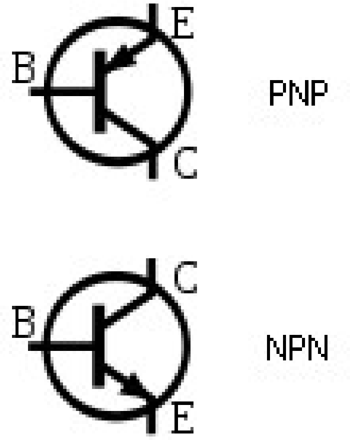
Bipolar transistors, Thyristors, and Latch-up

bipolar transistors



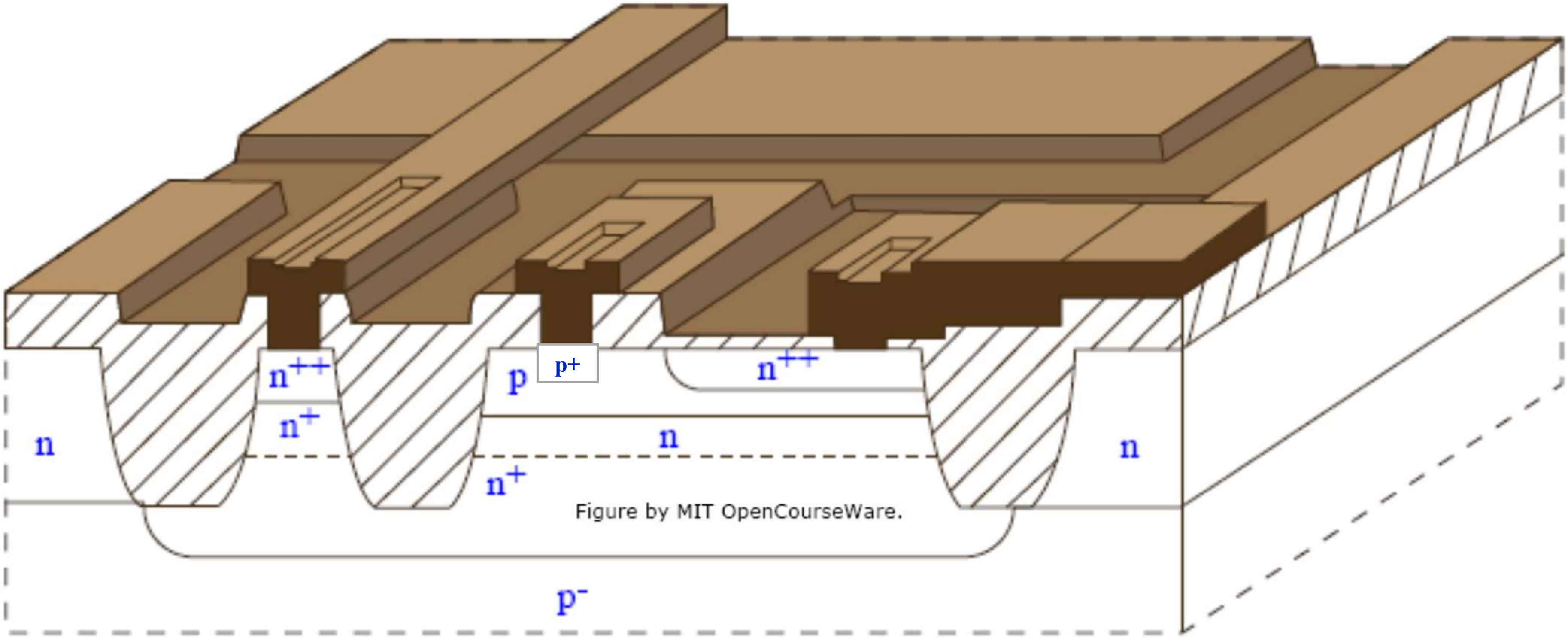
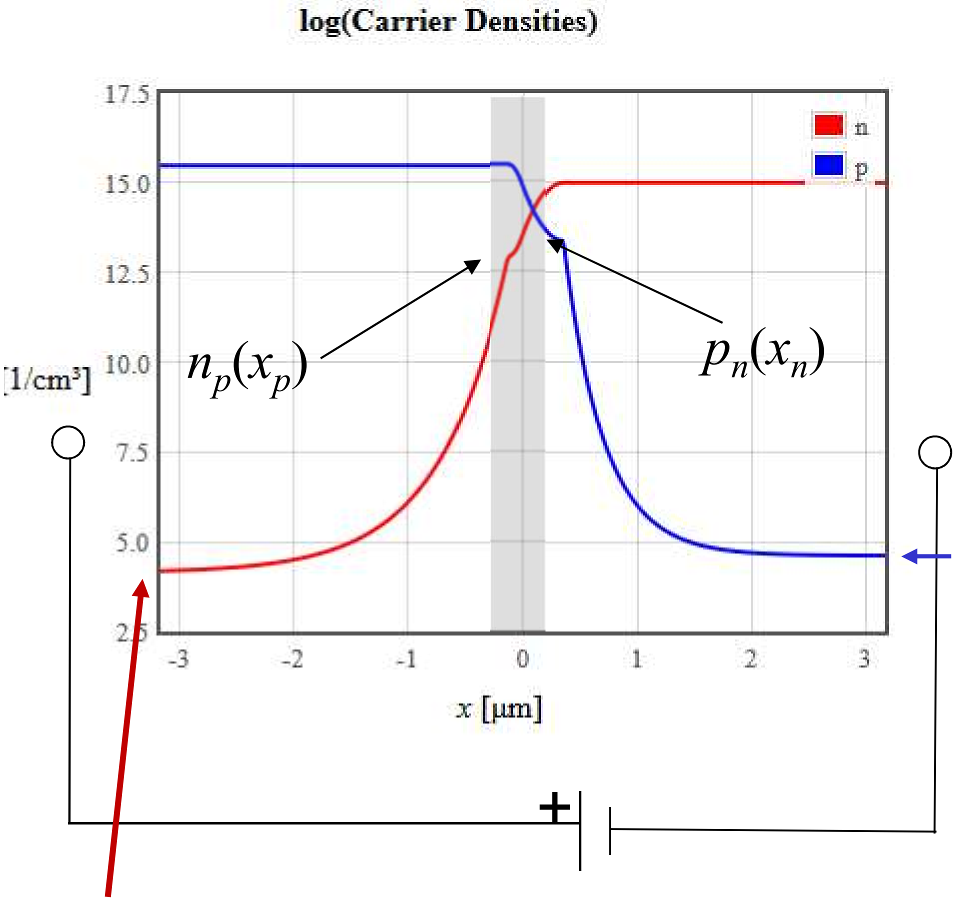


Figure by MIT OpenCourseWare.

Oxide isolated integrated BJT - a modern process

Forward bias, V > 0



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

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

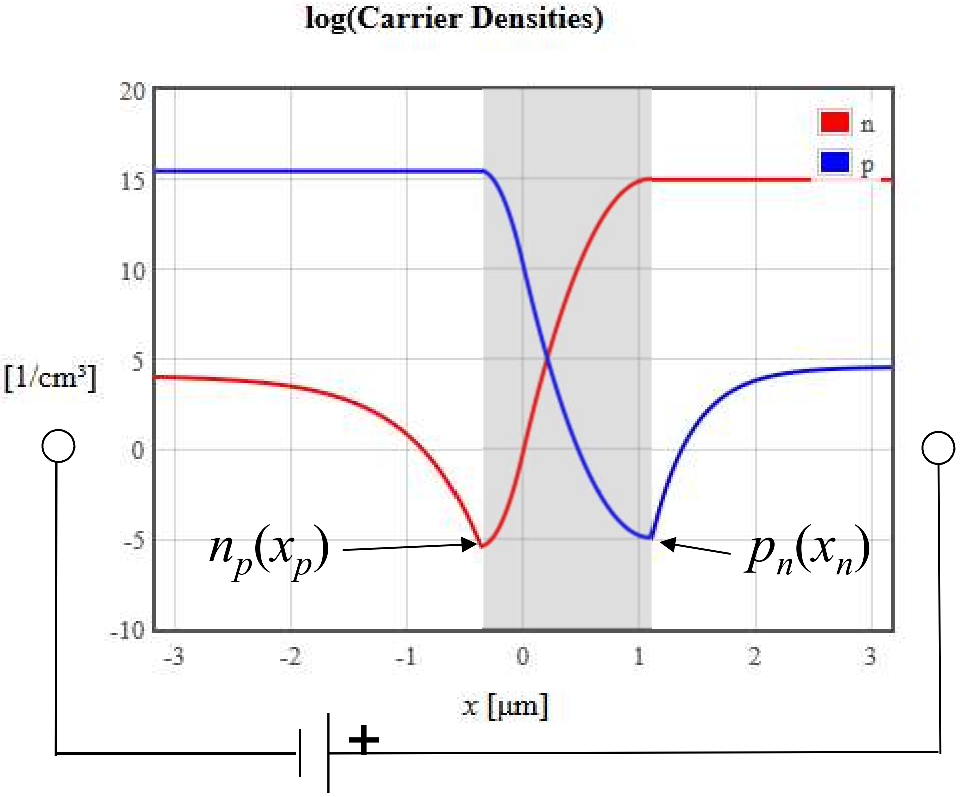
$$n_p(x_p) = n_{p0} \exp\left(\frac{eV}{k_B T}\right)$$

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

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

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

Reverse bias, V < 0



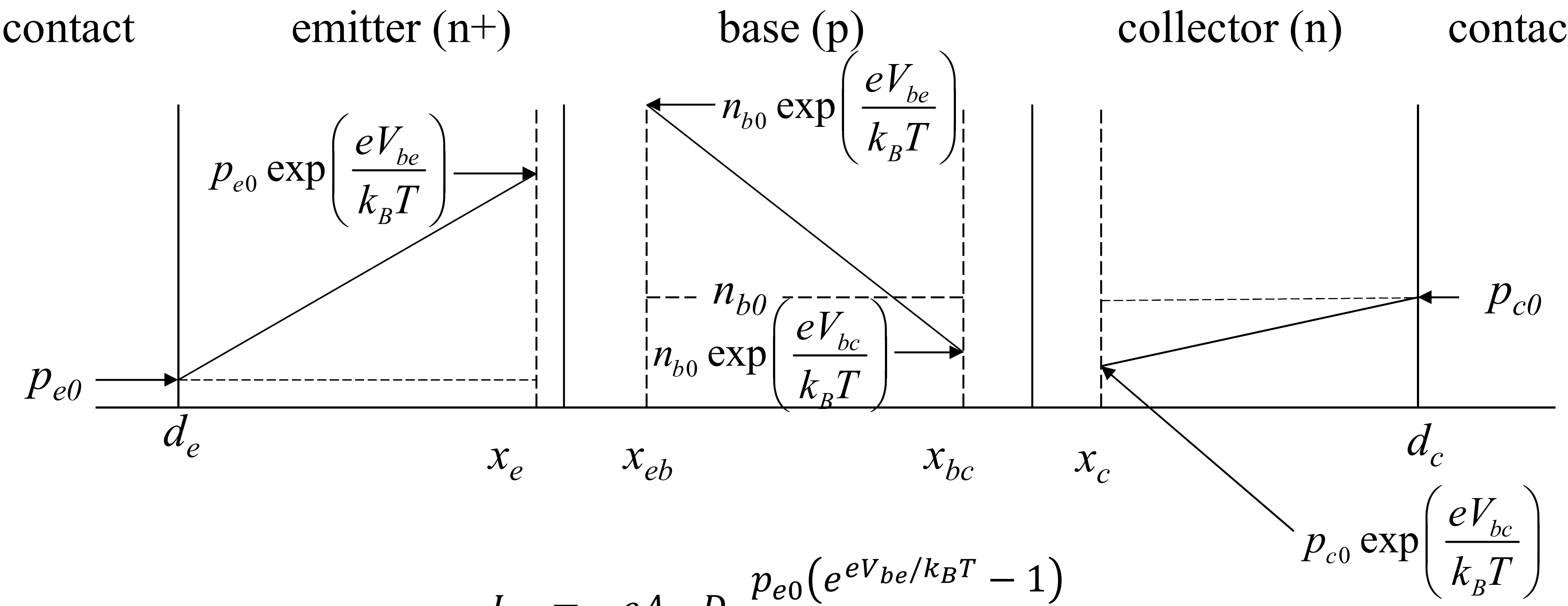
Electrons and holes are driven away from the junction.
The depletion region becomes wider

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

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

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

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 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

Early effect

Ebers - Moll:

