11

Bipolar junction transistors (BJT)

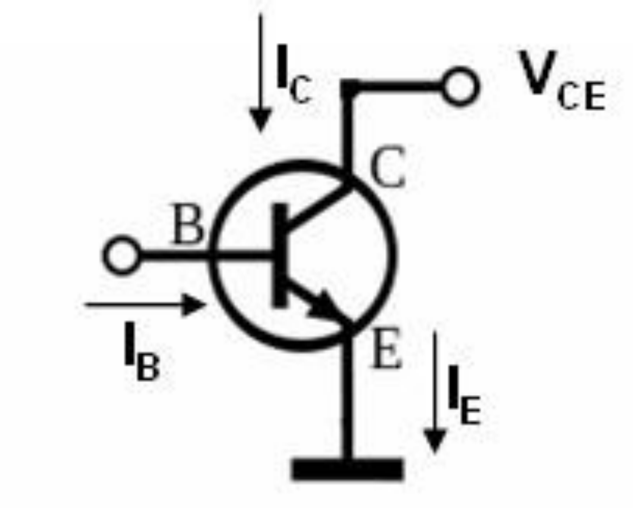
January 2026

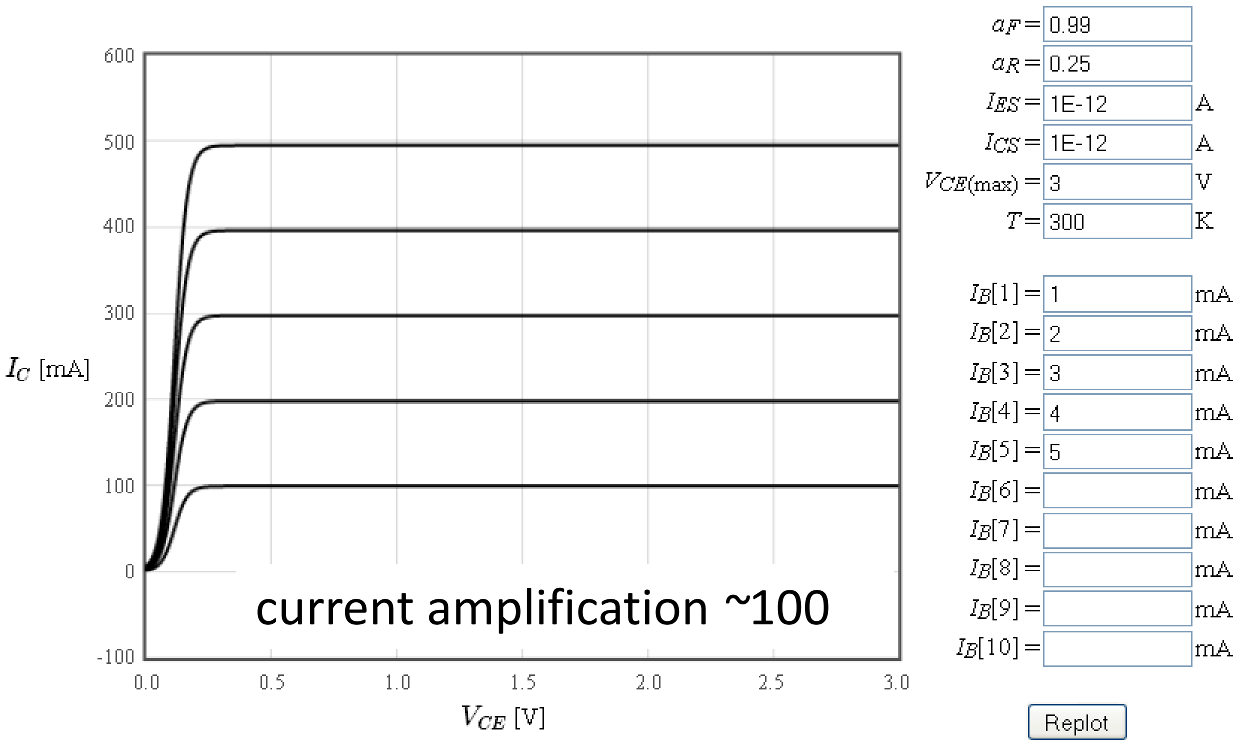
common emitter configuration

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

$$I_B = I_E - I_C$$

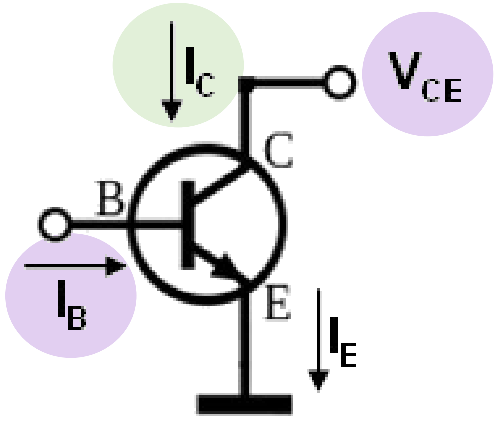
$$I_C = \alpha_F I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$





