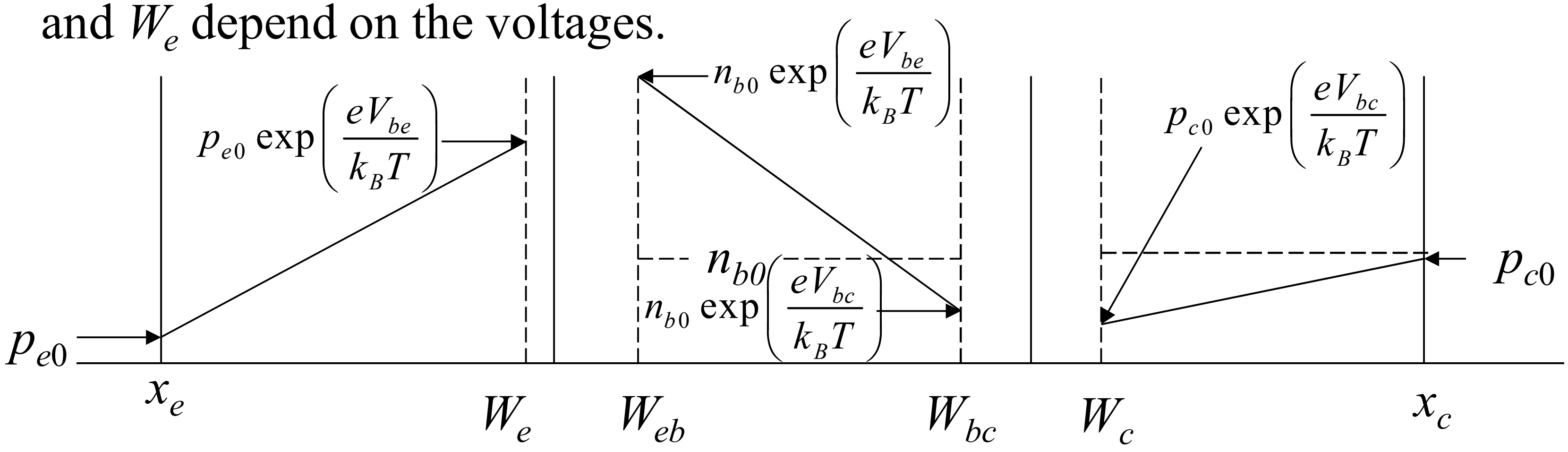
$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

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

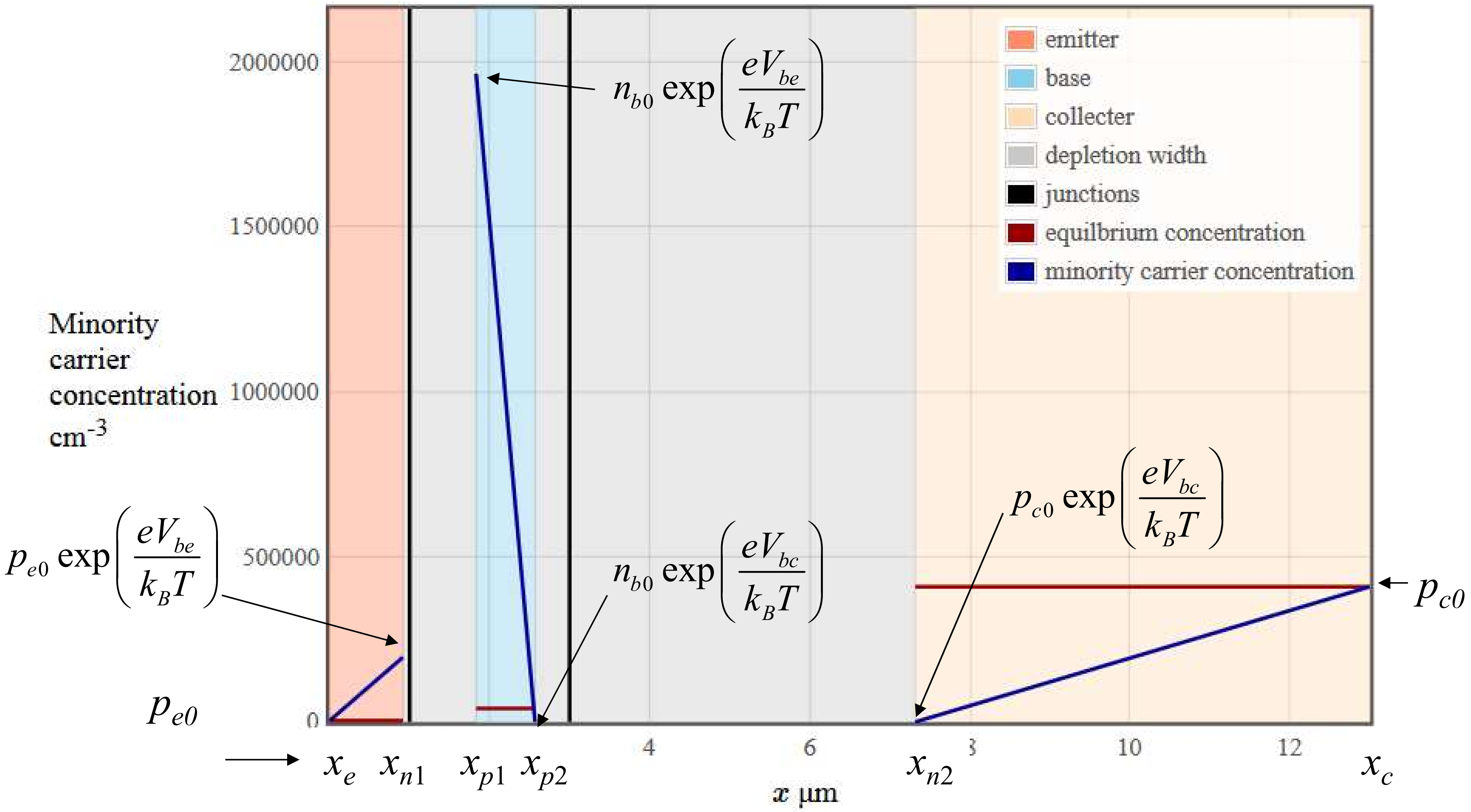
$$I_B = I_E - I_C$$

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

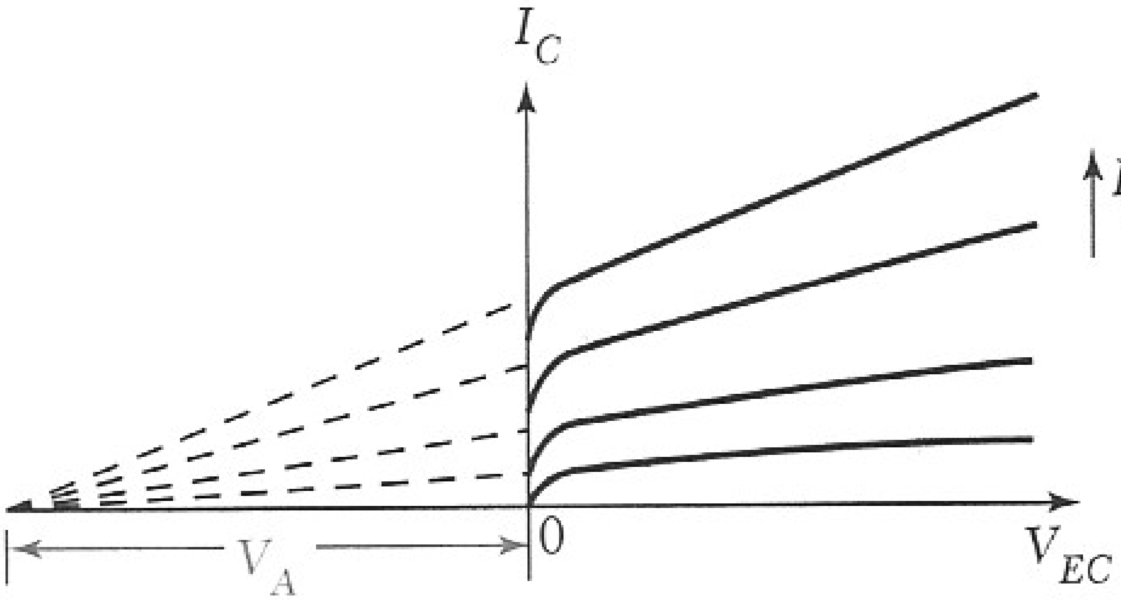
I_{ES} and I_{CS} are treated as constants but the depletion widths W_{bc}, W_{be}, W_c, and W_e depend on the voltages.