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

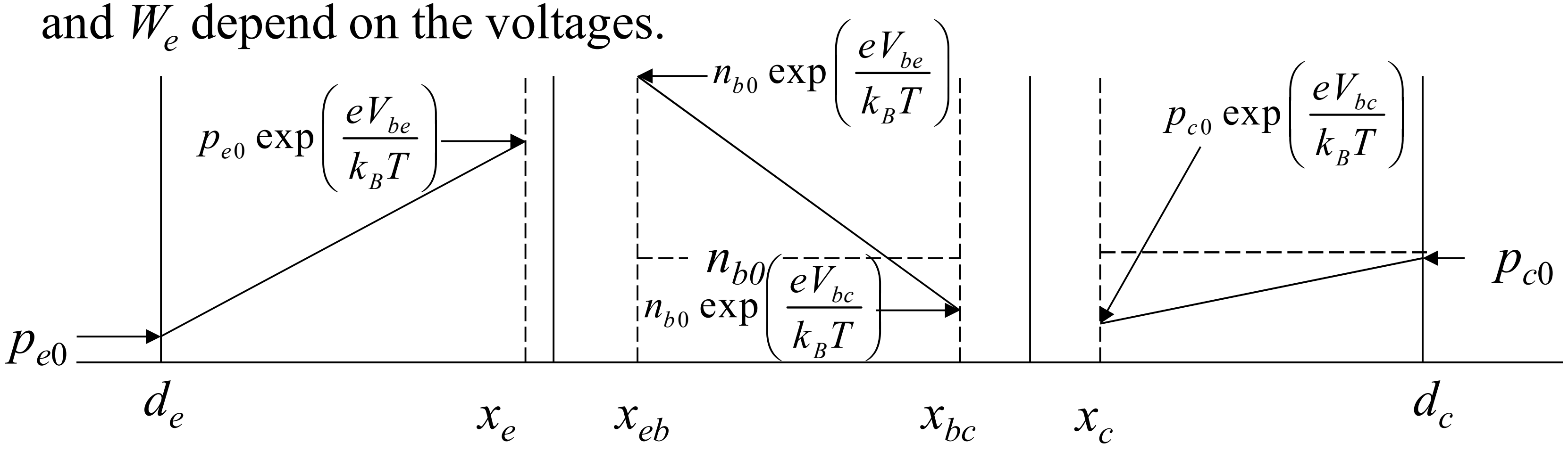
$$I_c = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$

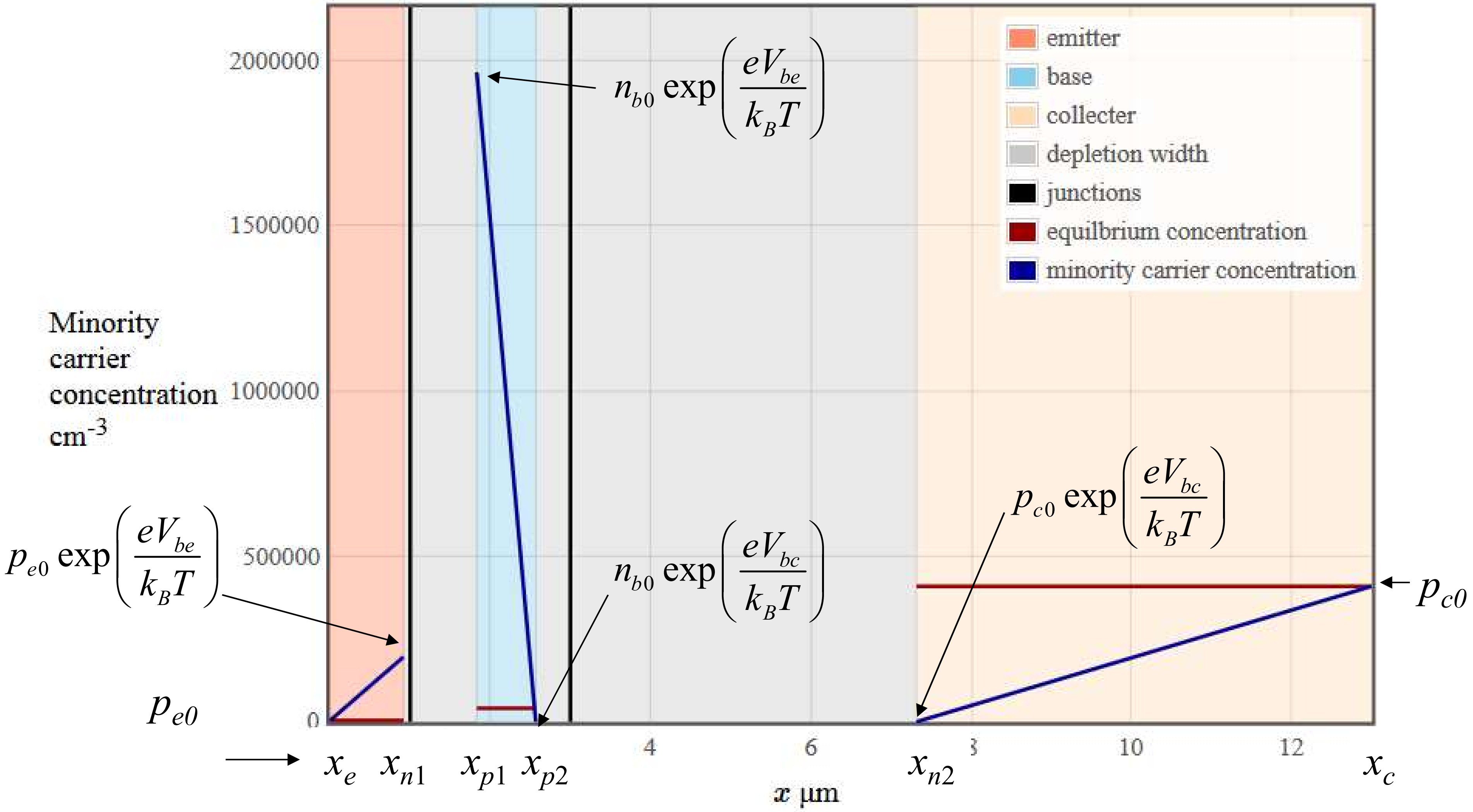
$$I_{ES} = \left[\frac{eA_{be}D_p p_{e0}}{x_{eb} - d_e} + \frac{eA_{be}D_n n_{b0}}{x_{bc} - x_{be}}\right]$$

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

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.

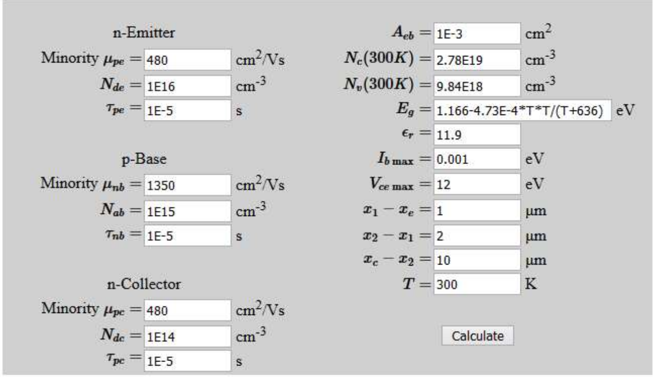


Minority carrier concentration



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

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

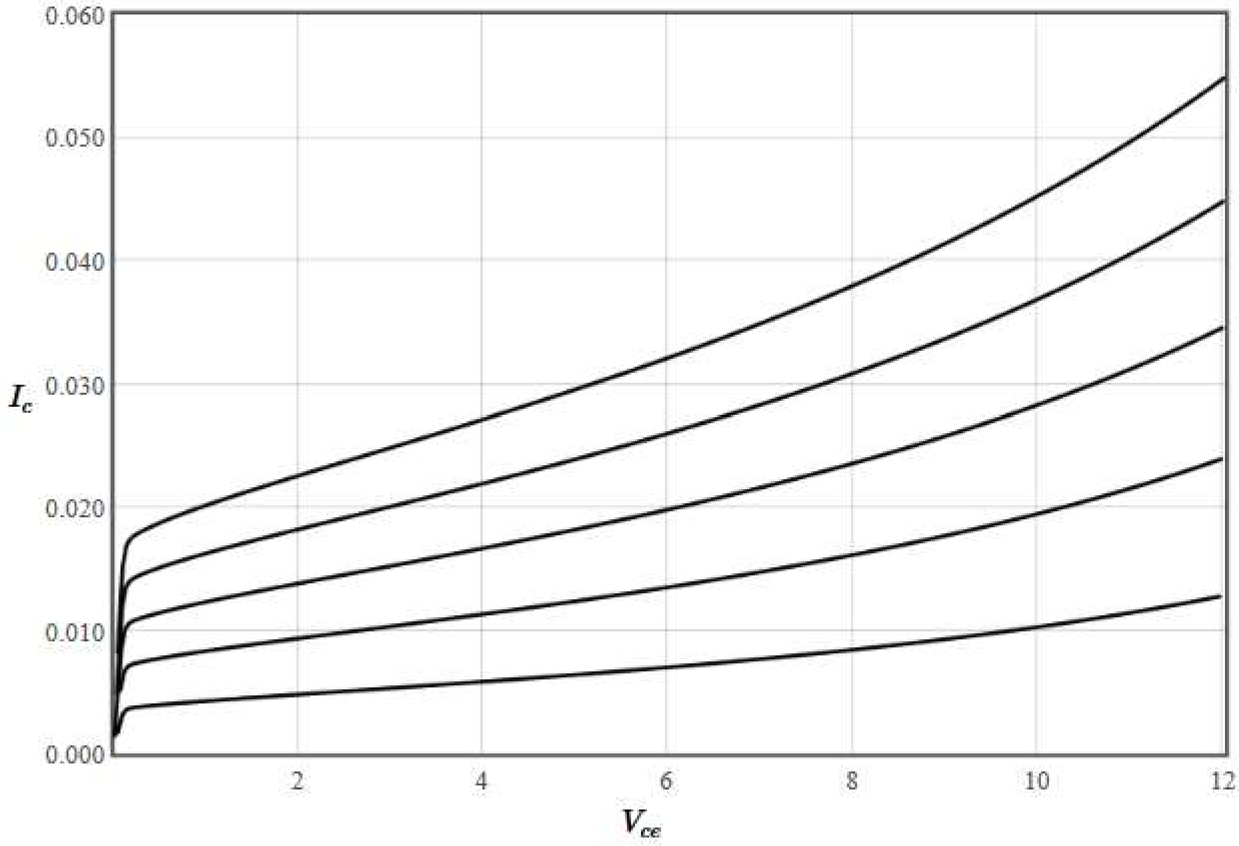
Minority μ_{nb} = 1350 cm^2/Vs
N_{ab} = 1E15 cm^{-3}
τ_{nb} = 1E-5 s

n-Collector

Minority μ_{pc} = 480 cm^2/Vs
N_{dc} = 1E14 cm^{-3}
τ_{pc} = 1E-5 s

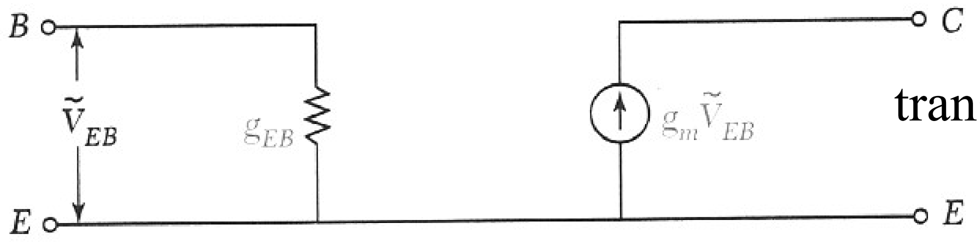
A_{eb} = 1E-3 cm^2
$N_c(300K)$ = 2.78E19 cm^{-3}
$N_v(300K)$ = 9.84E18 cm^{-3}
E_g = 1.166-4.73E-4*T*T/(T+636) eV
ϵ_r = 11.9
$I_{b\,\max}$ = 0.001 eV
$V_{ce\,\max}$ = 12 eV
$x_1 - x_e$ = 1 µm
$x_2 - x_1$ = 2 µm
$x_c - x_2$ = 10 µm
T = 300 K

$I_C \sim \beta I_B$



Small signal response

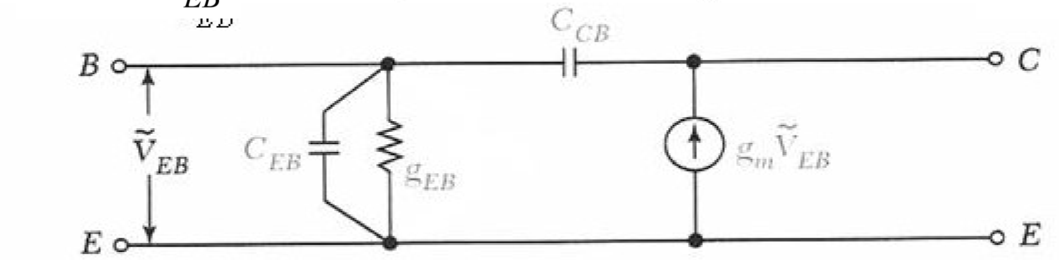
$$\tilde{i}_c = \beta \tilde{i}_B = \beta g_{EB} \tilde{v}_{EB}$$