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

common emitter configuration



$$V_{CE} = V_{BE} + V_{CB}$$

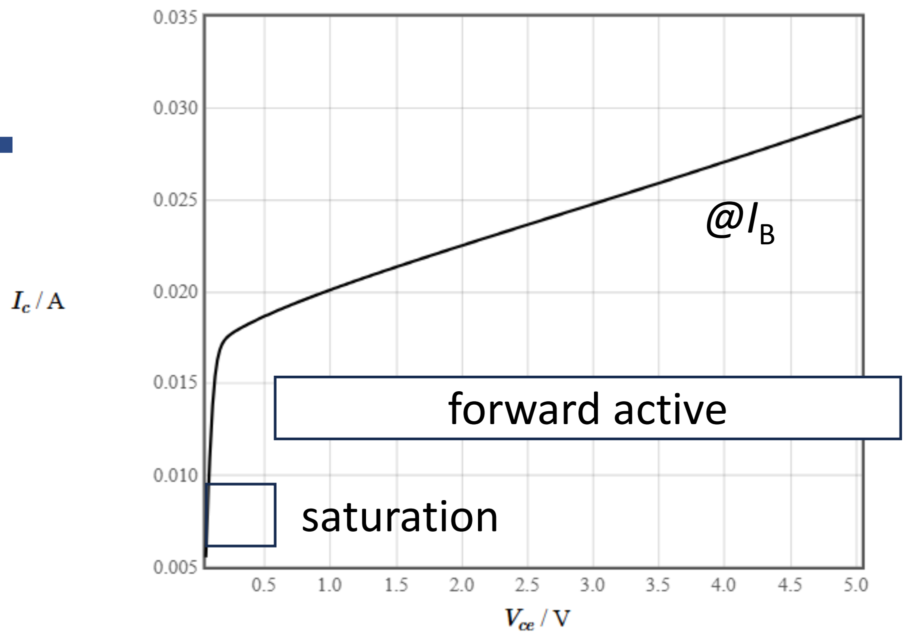
$$I_B = I_E(V_{BE}, V_{CB}) - I_C(V_{BE}, V_{CB})$$

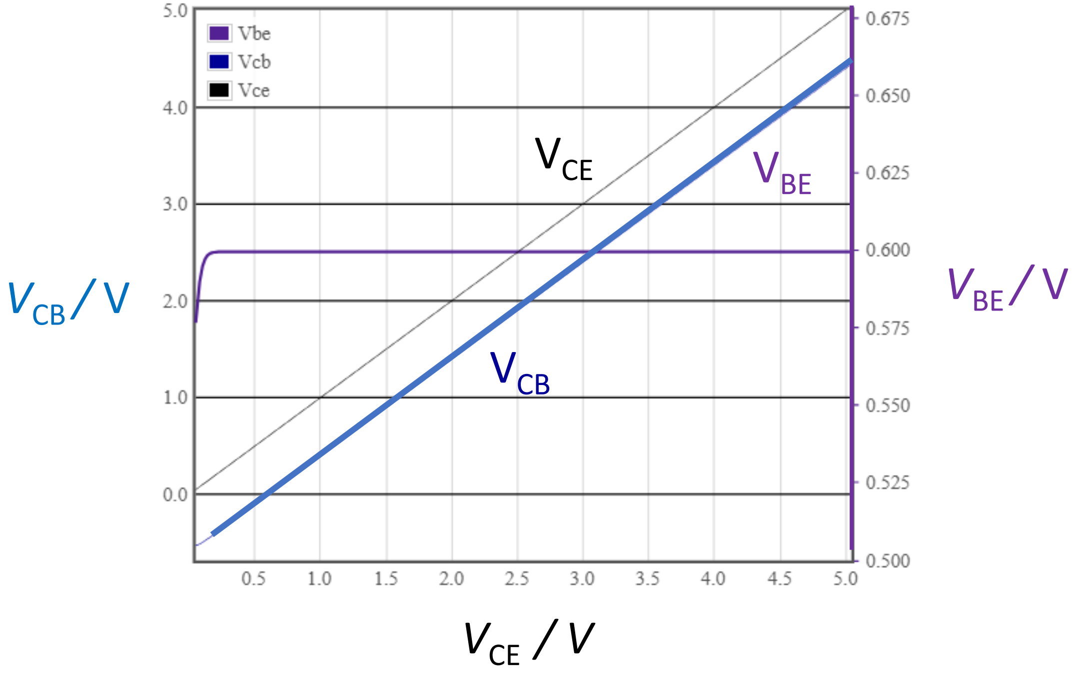
$$I_E = I_{ES}\left(e^{eV_{be}/k_BT} - 1\right) - \alpha_R I_{CS}\left(e^{eV_{bc}/k_BT} - 1\right)$$