Minority carrier concentration



Early effect

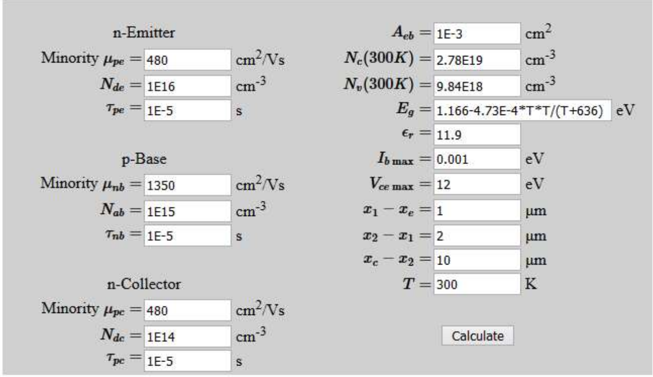


Common emitter configuration
Base width modulation: smaller width increases the diffusion current and increases the gain.

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

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



n-Emitter

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

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

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

p-Base

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

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

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

n-Collector

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

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

$\tau_{pc} =$ 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

$\epsilon_r =$ 11.9

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

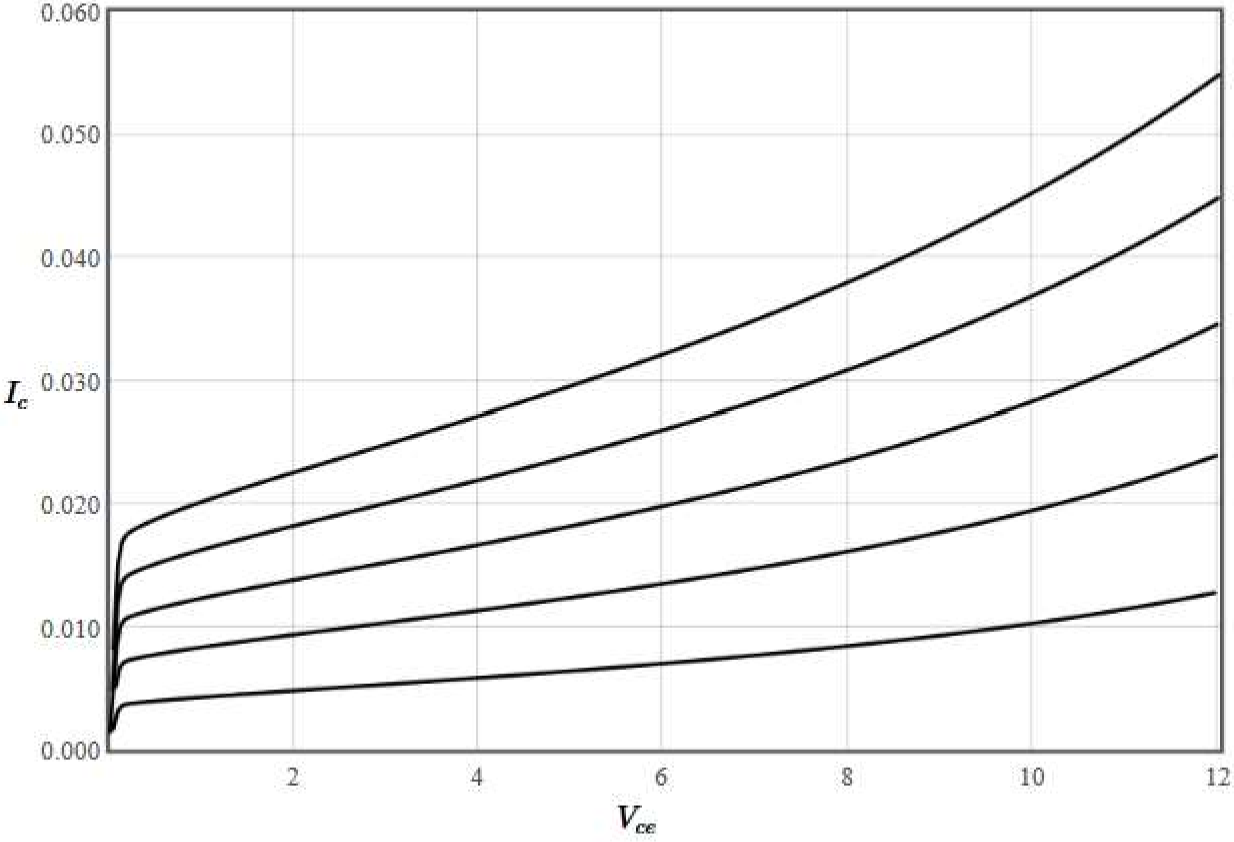
$V_{ce\,\max} =$ 12 eV

$x_1 - x_e =$ 1 µm

$x_2 - x_1 =$ 2 µm

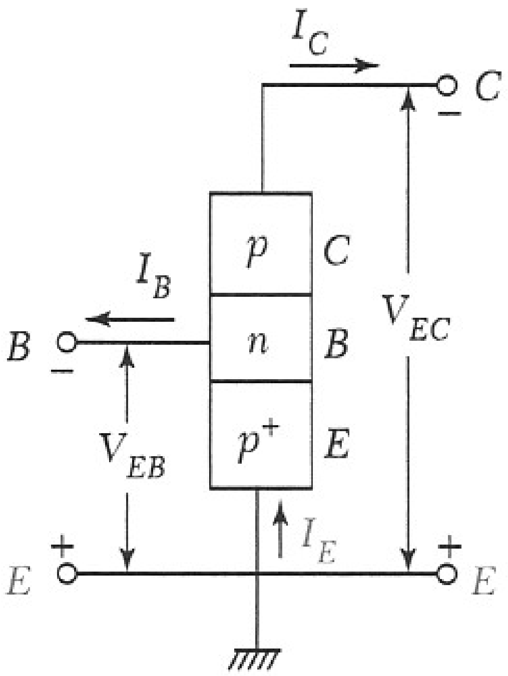
$x_c - x_2 =$ 10 µm

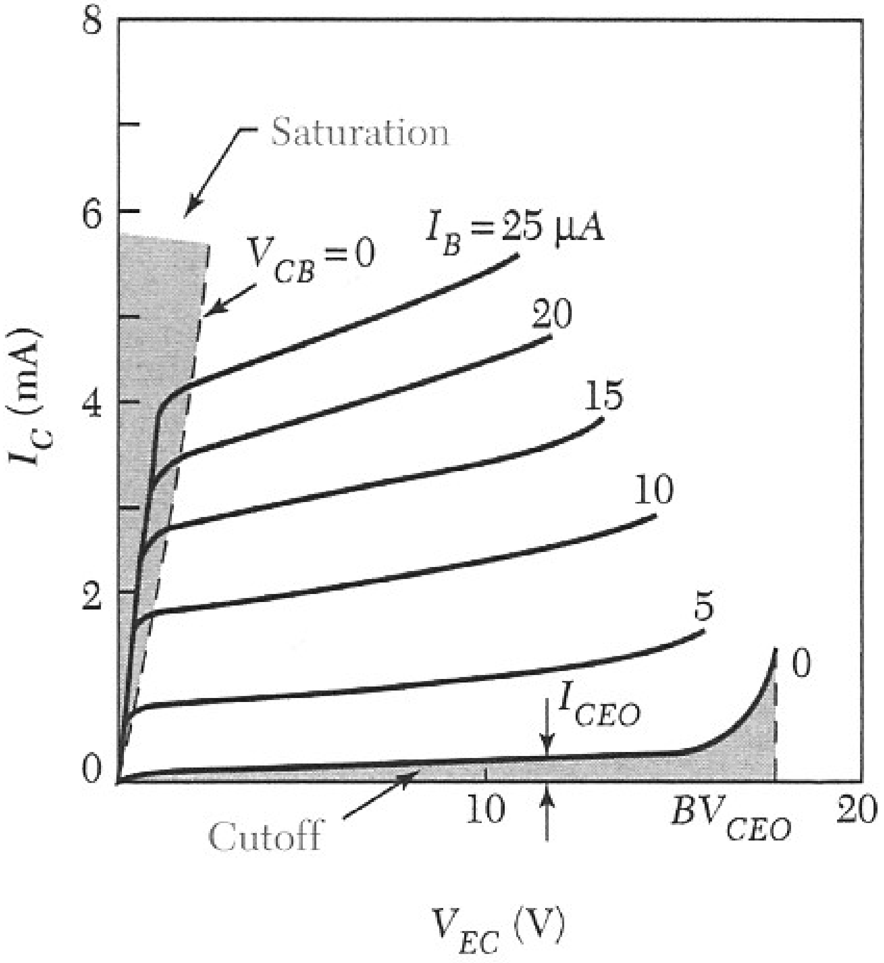
$T =$ 300 K



$$I_C \sim \beta I_B$$

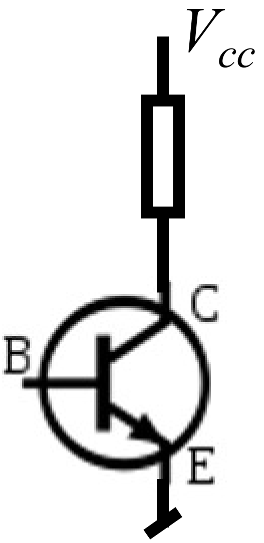
Common emitter configuration

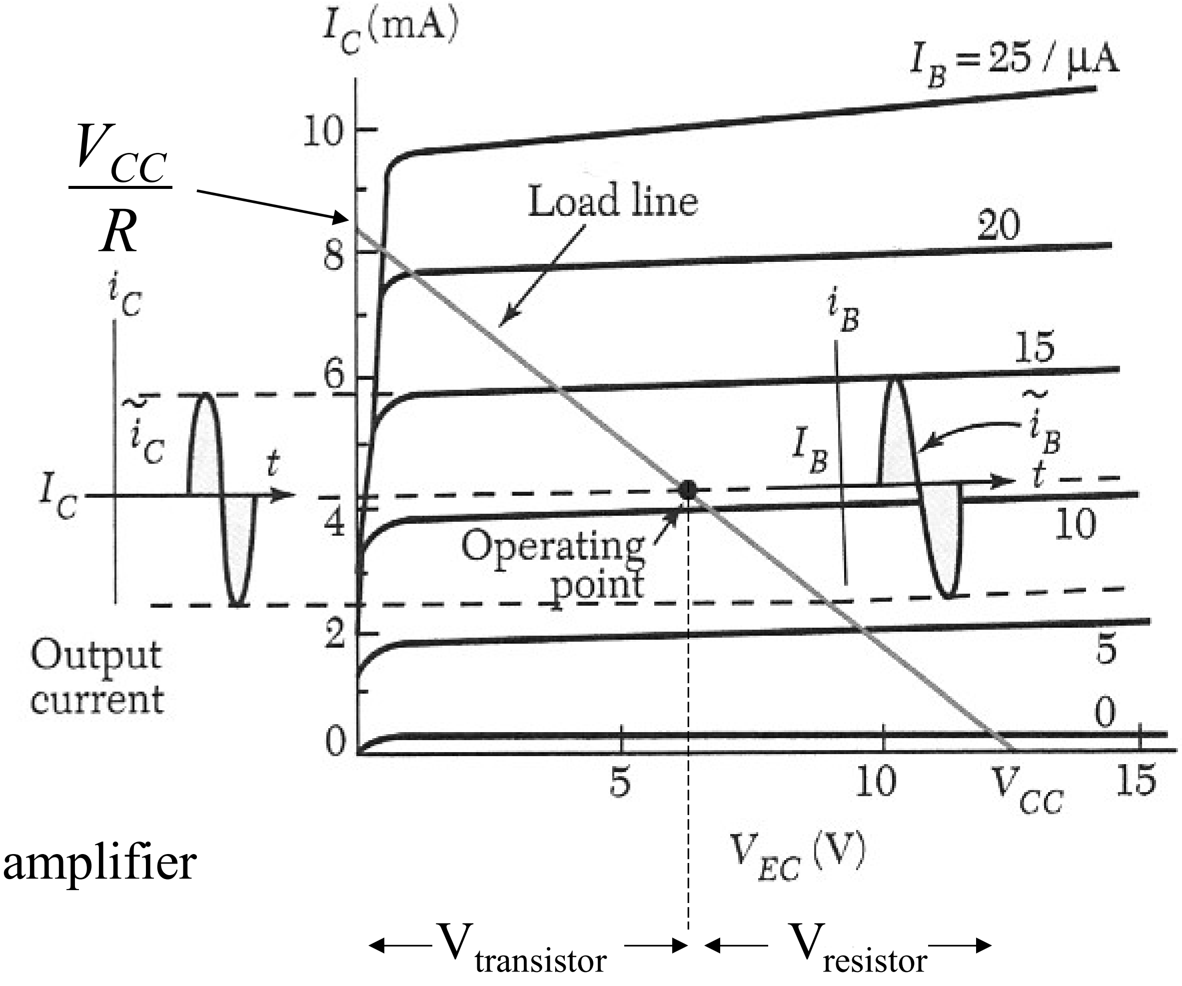




$I_C \sim \beta I_B$ amplifier

Small signal response

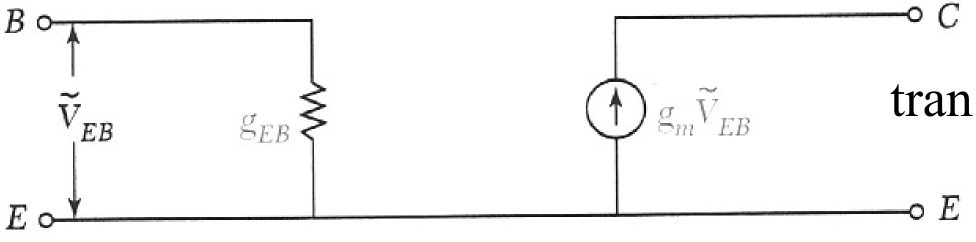




Low input impedance amplifier

Small signal response

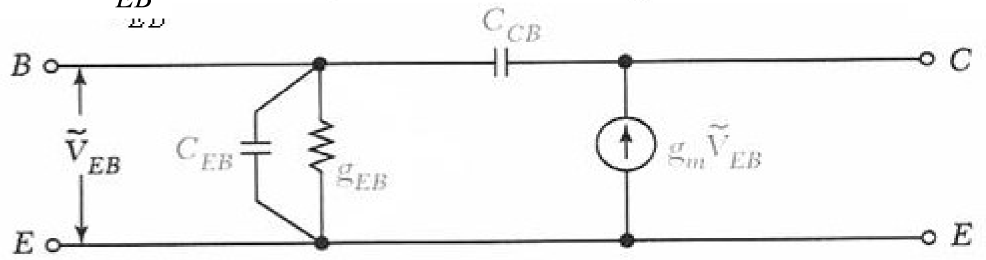
$$\tilde{i}_c = \beta \tilde{i}_B = \beta g_{EB} \tilde{v}_{EB}$$