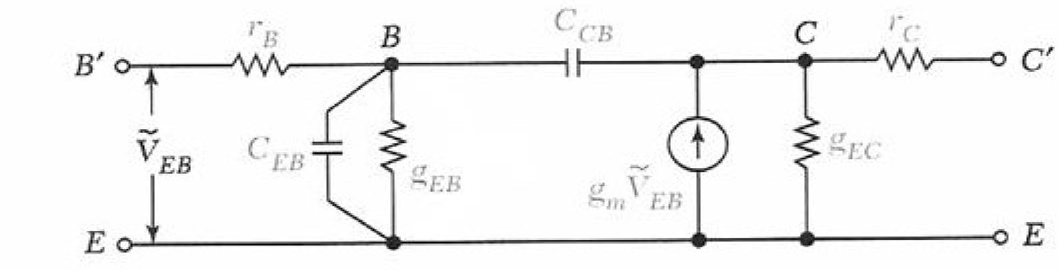


transistor man

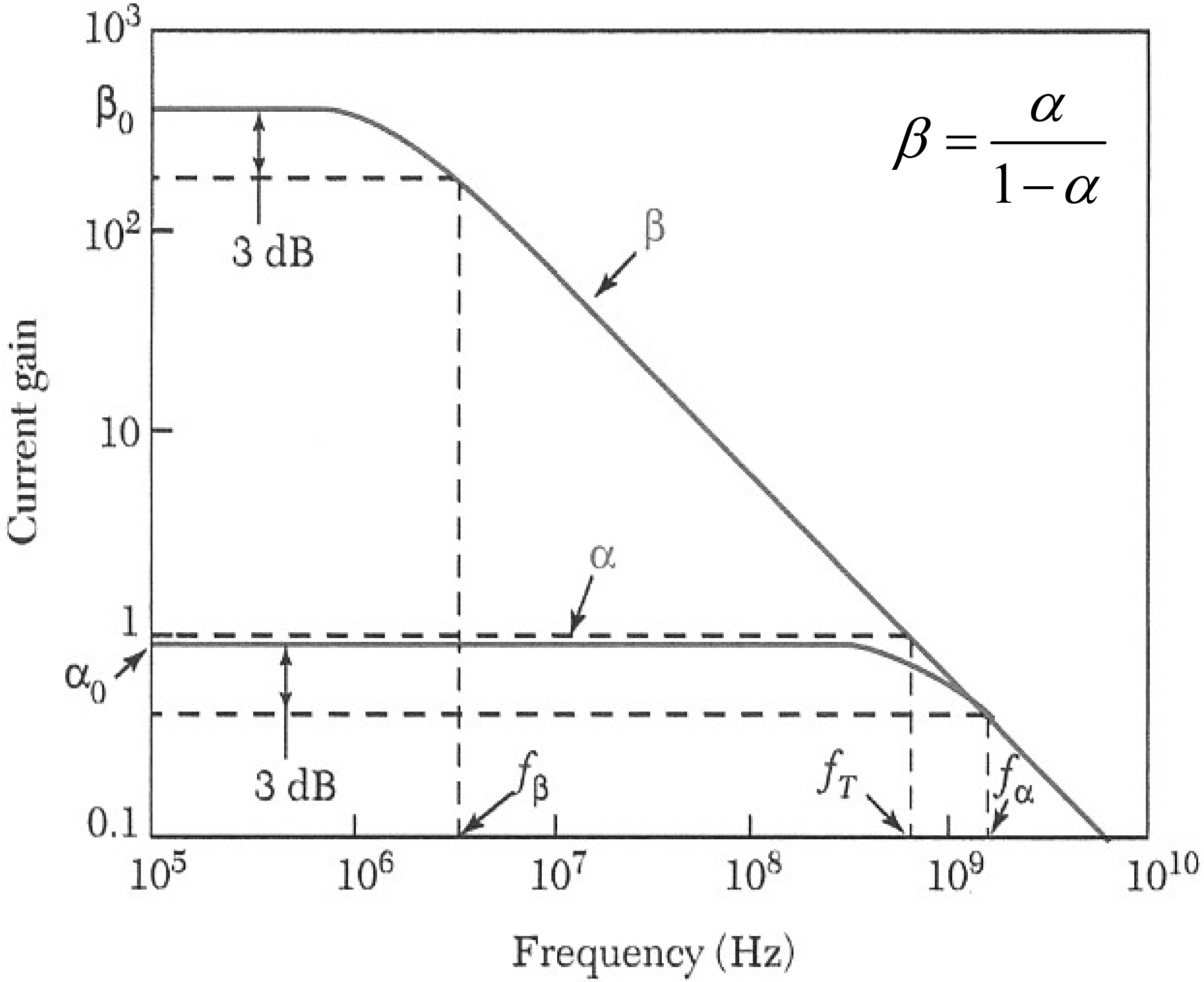
input conductance: $g_{EB} = \dfrac{\tilde{i}_B}{\tilde{v}_{EB}}$

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





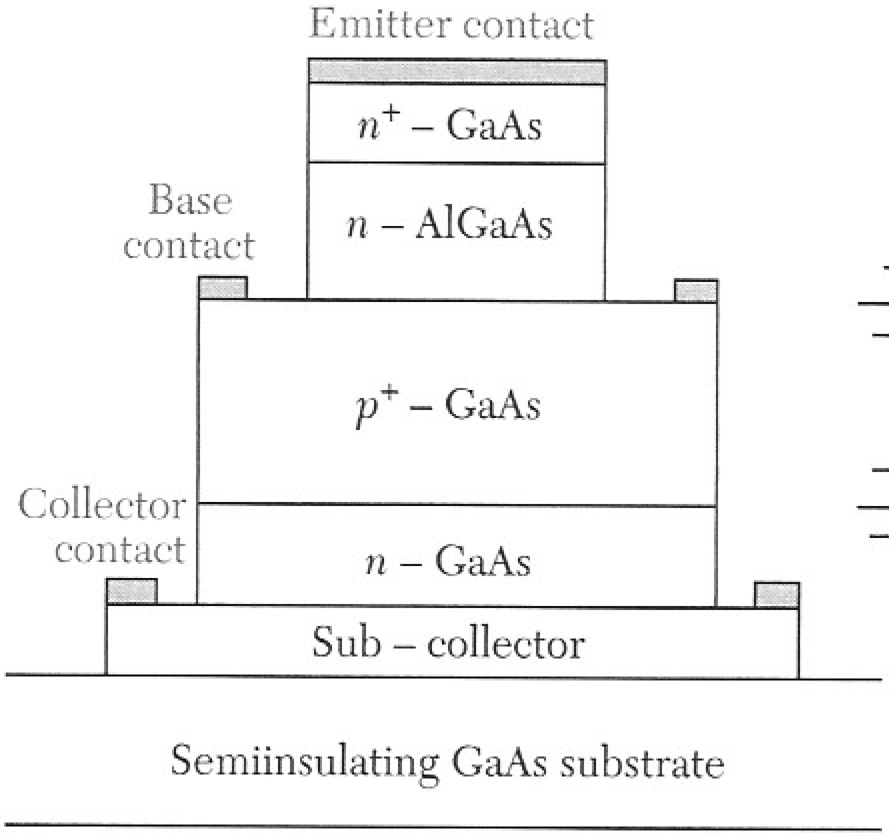
Small signal response

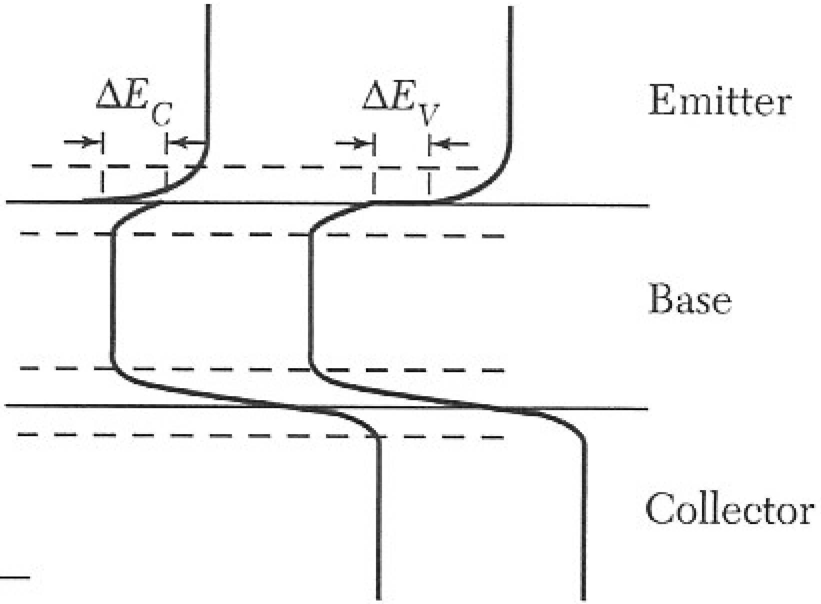


$$\beta = \frac{\alpha}{1-\alpha}$$

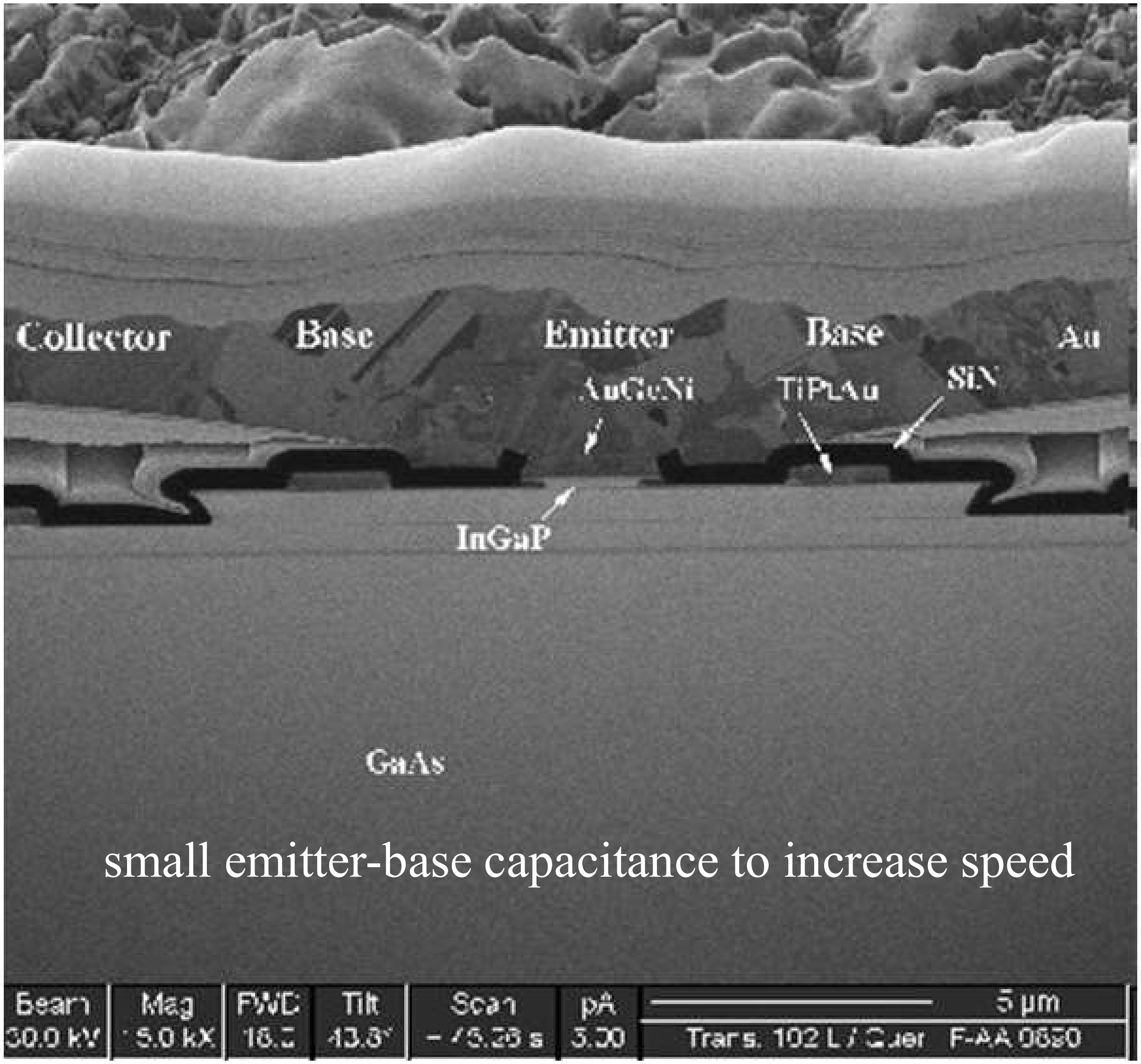
$$f_\beta = \left(1-\alpha_0\right) f_\alpha \qquad f_T = \alpha_0 f_\alpha$$

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 in a normal transistor the bandgap is smaller in the emitter.