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

supply I_B

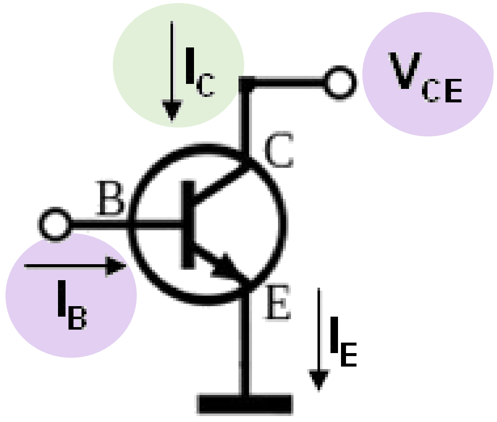
- enhance *n* in base
- EB junction “more forward” biased
- $V_{BE} > 0$ and determined by I_B





http://lampz.tugraz.at/~hadley/psd/L13/common_e_early2.php

common emitter configuration



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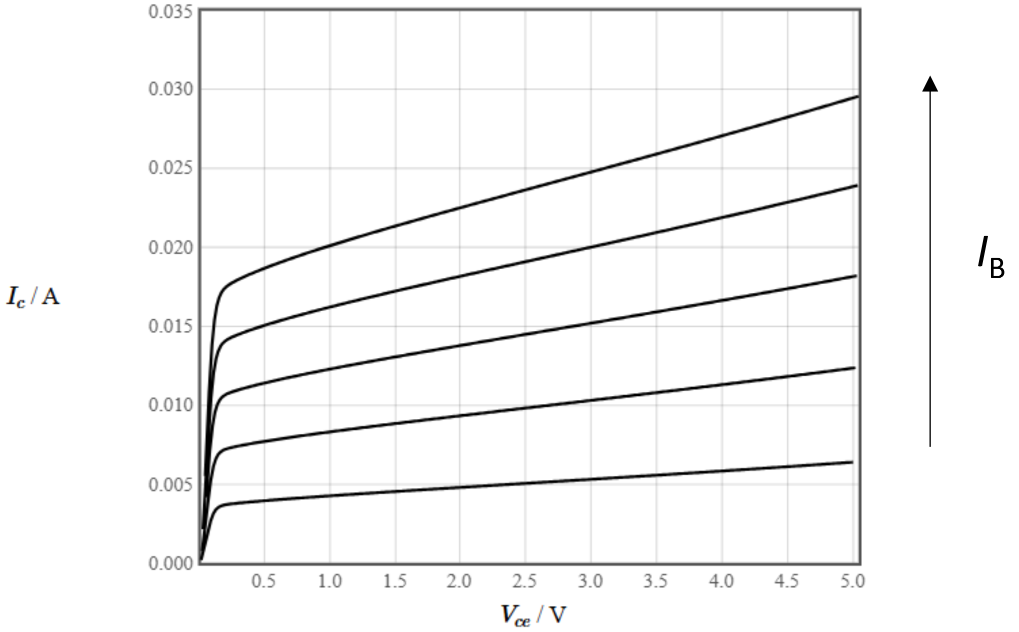
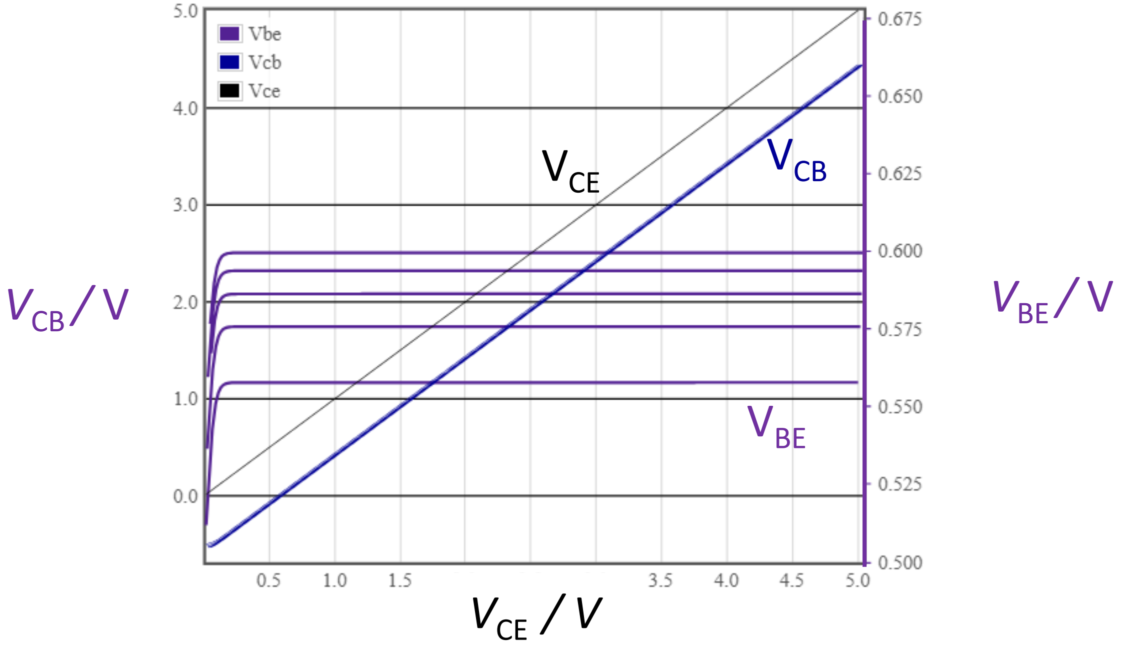
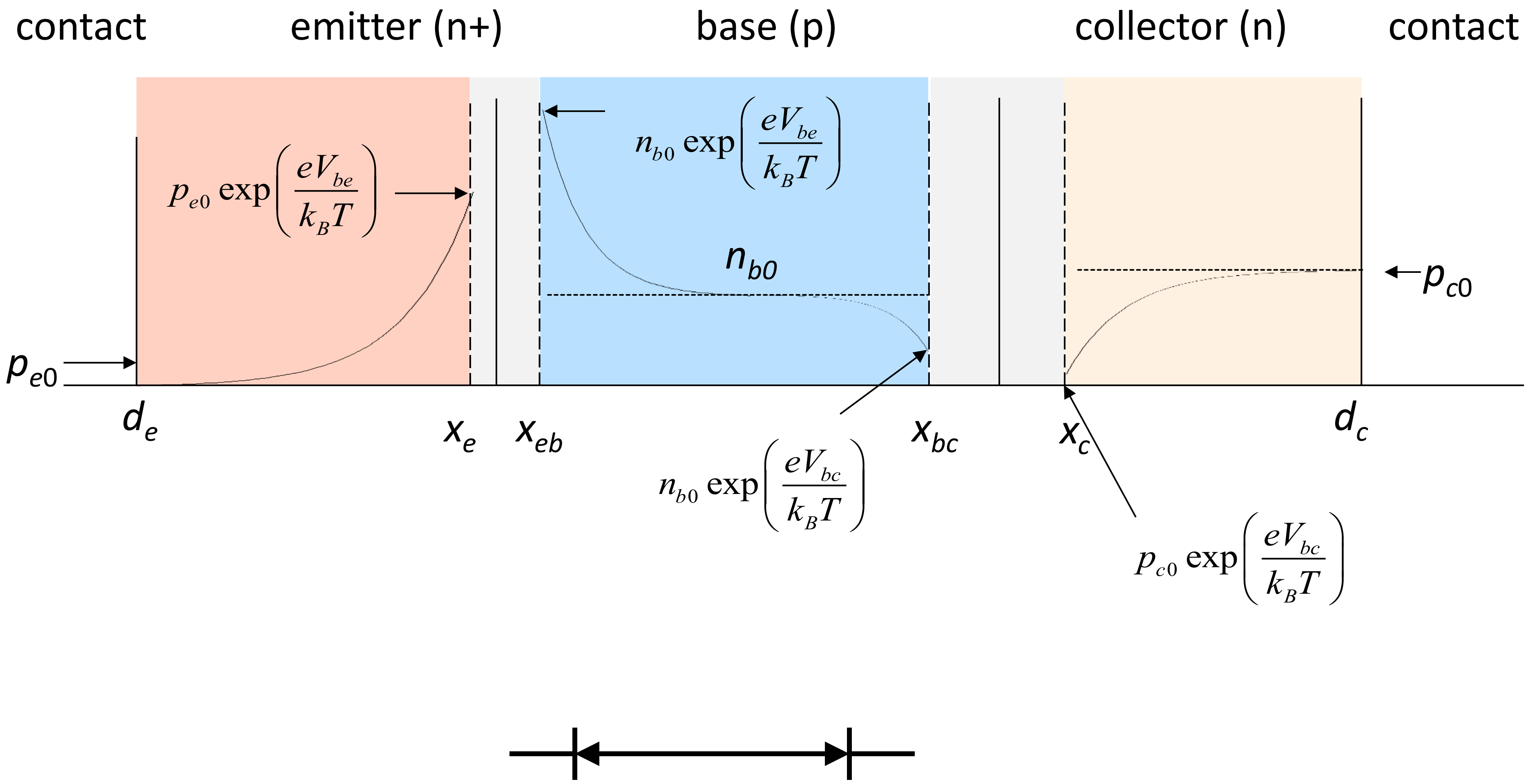
- enhance *n* in base
- EB junction "more forward" biased
- $V_{BE} >$ 0 and determined by I_B