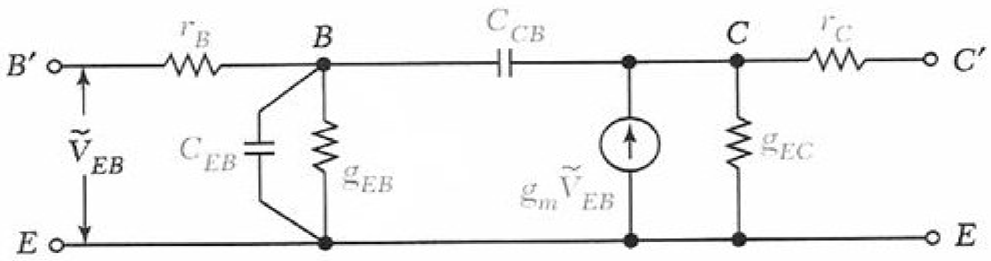


transistor man

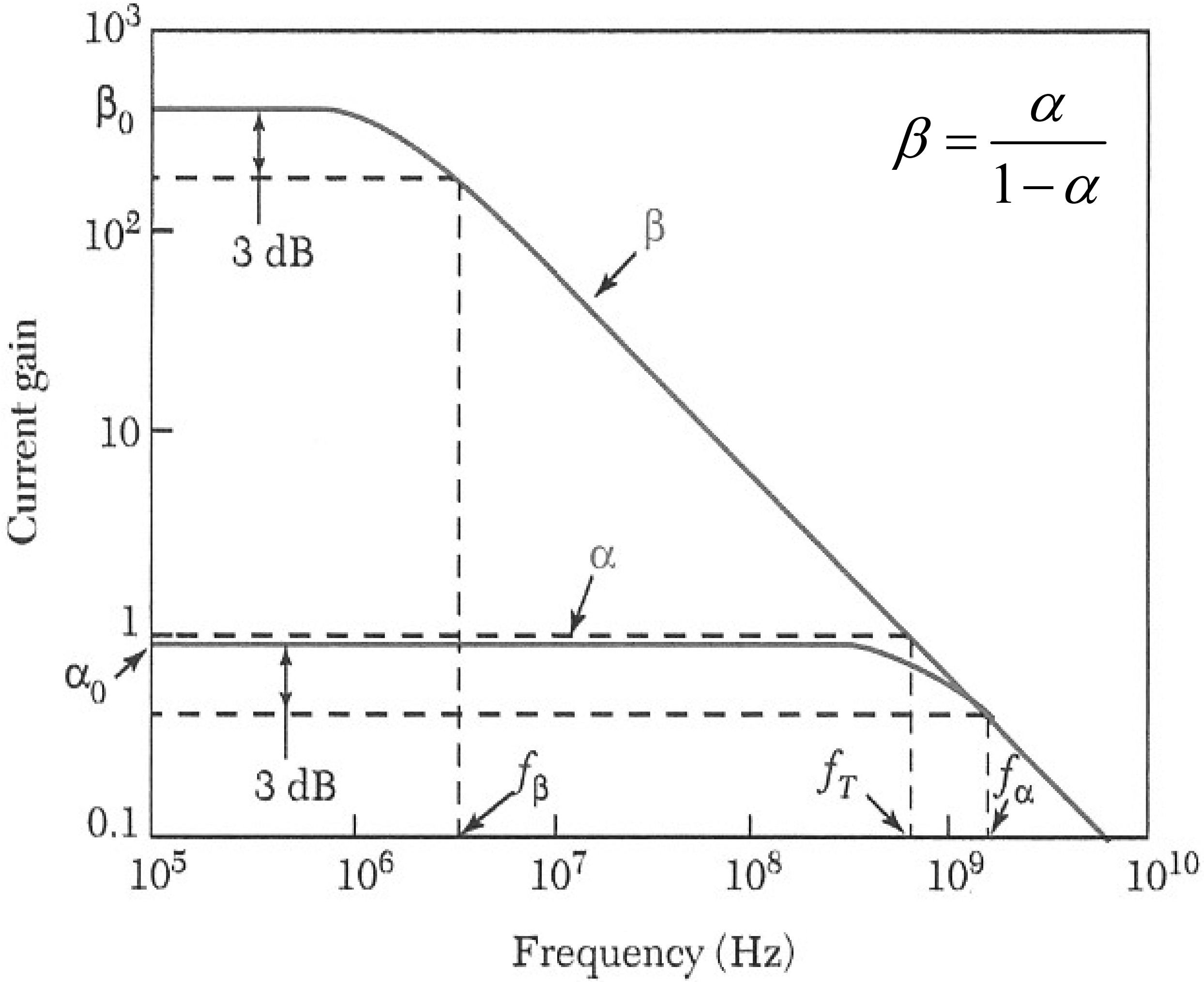
input conductance: $g_{EB} = \dfrac{\tilde{i}_B}{\tilde{v}_{EB}}$