HBT

Trade off gain for higher speed

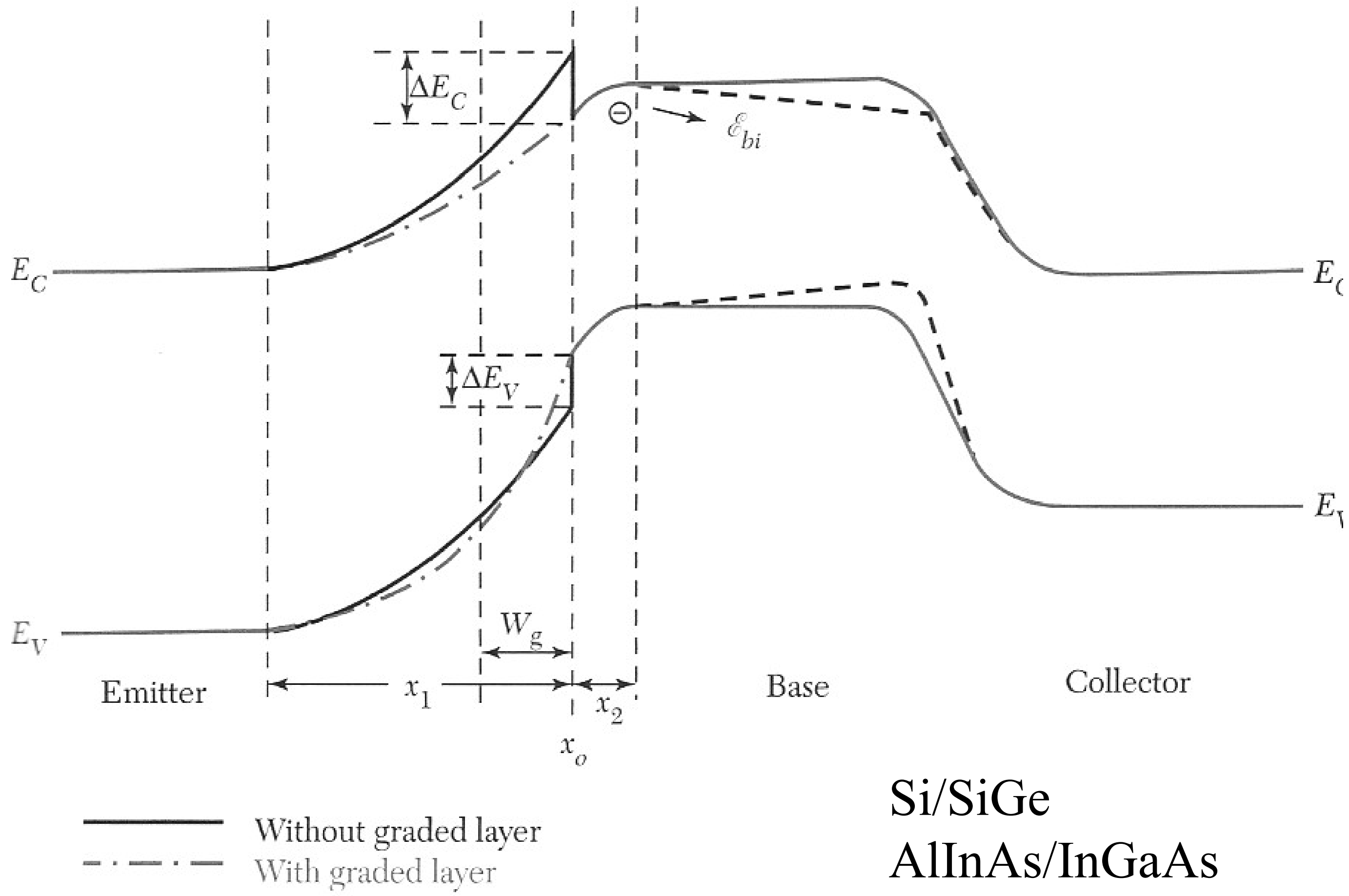
Higher base doping

- 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 punchthrough

- lower collector resistance

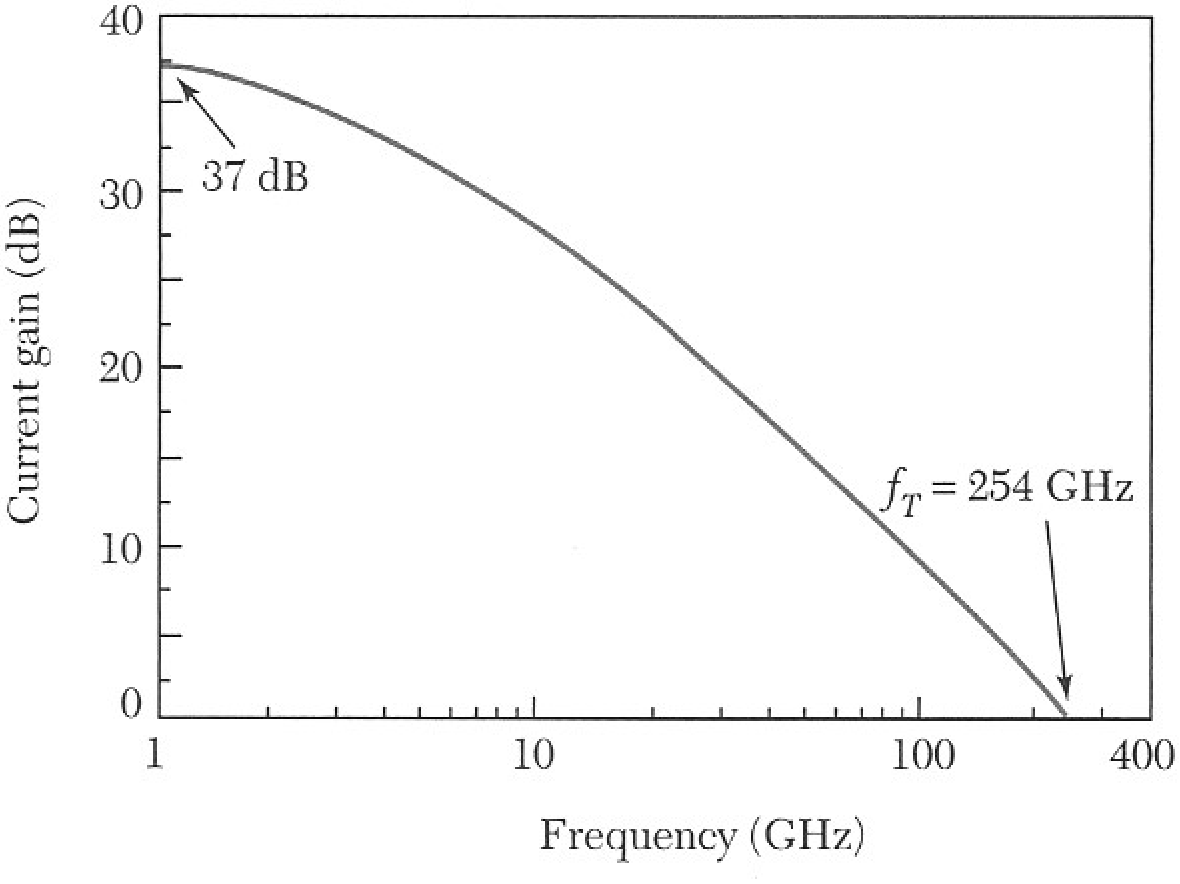
HBT current gain



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

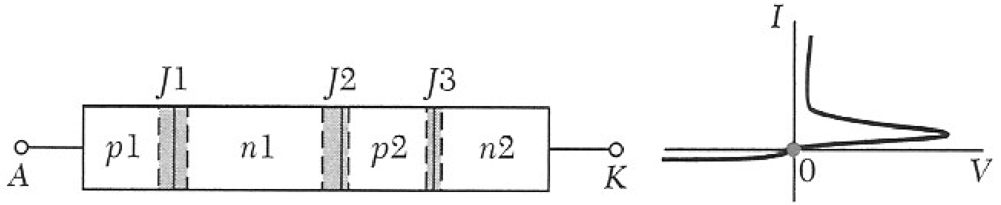
Electronics: $L << \lambda$ $f <\sim 10$ GHz

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

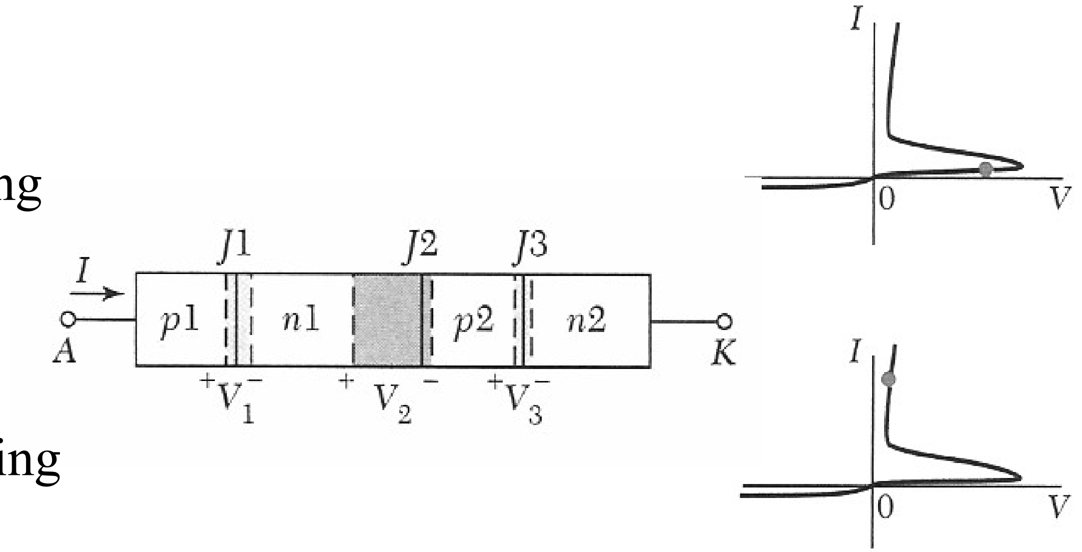
TeraHertz: $\lambda << L$ 1 THz $< f <$ 100 THz

Optics: $\lambda << L$ 100 THz

Thyristors

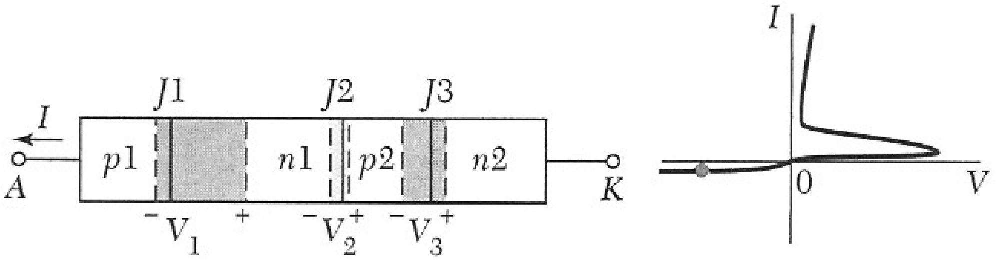


Forward blocking

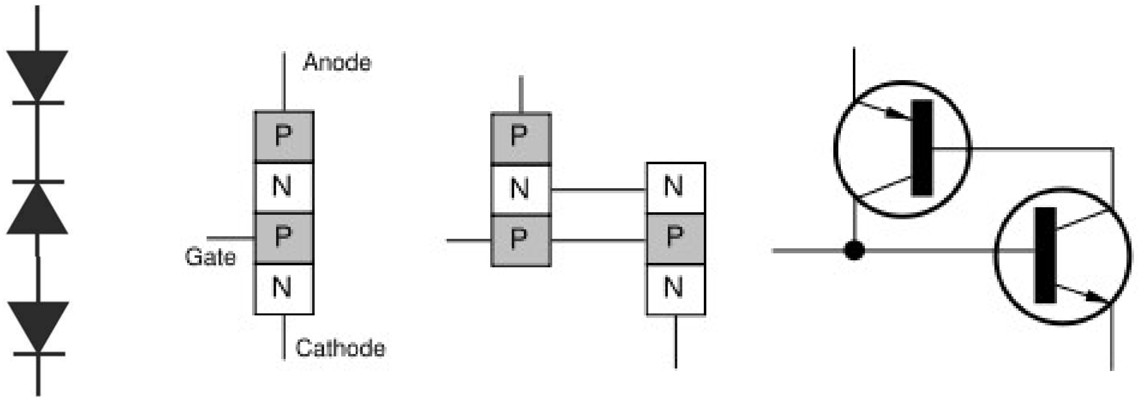


Forward conducting

Reverse blocking

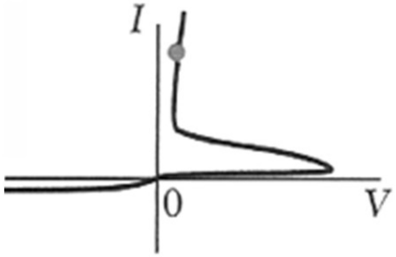


Thyristors

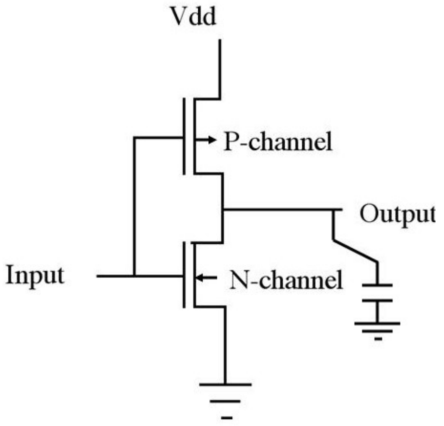


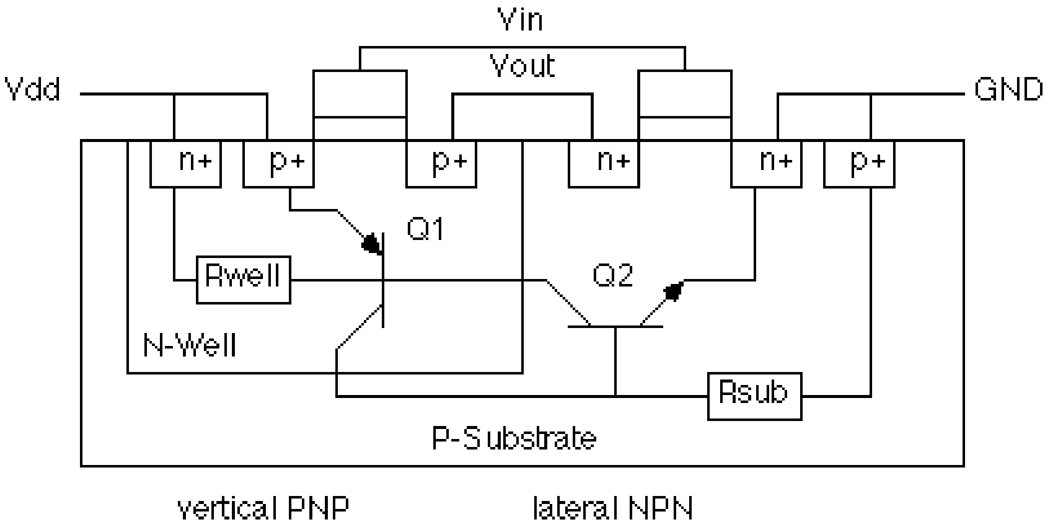
$\beta_1 * \beta_2 > 1$

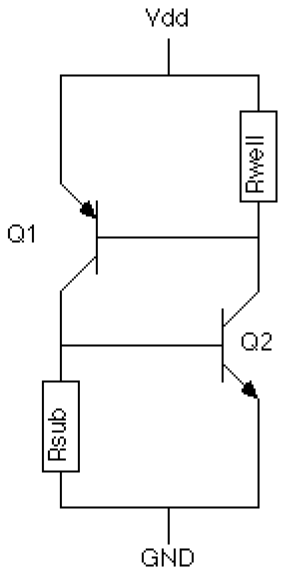
Used for switching high currents or voltages