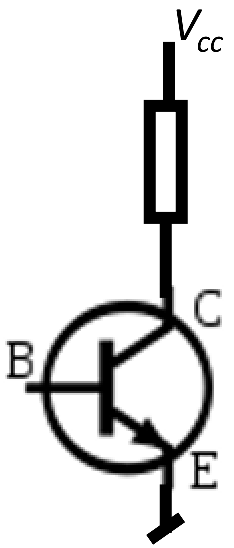


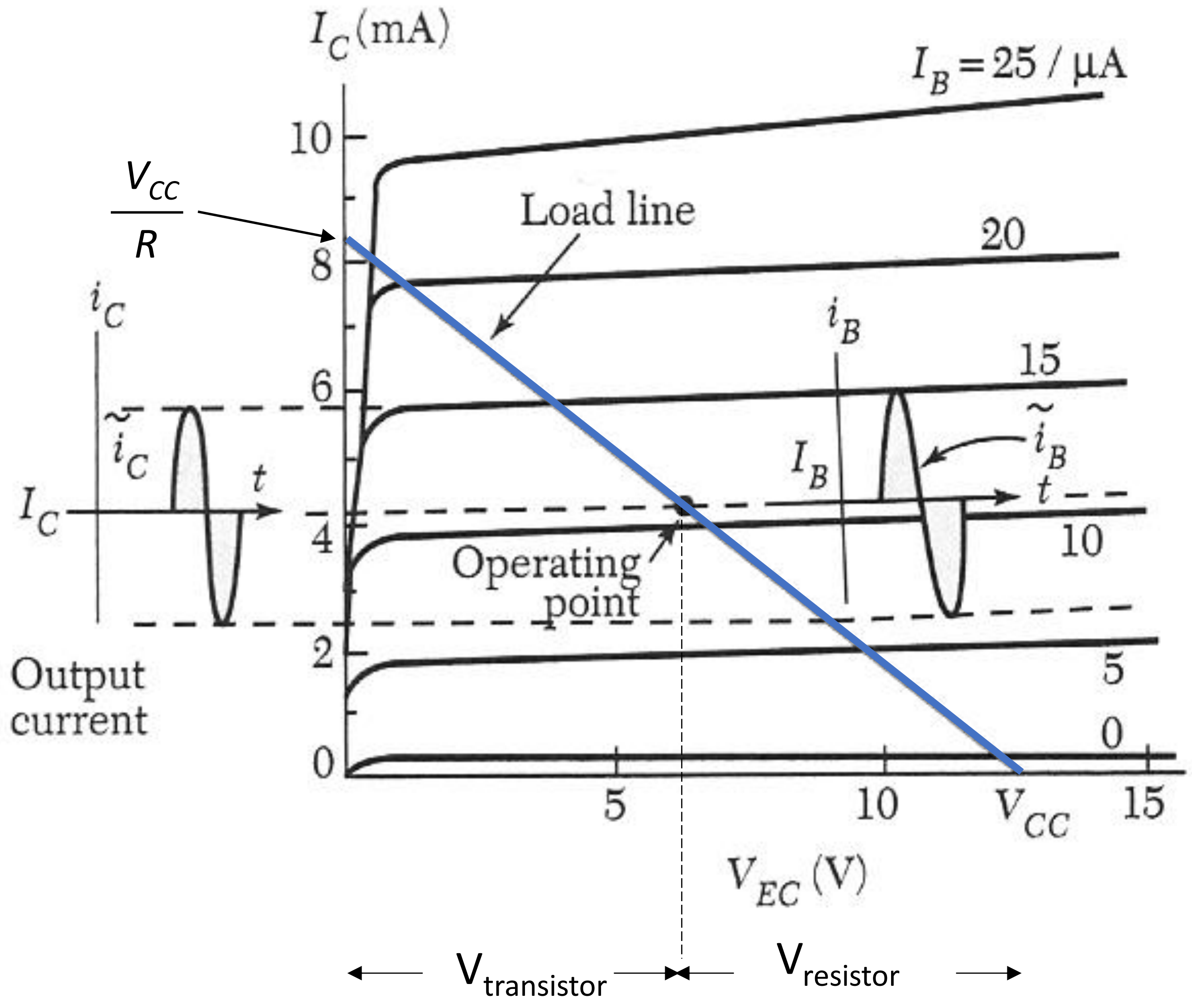
http://lampz.tugraz.at/~hadley/psd/L13/common_e_early2.php

not an npn transistor



small signal response

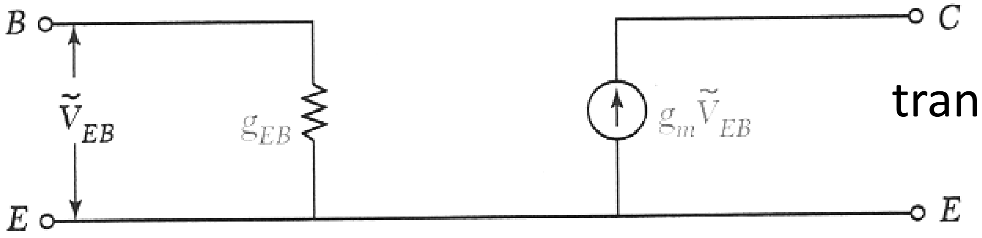




Low input impedance amplifier

small signal response

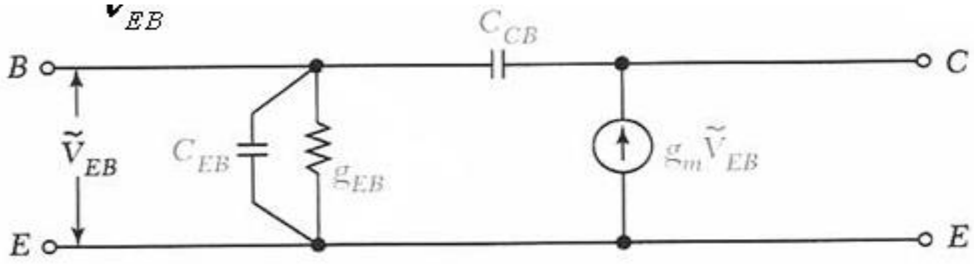
$\tilde{\imath}_c = \beta \tilde{\imath}_B = \beta g_{EB} \tilde{v}_{EB}$