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





Small signal response

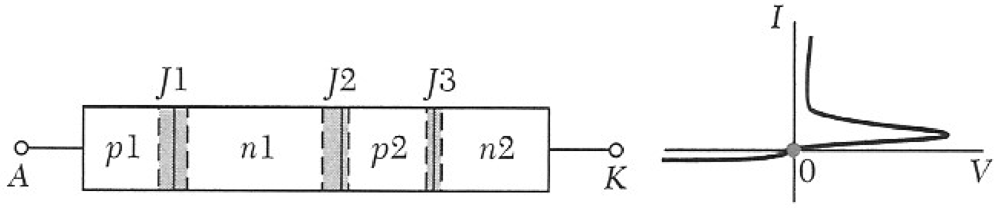


$$\beta = \frac{\alpha}{1-\alpha}$$

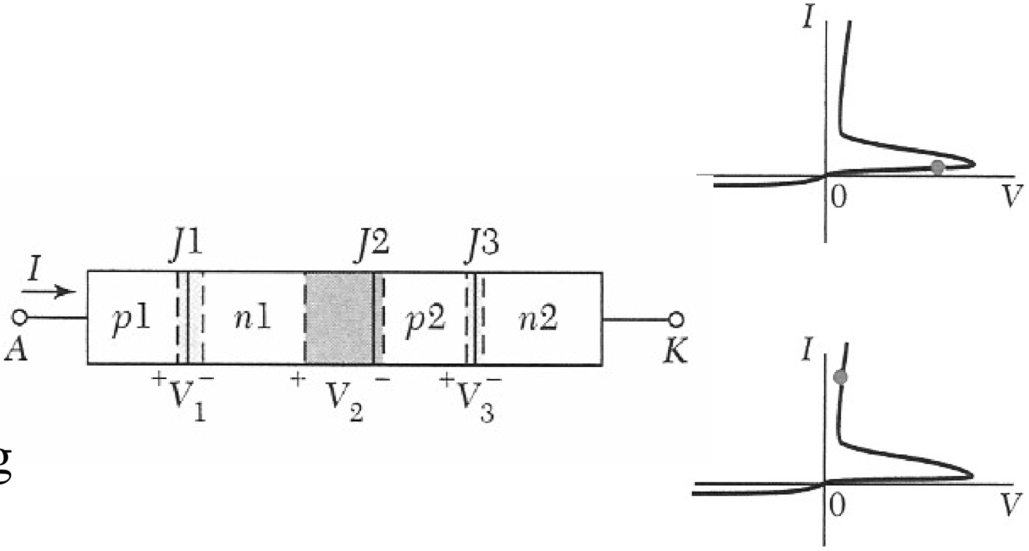
$$f_\beta = (1-\alpha_0) f_\alpha$$

$$f_T = \alpha_0 f_\alpha$$

Thyristors

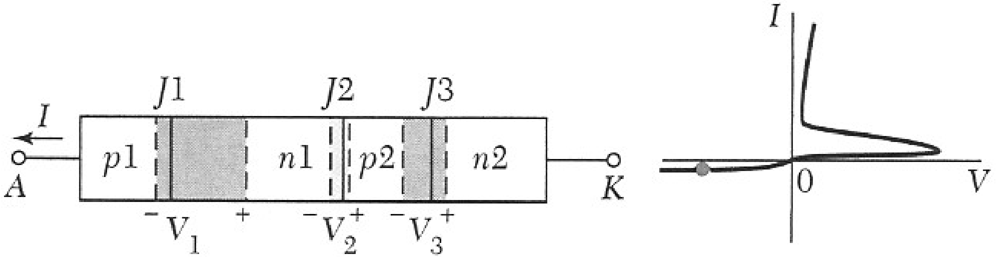


Forward blocking

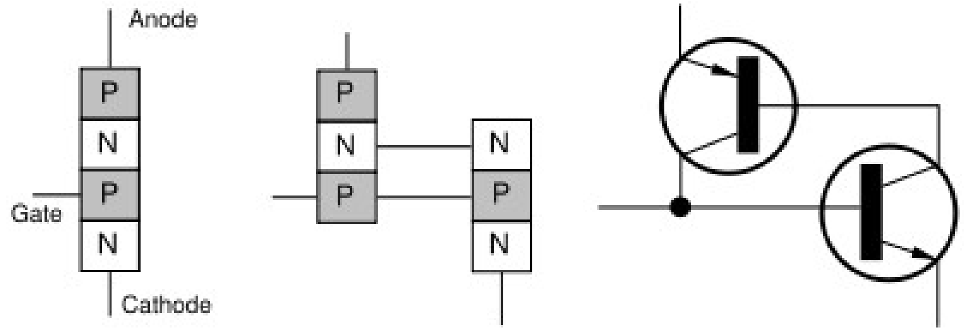


Forward conducting

Reverse blocking



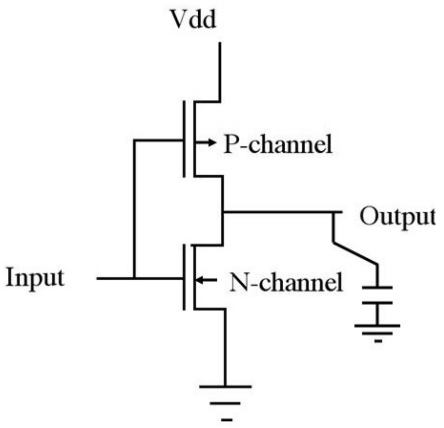
Thyristors

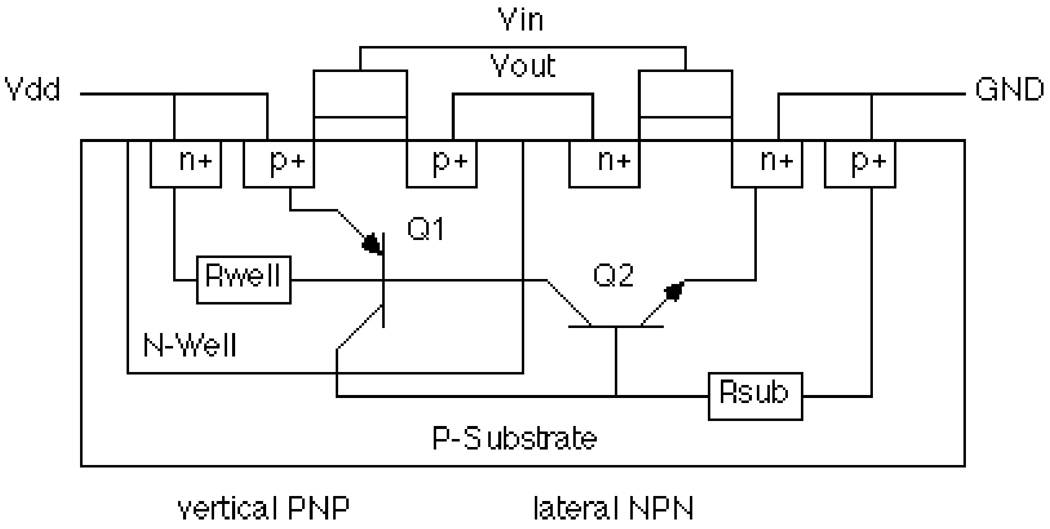


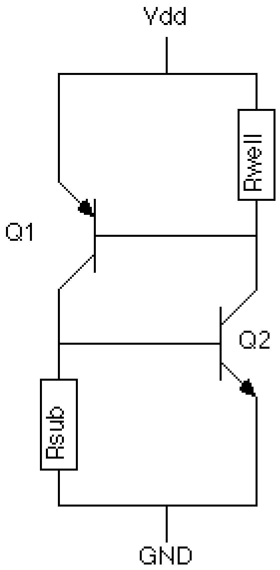
$\beta_1 * \beta_2 > 1$

Used for switching high currents or voltages

Latch-up



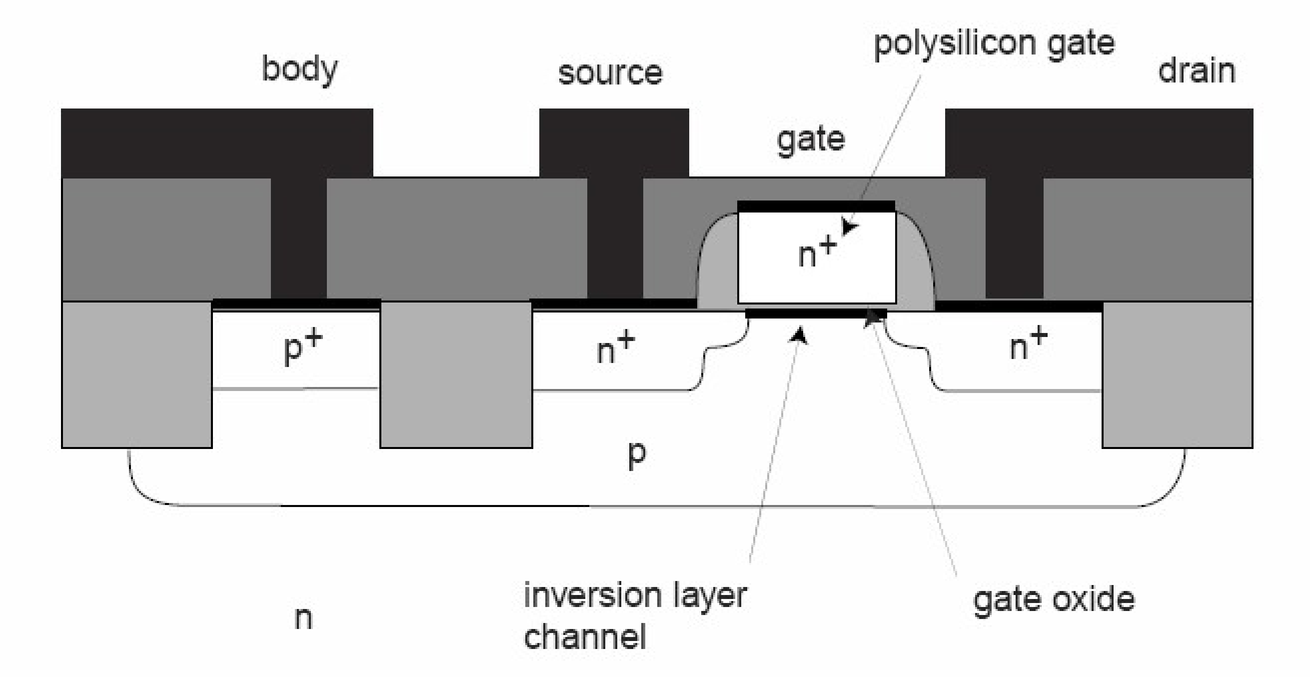




Both BJT's conduct, creating a low resistance path between V_{dd} and GND. The product of the gains of the two transistors in the feedback loop, is greater than one. The result of latchup is at the minimum a circuit malfunction, and in the worst case, the destruction of the device.