Latch-up



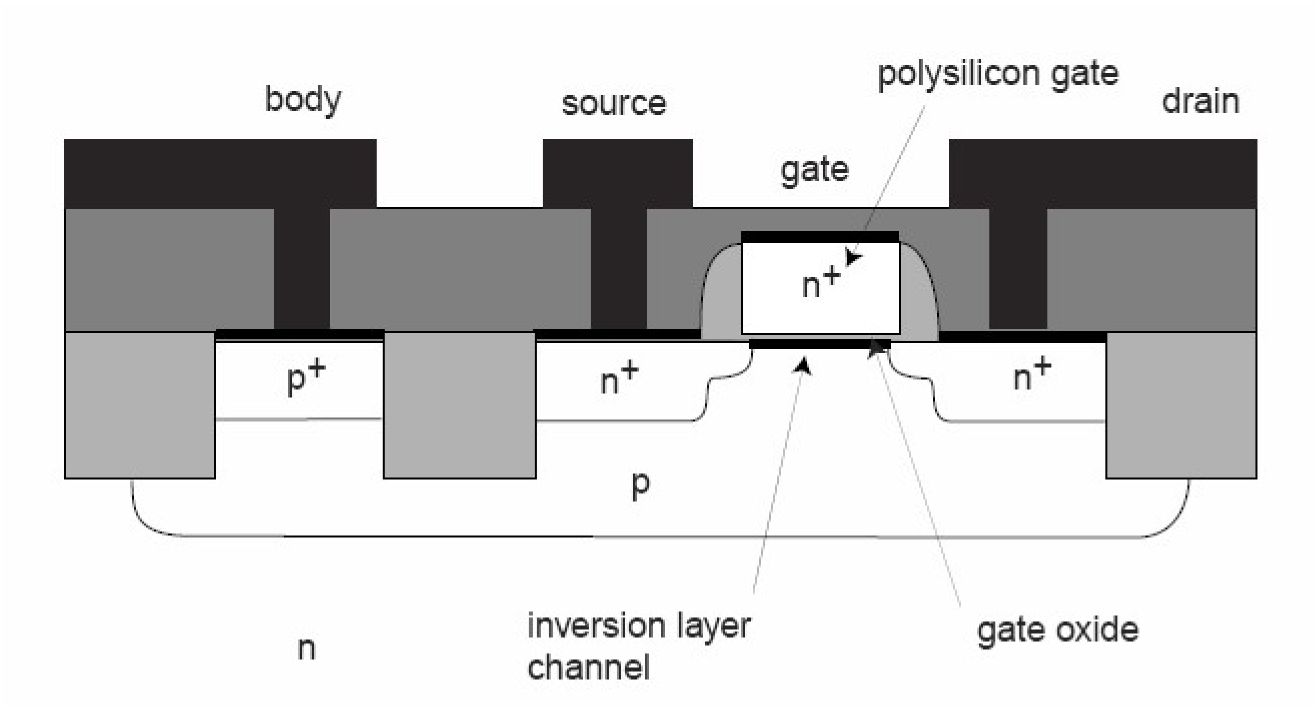




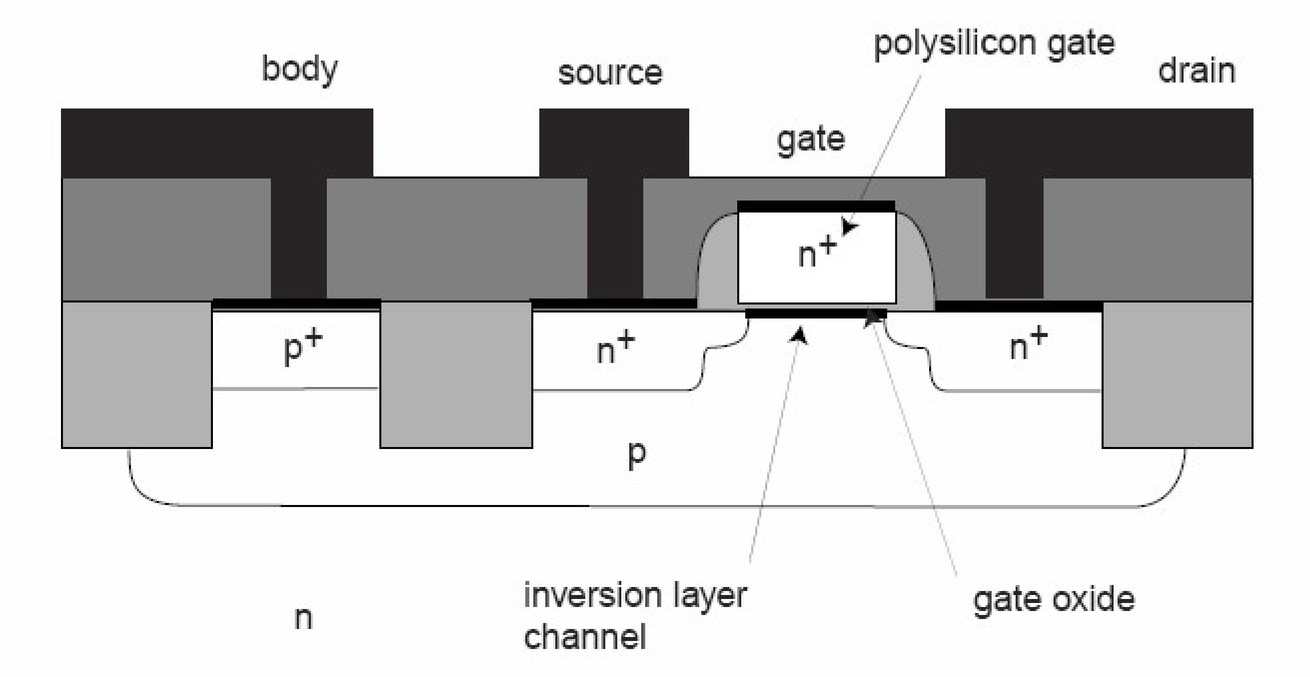
Both BJT's conduct, creating a low resistance path between V_{dd} and GND. The product of the gains of the two transistors in the feedback loop, is greater than one. The result of latchup is at the minimum a circuit malfunction, and in the worst case, the destruction of the device.

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

Can you operate like a BJT?



Subthreshold current

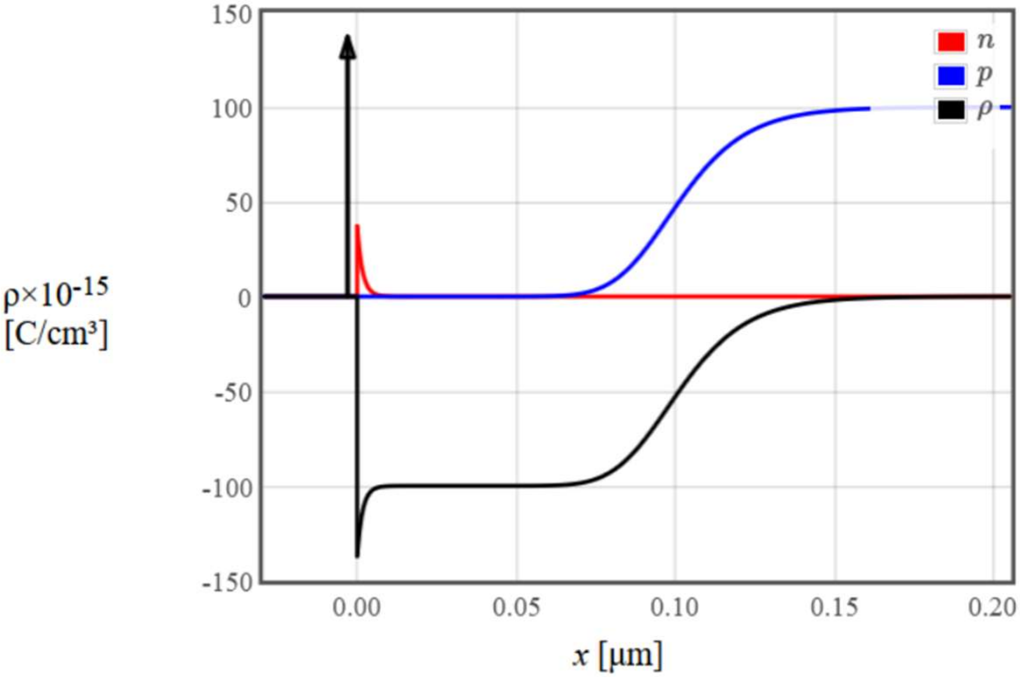


If the p-concentration in the channel is low, electrons emitted into the channel by the forward biased junction diffuse across the channel without recombining.

Subthreshold current – depletion approximation

$$x_p = -\frac{\epsilon_s}{\epsilon_{\text{ox}}}t_{\text{ox}} + \sqrt{\left(\frac{\epsilon_s}{\epsilon_{\text{ox}}}t_{\text{ox}}\right)^2 + \frac{2\epsilon_s}{eN_A}(V_g - V_{fb})}$$

$$n(x) = \begin{cases} \frac{n_i^2}{N_A}\exp\left(\frac{e^2N_A(x_p-x)^2}{2\epsilon_s k_B T}\right) & \text{for } 0 < x < x_p, \\ \frac{n_i^2}{N_A} & \text{for } x > x_p, \end{cases}$$

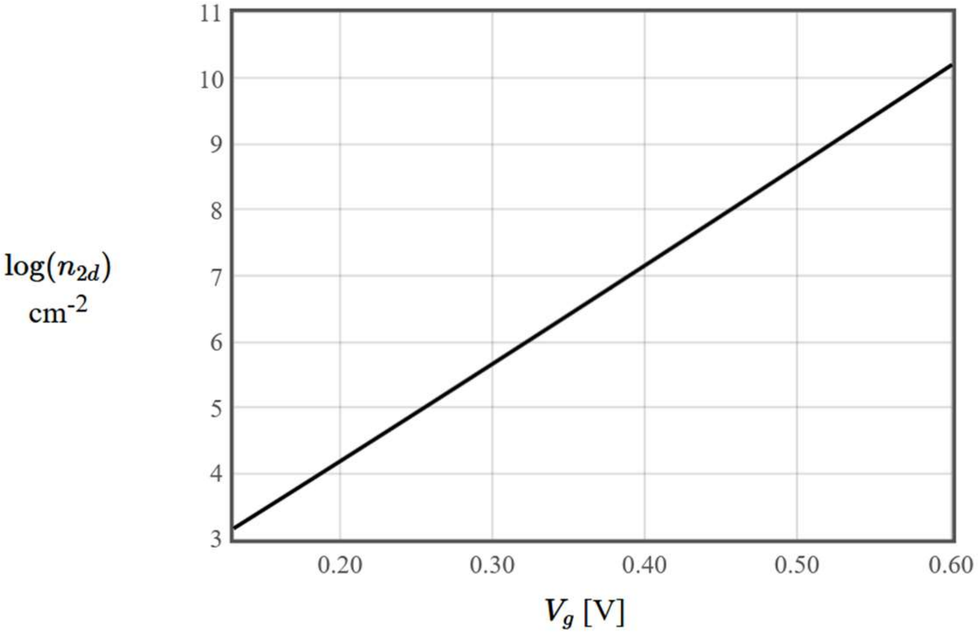


Subthreshold current – depletion approximation

$$n(x) = \frac{n_i^2}{N_A}\exp\left(\frac{e^2 N_A (x_p - x)^2}{2\epsilon_s k_B T}\right)$$

$$n(x) \approx \frac{n_i^2}{N_A}\exp\left(\frac{e^2 N_A (x_p^2 - 2x_p x)}{2\epsilon_s k_B T}\right)$$