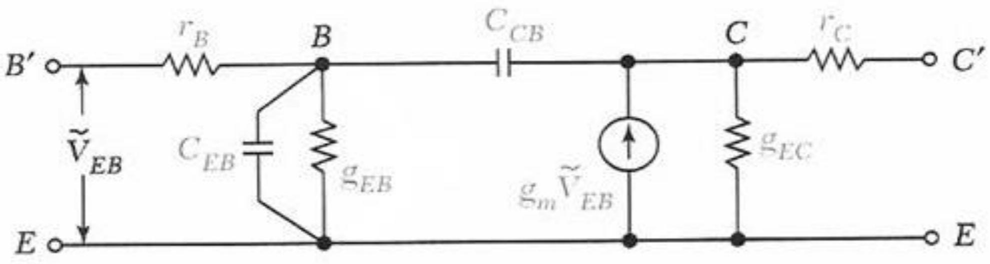


transistor man

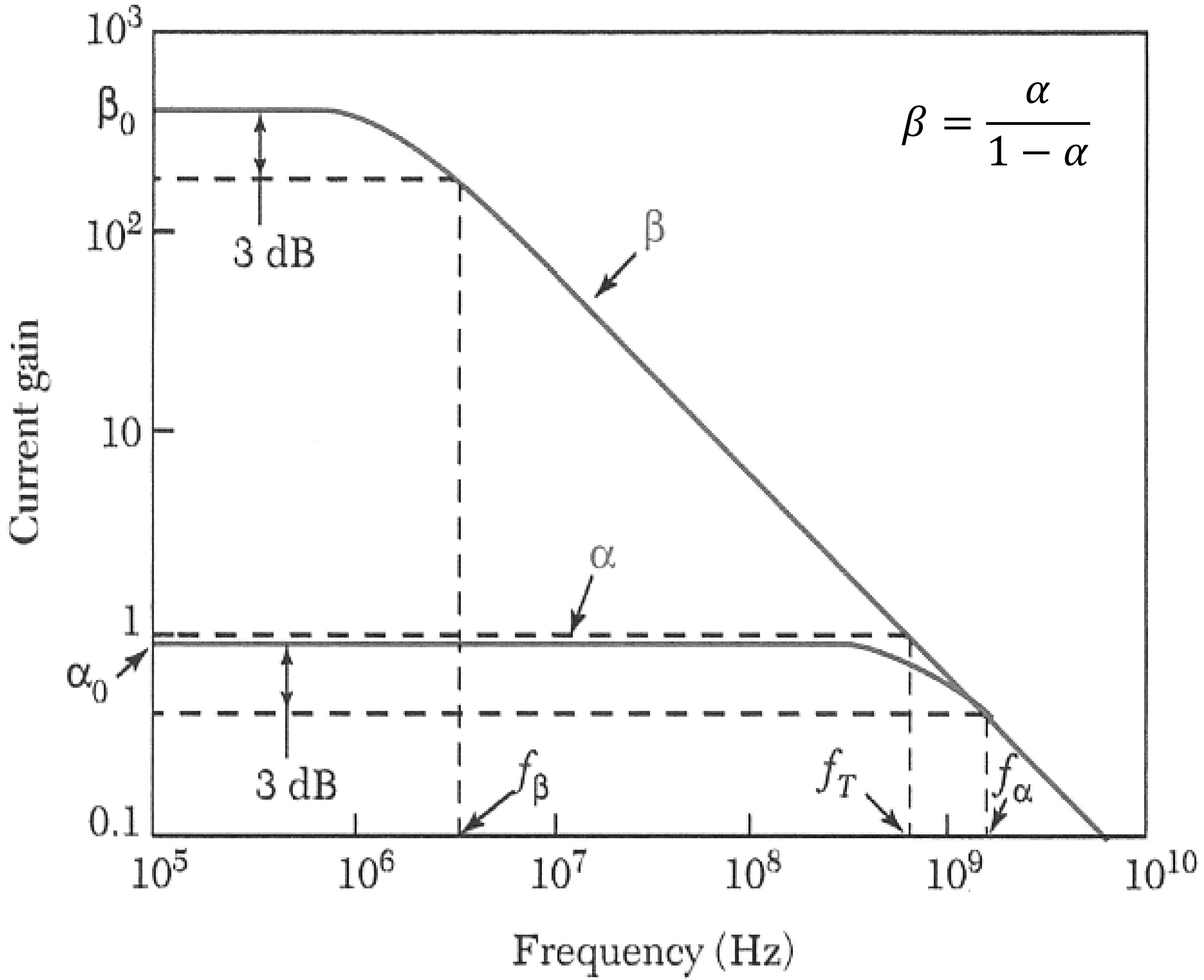
input conductance: $g_{EB} = \dfrac{\tilde{\imath}_B}{\tilde{v}_{EB}}$