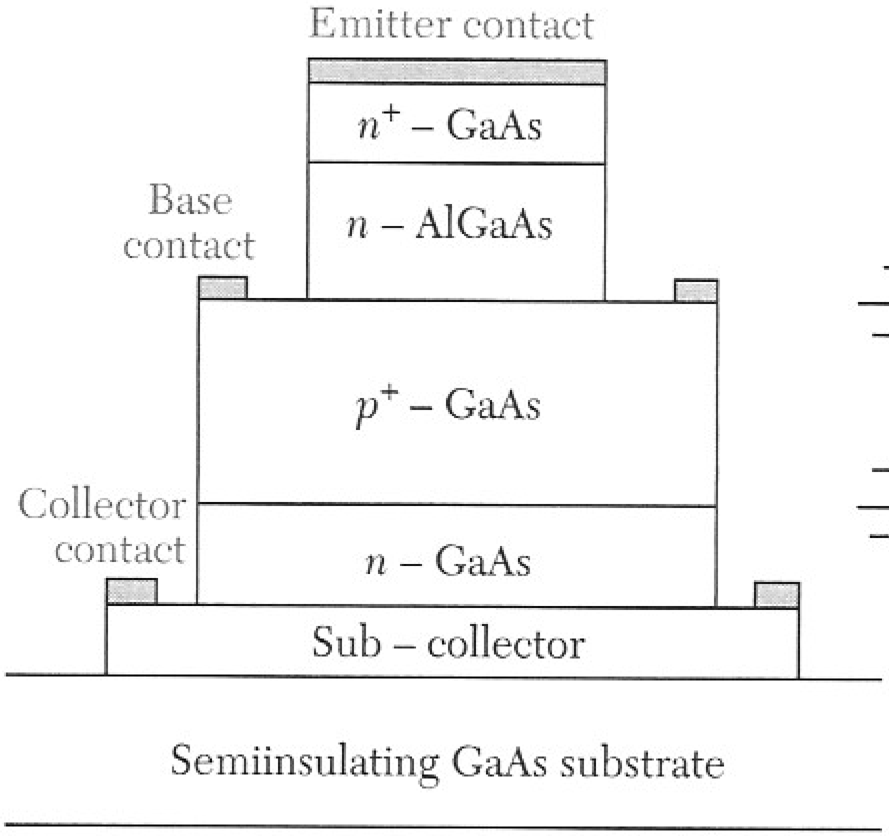
http://www.ece.drexel.edu/courses/ECE-E431/latch-up/latch-up.html

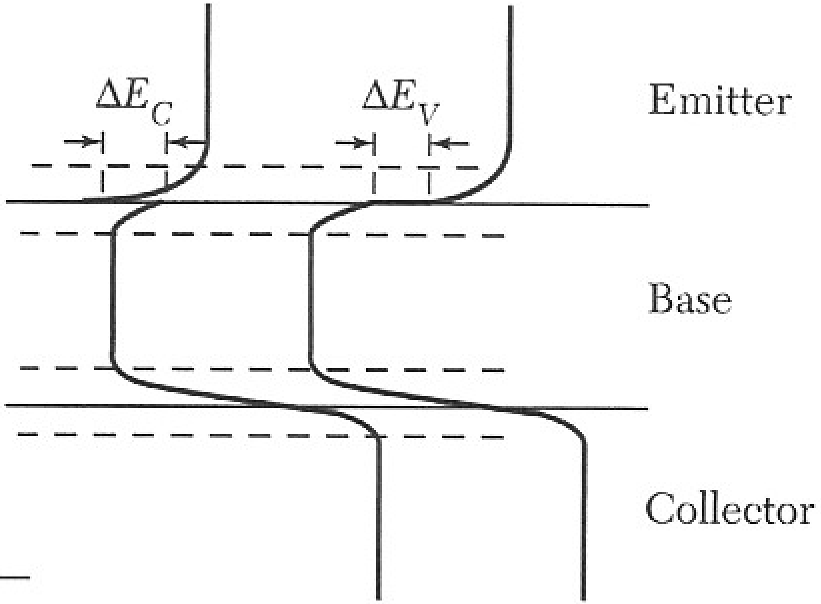
Subthreshold current



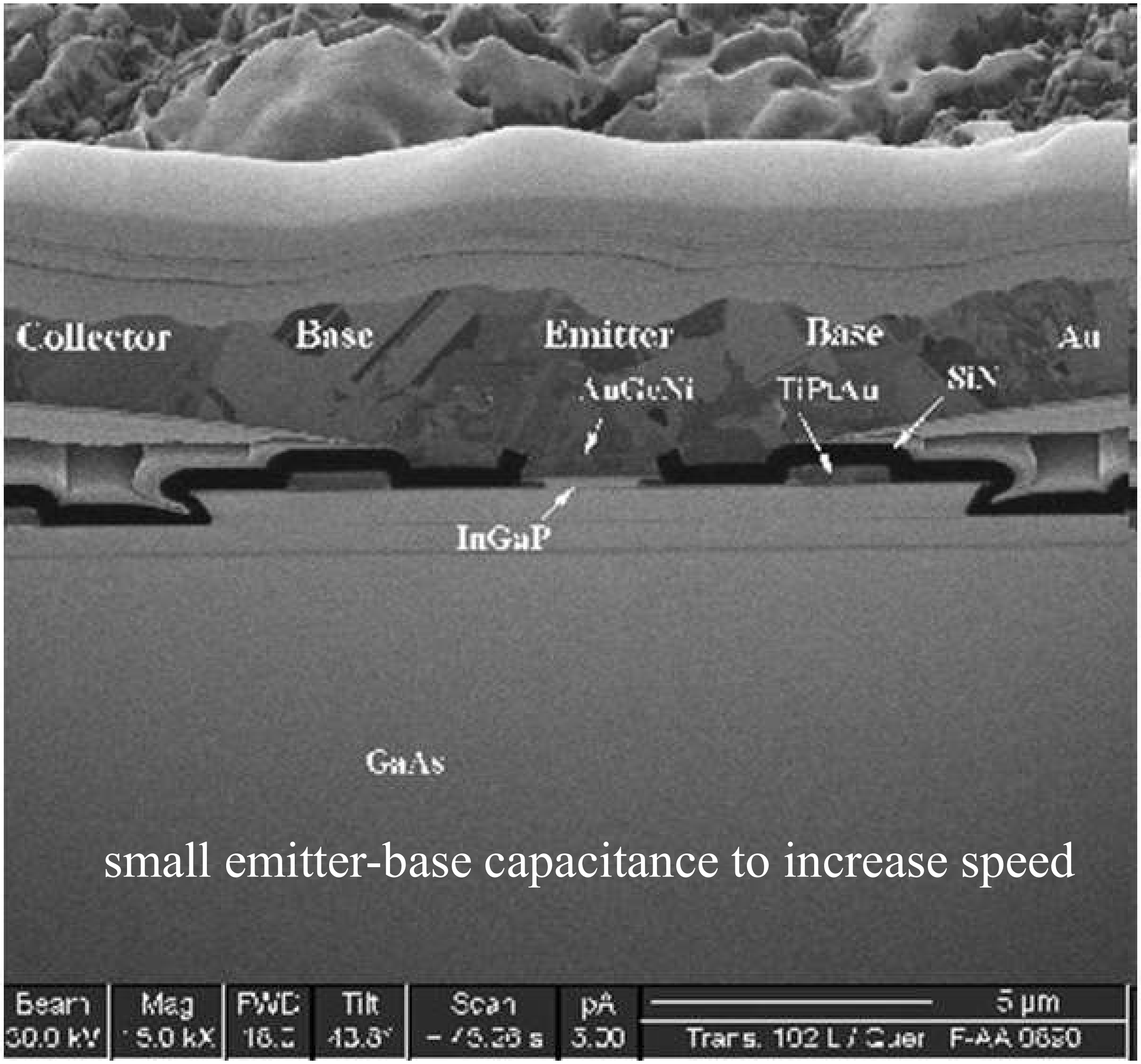
If the p-concentration in the channel is low, electrons emitted into the channel by the forward biased junction diffuse across the channel without recombining.

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?