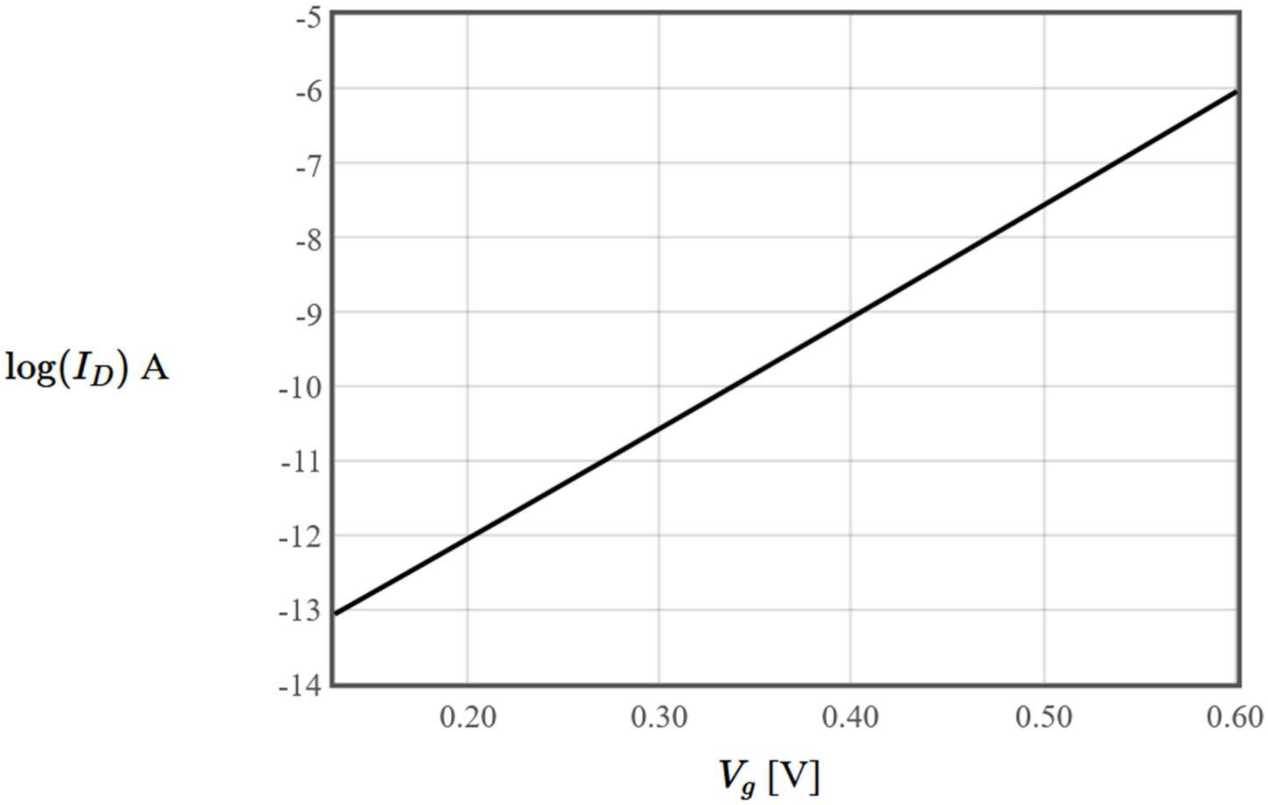
$$n_{2d} = \frac{n_i^2}{N_A}\exp\left(\frac{e^2 N_A x_p^2}{2\epsilon_s k_B T}\right)\frac{\epsilon_s k_B T}{e^2 N_A x_p}$$



Subthreshold current – depletion approximation

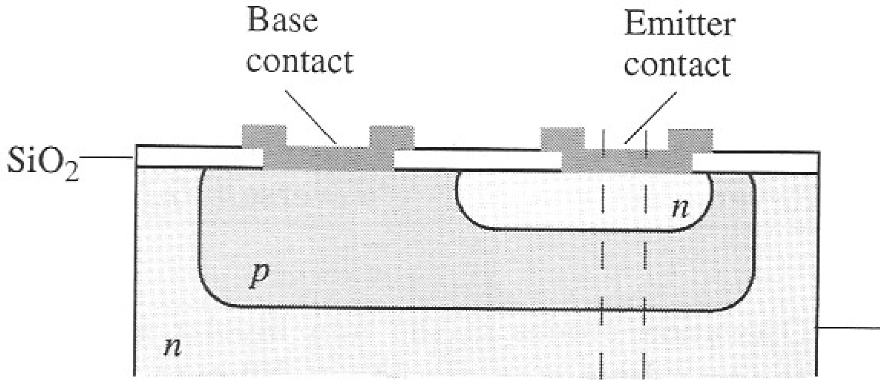
$$\nabla n \approx -\frac{n_{2d}}{L}$$

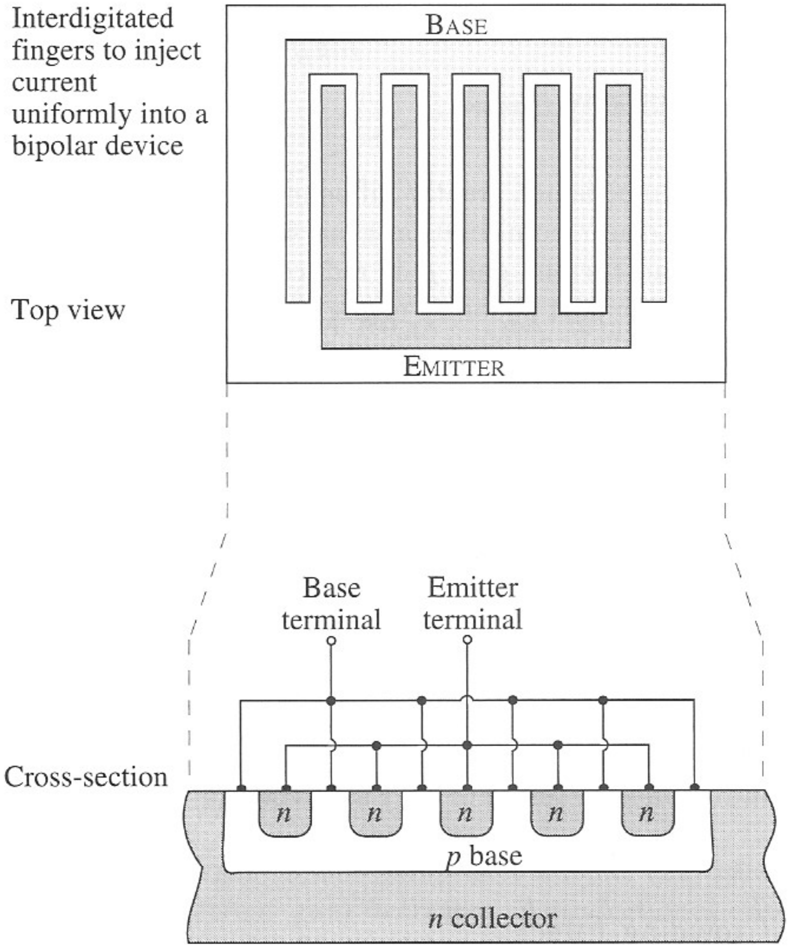
$$I_D \approx \frac{k_B T \mu W n_{2d}}{L} = \frac{n_i^2 \mu \epsilon_s k_B^2 T^2 W}{e^2 N_A^2 x_p L}\exp\left(\frac{e^2 N_A x_p^2}{2\epsilon_s k_B T}\right)$$