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

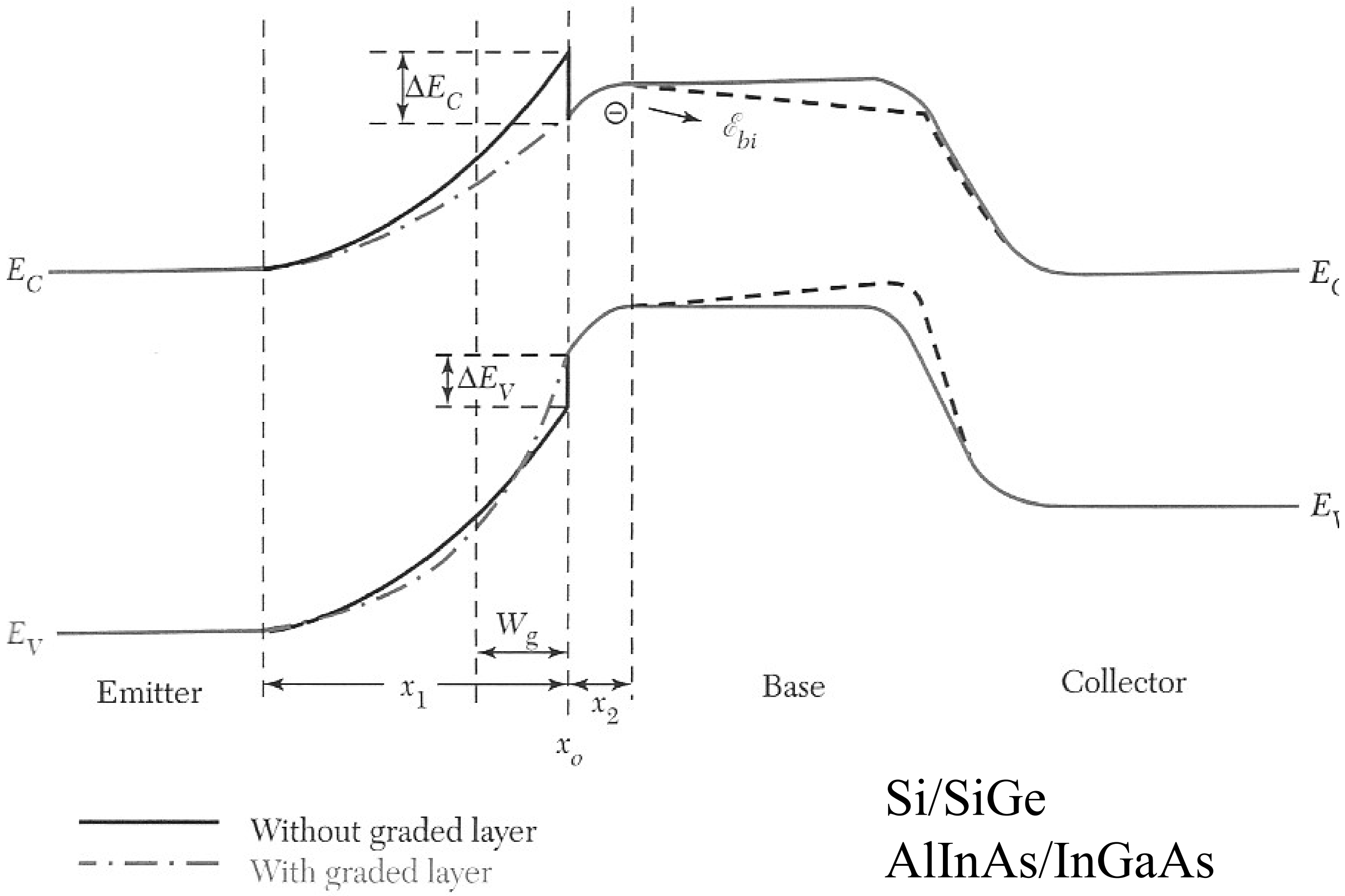
HBT

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

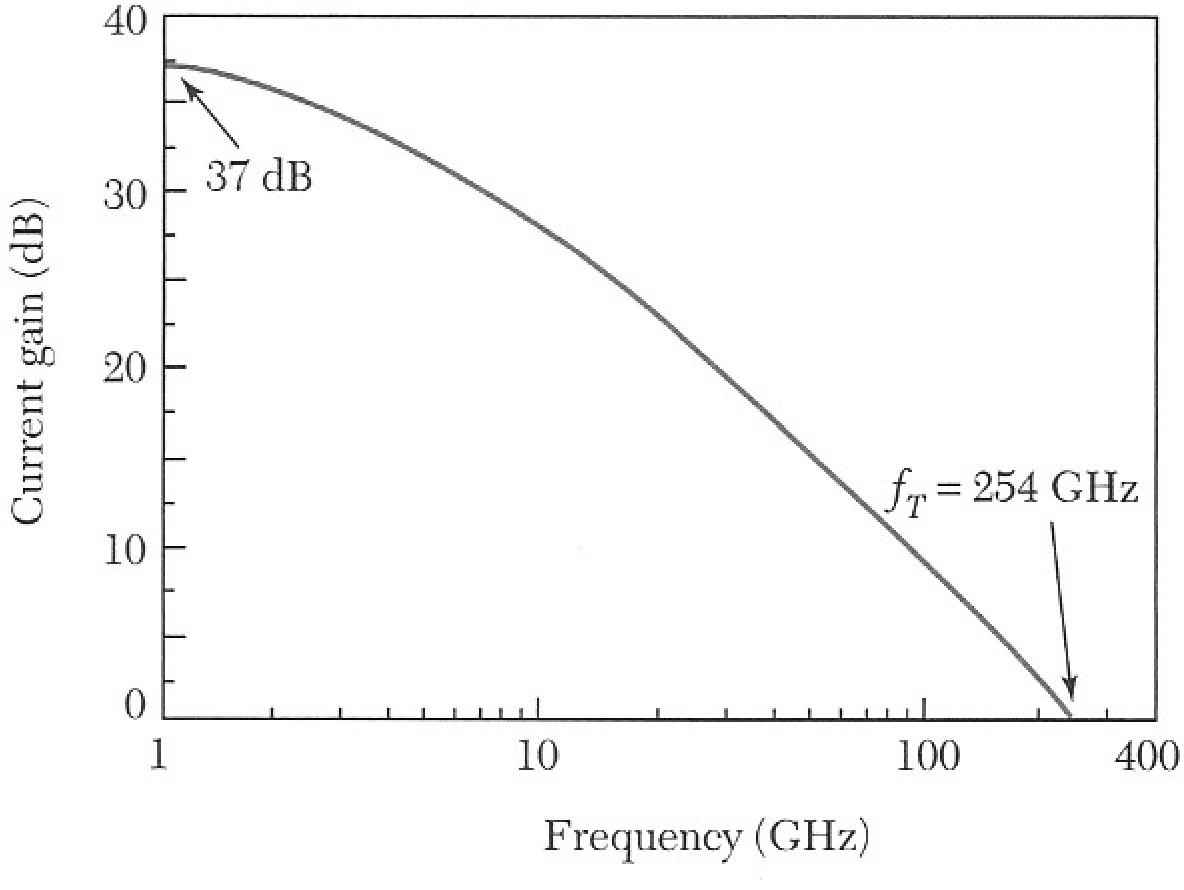
HBT current gain



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

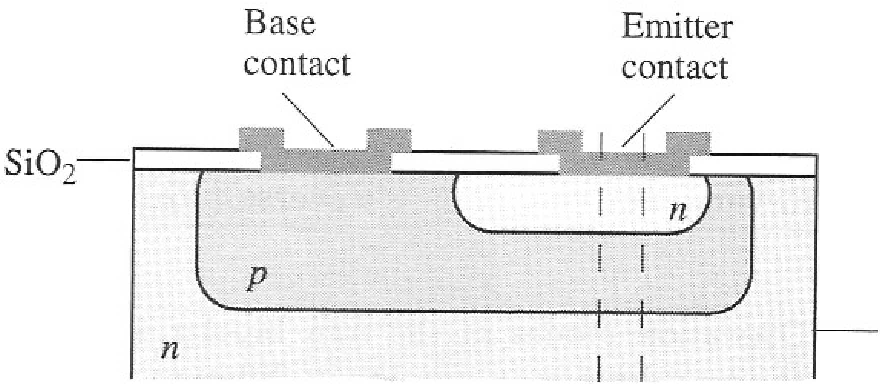
Electronics: $L \ll \lambda$ $f <\sim 10$ GHz

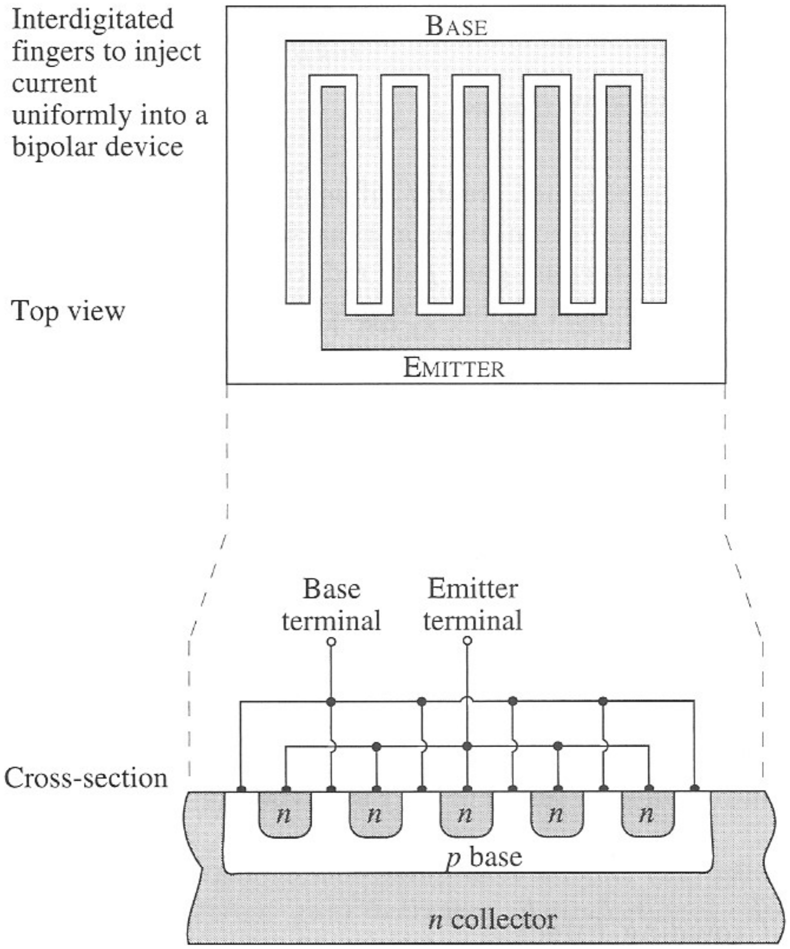
Microwave: $\lambda < L$ 10 GHz $< f <$ 1 THz

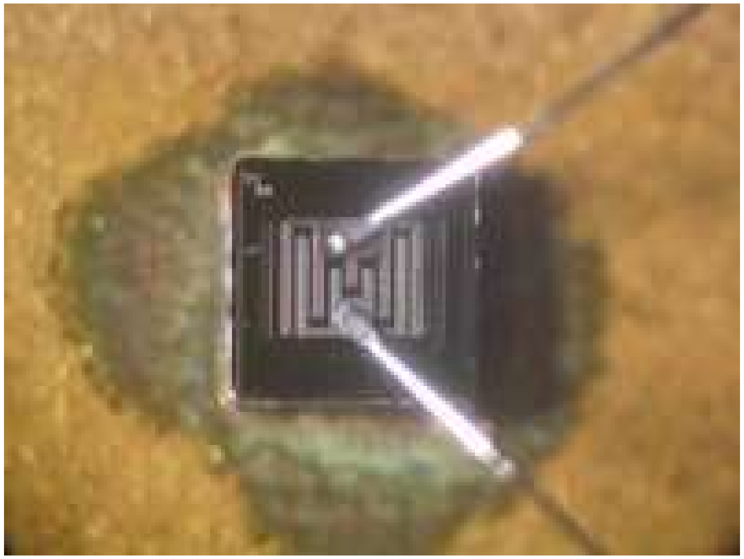
TeraHertz: $\lambda \ll L$ 1 THz $< f <$ 100 THz

Optics: $\lambda \ll L$ 100 THz

Interdigitated contacts in power transistors

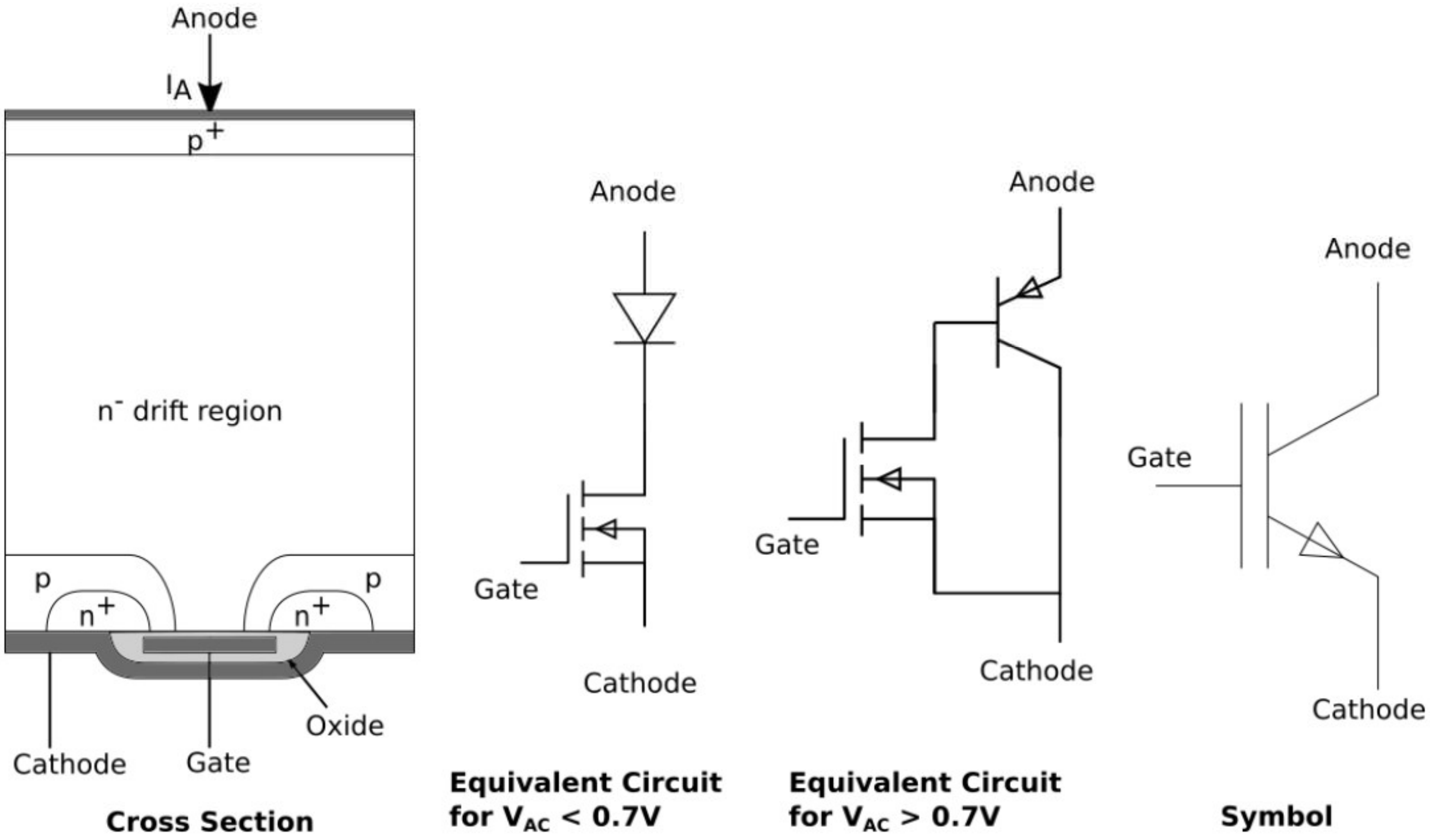



Interdigitated fingers to inject current uniformly into a bipolar device



IGBT - Insulated Gate Bipolar Transistor

An IGBT is a combination of an insulated gate FET and a bipolar transistor. It is primarily used for switching high power loads



Cross Section

Equivalent Circuit for $V_{AC} < 0.7V$

Equivalent Circuit for $V_{AC} > 0.7V$

Symbol

Used to switch large currents (in electric cars or trains).

http://lampx.tugraz.at/~hadley/psd/L13/igbt.html