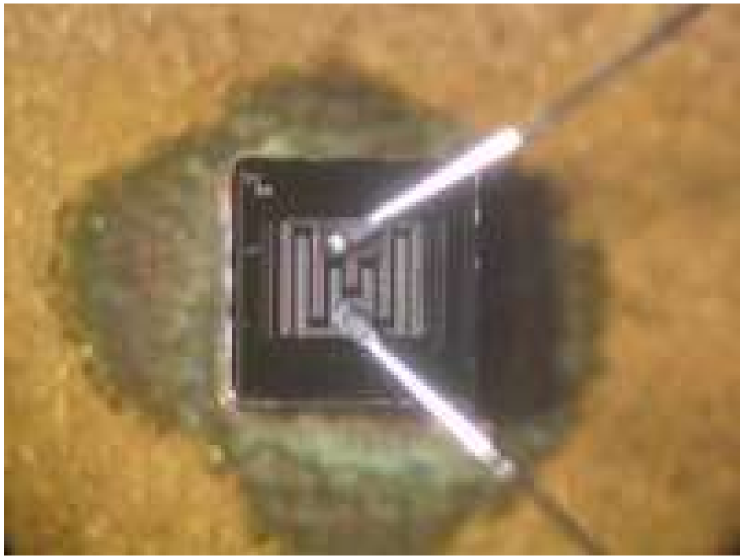


Subthreshold slope: 70-100 mV/decade

Interdigitated contacts in power transistors

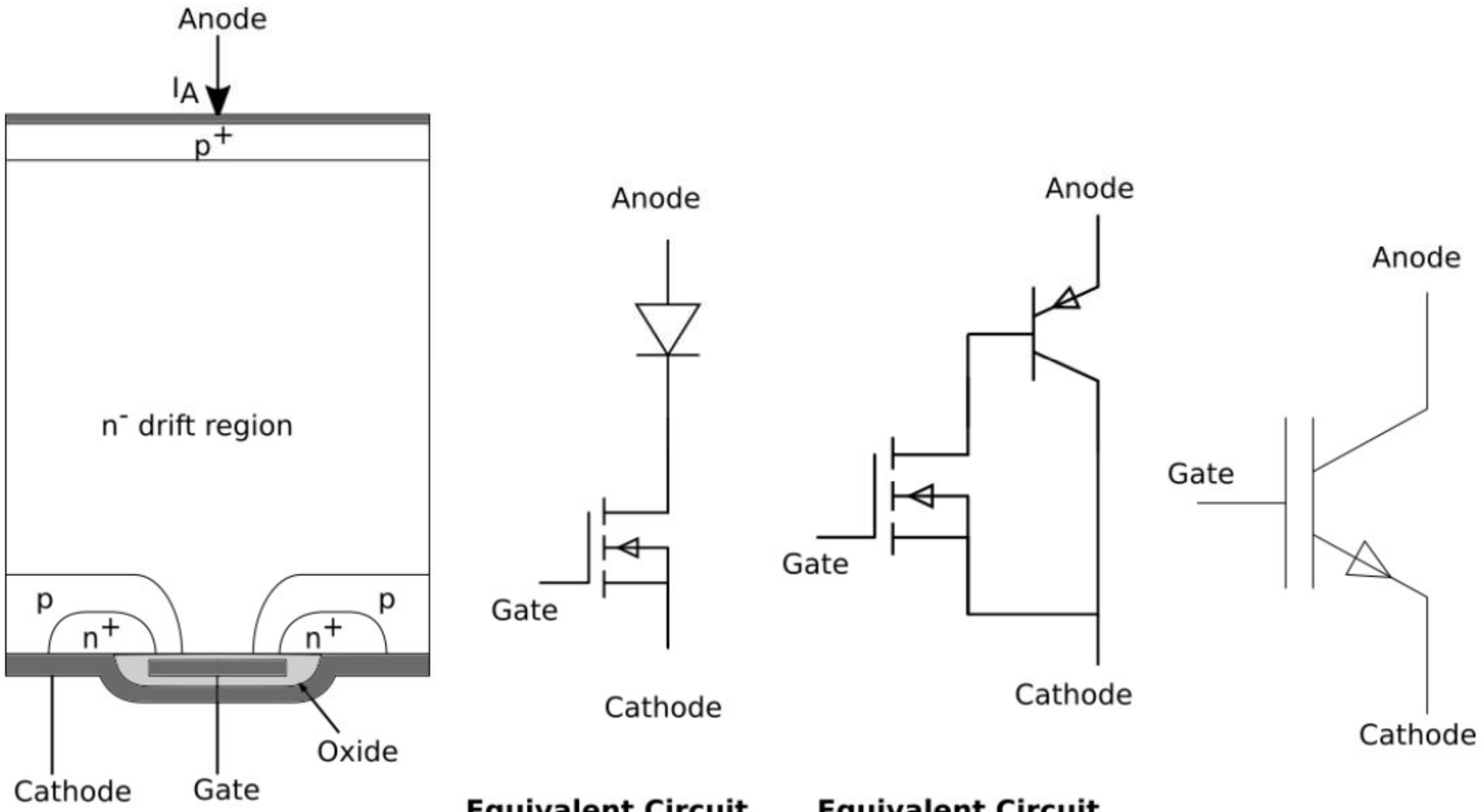






IGBT - Insulated Gate Bipolar Transistor

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 $V_{AC} < 0.7V$

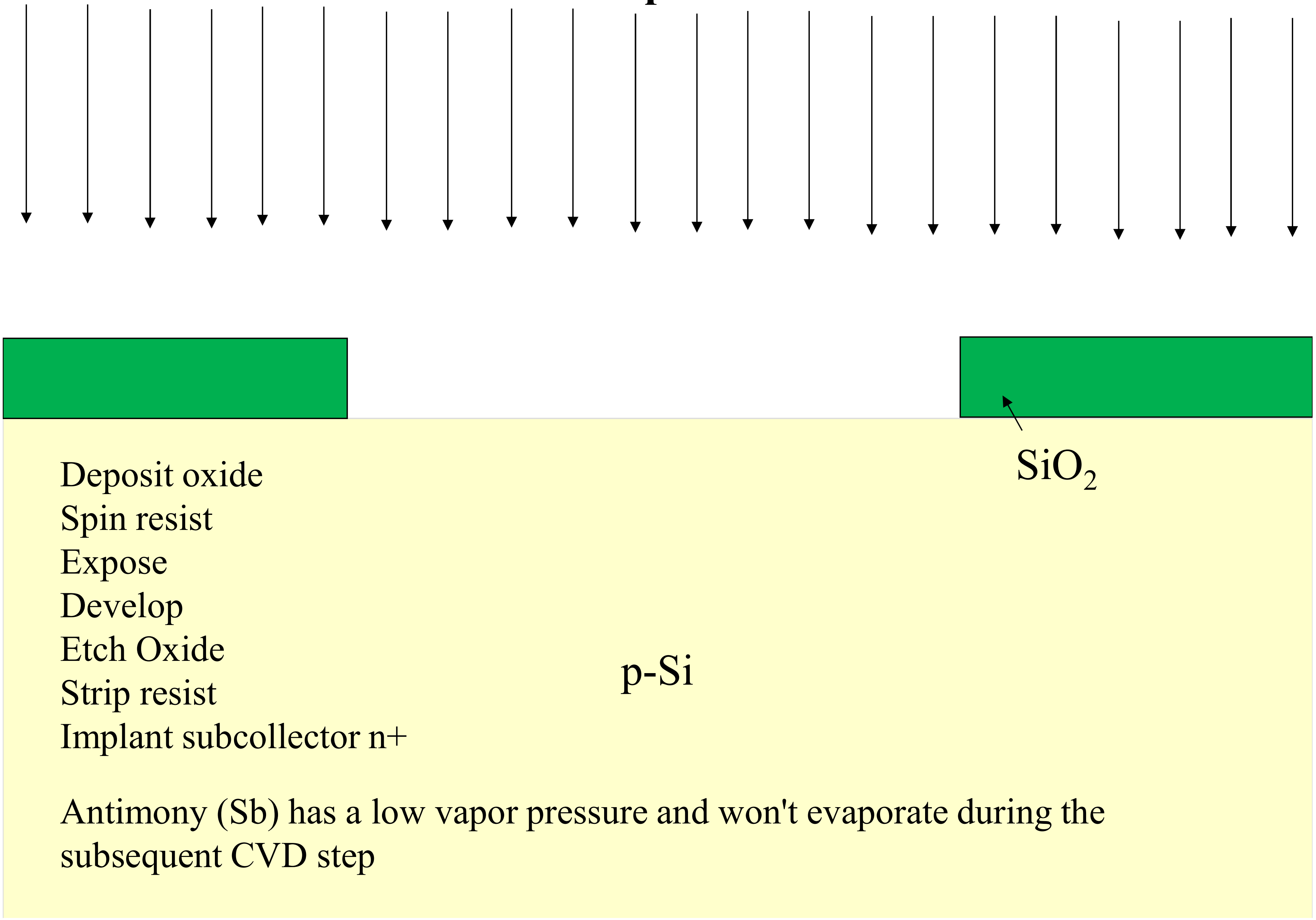
Equivalent Circuit for $V_{AC} > 0.7V$

Symbol

Used to switch large currents (in electric cars or trains).
Like a thyristor for high voltages.

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

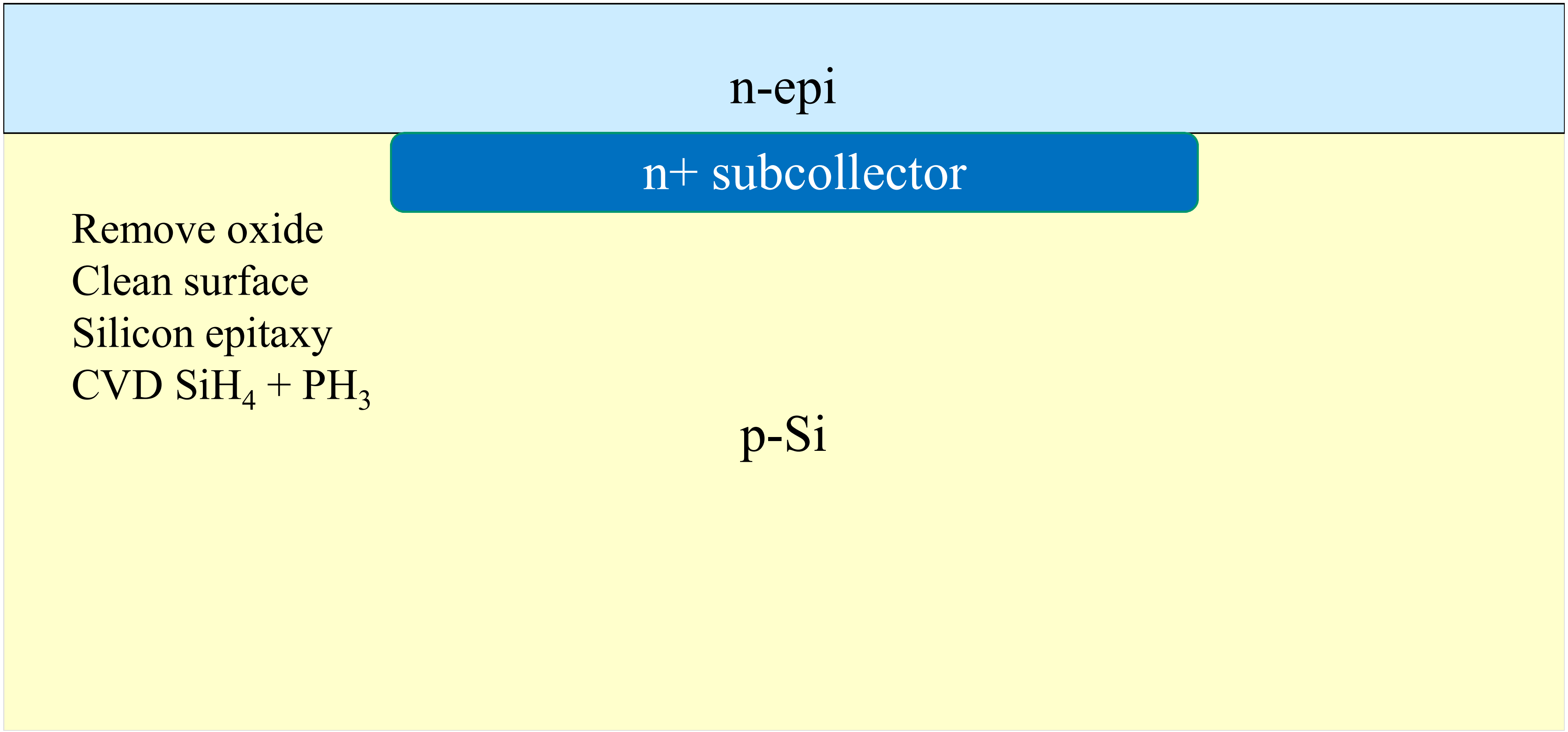
Implant



Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant subcollector n+

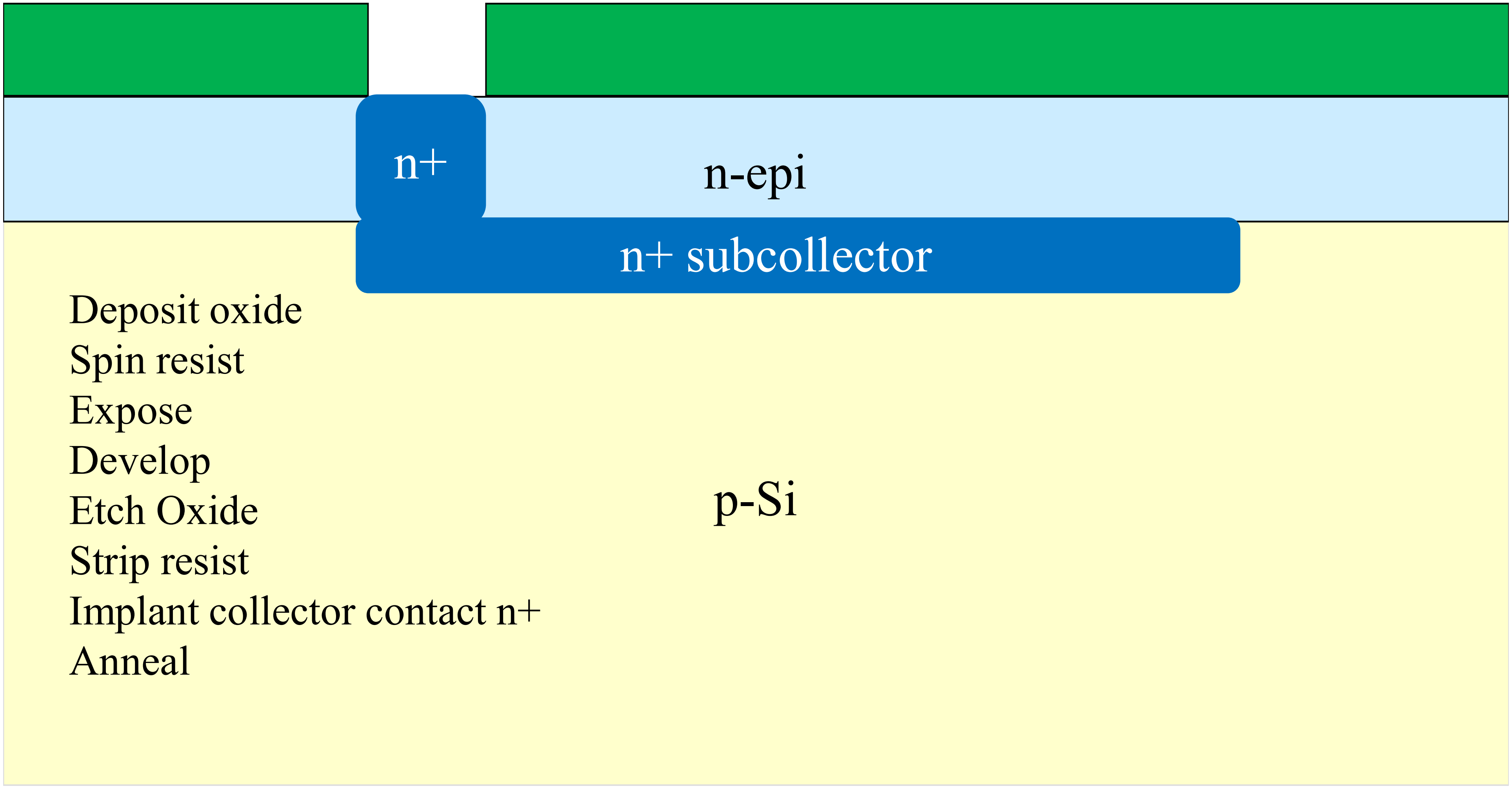
Antimony (Sb) has a low vapor pressure and won't evaporate during the subsequent CVD step

Epi-growth



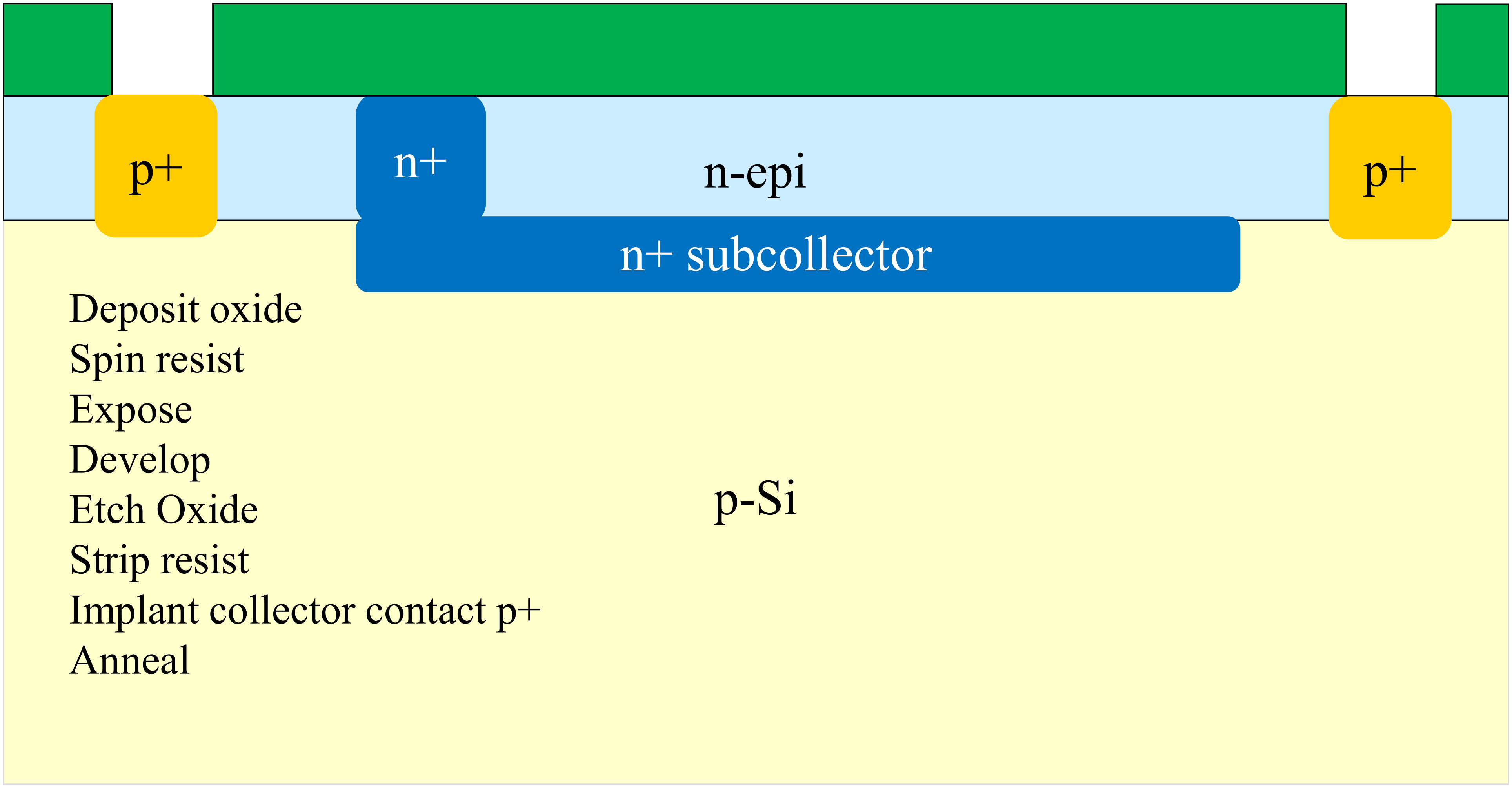
Remove oxide
Clean surface
Silicon epitaxy
CVD $SiH_4 + PH_3$

Collector Contact



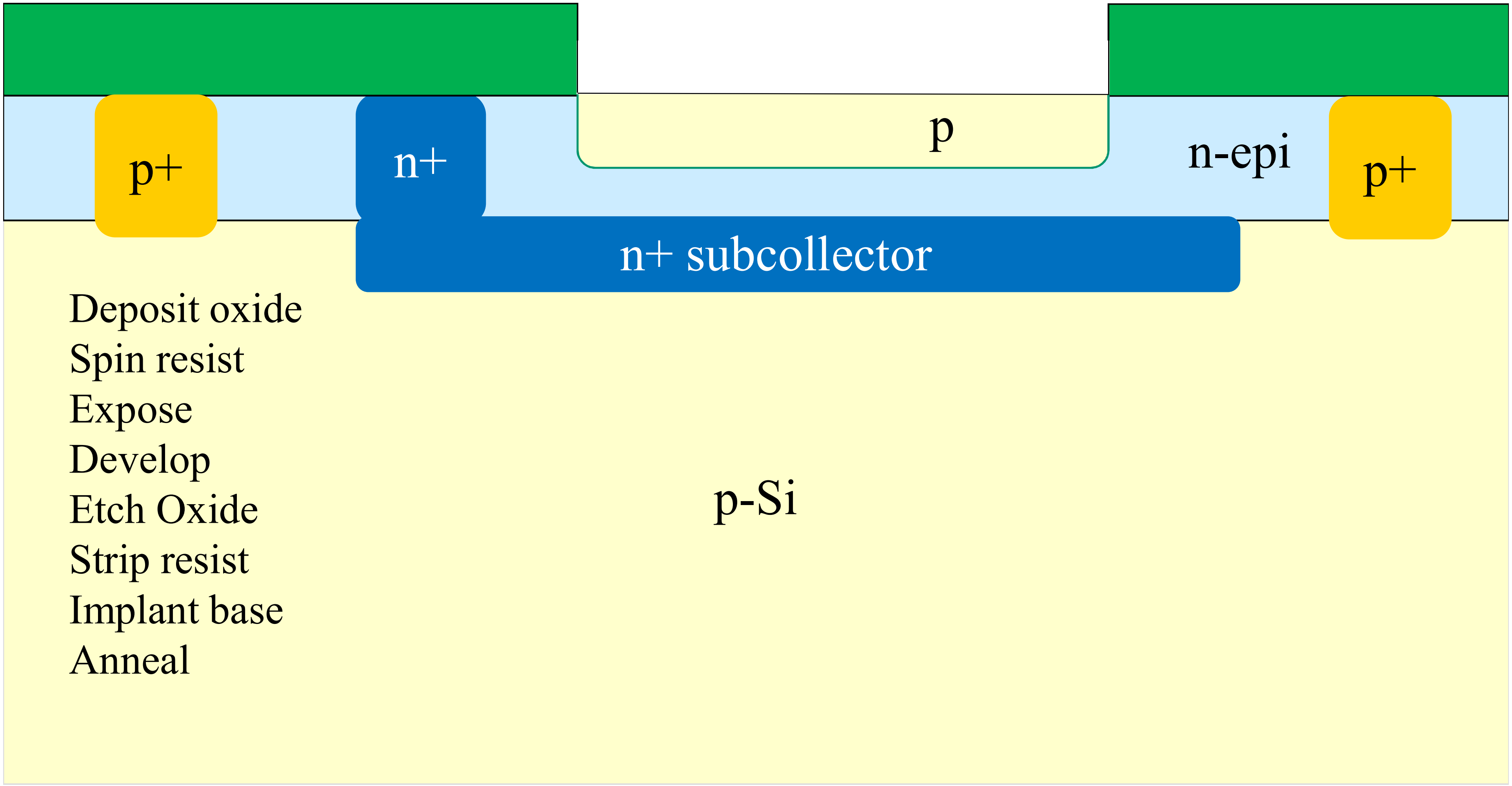
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant collector contact n+
Anneal

Guard ring

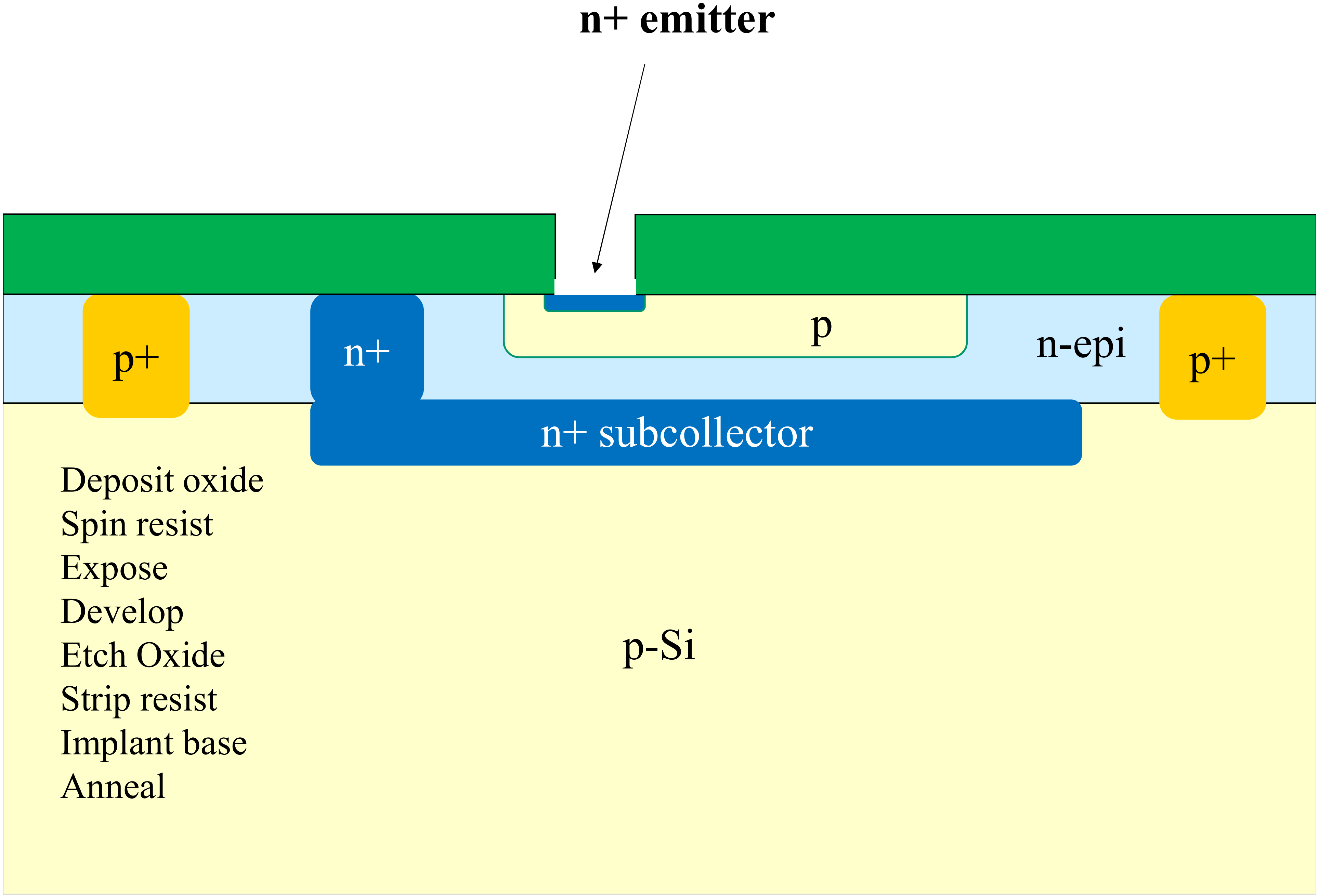


Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant collector contact p+
Anneal

p-well



Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal



Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal

BiCMOS

Only one additional step to CMOS is needed for BiCMOS

Bipolar junction transistors:
high speed
high gain
low output impedance
good for analog amplifiers

CMOS
high impedance
low power logic

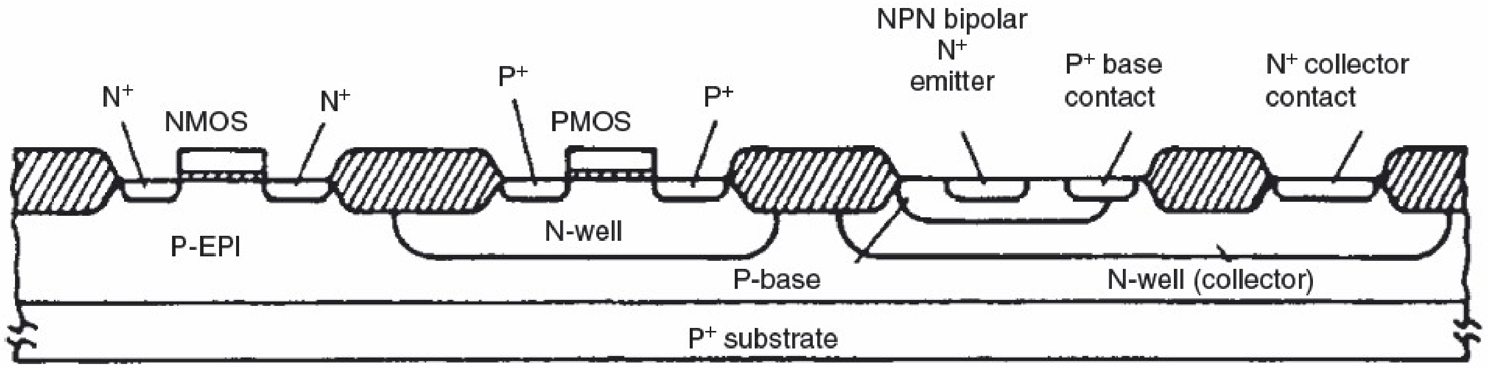
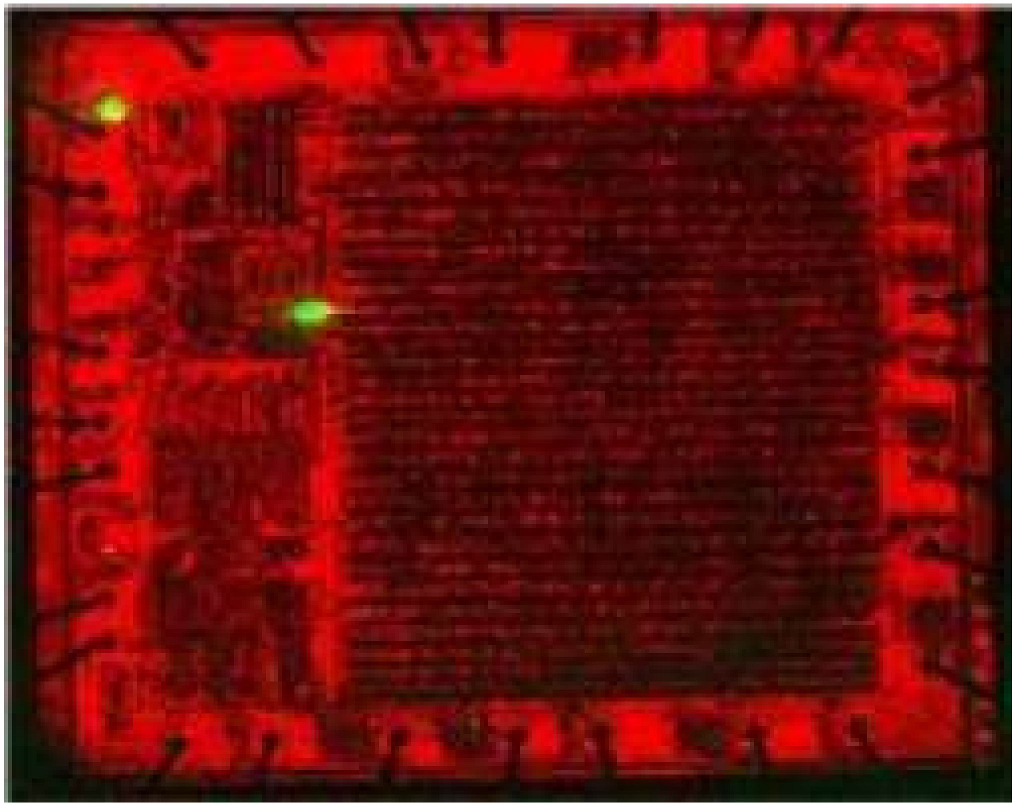


Figure 27.6 Simple BiCMOS technology: triple diffused-type bipolar transistor added to a CMOS process with minimal extra steps: only p-base diffusion mask is added to CMOS process flow. Reproduced from Alvarez (1989) by permission of Kluwer

Fransila

See: http://www.iue.tuwien.ac.at/phd/puchner/node48_app.html

Emission Microscope



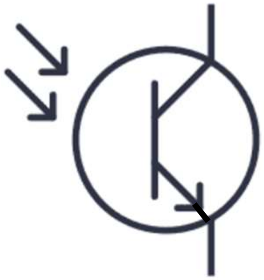
Forward biased diodes emit light. (BJT)
Defects often emit light.

http://www.muanalysis.com/techniques/emission-microscopy-emmi

When does it emit light?

Thyristor
Bipolar junction transistors
MOSFET
JFET
Si diode

Phototransistor



What happens to all devices when you shine light on them? What if you make the devices out of direct band gap materials. Do they emit?