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





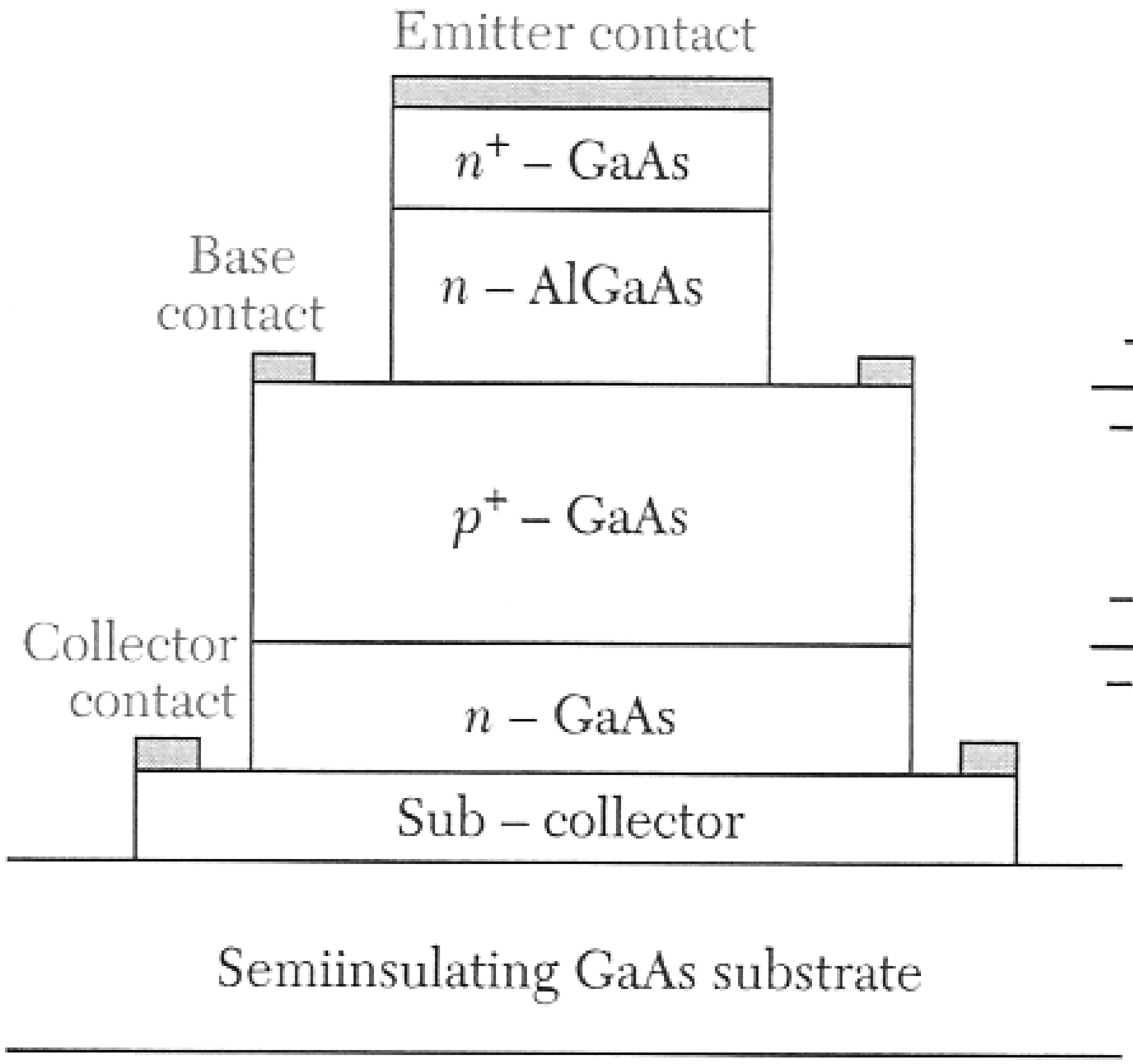
small signal response

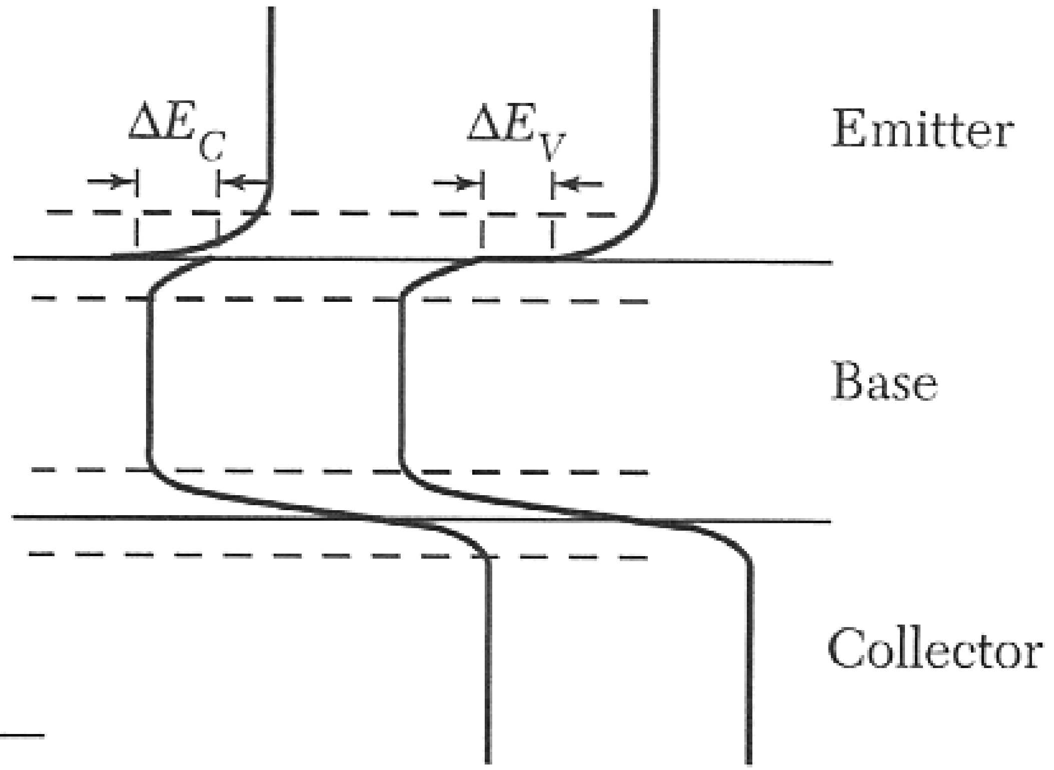


$f_\beta = (1-\alpha_0) f_\alpha$

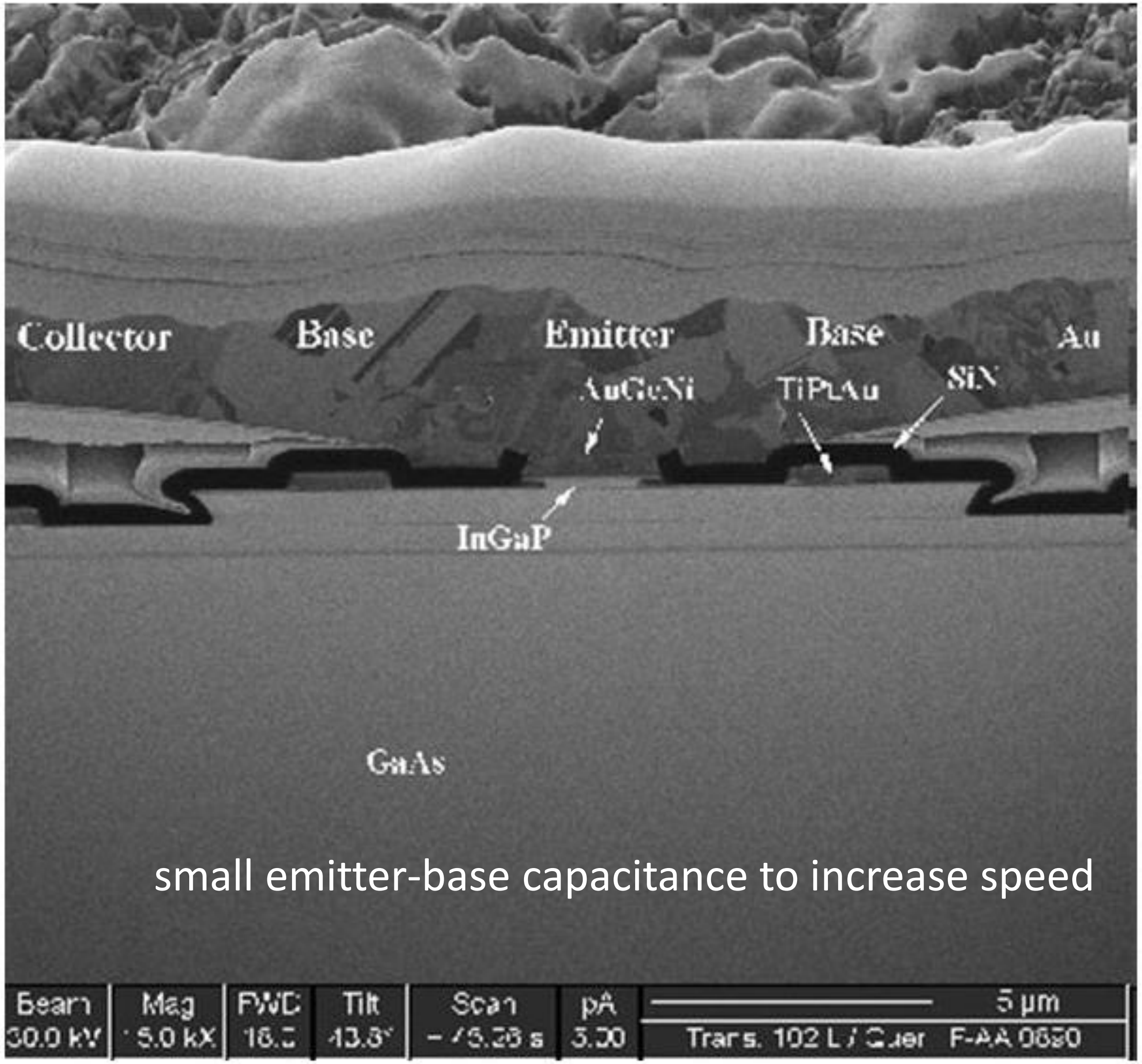
$f_T = \alpha_0 f_\alpha$

Heterojunction bipolar transistors





Heterojunction bipolar transistors



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: lowers minority carrier concentration 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

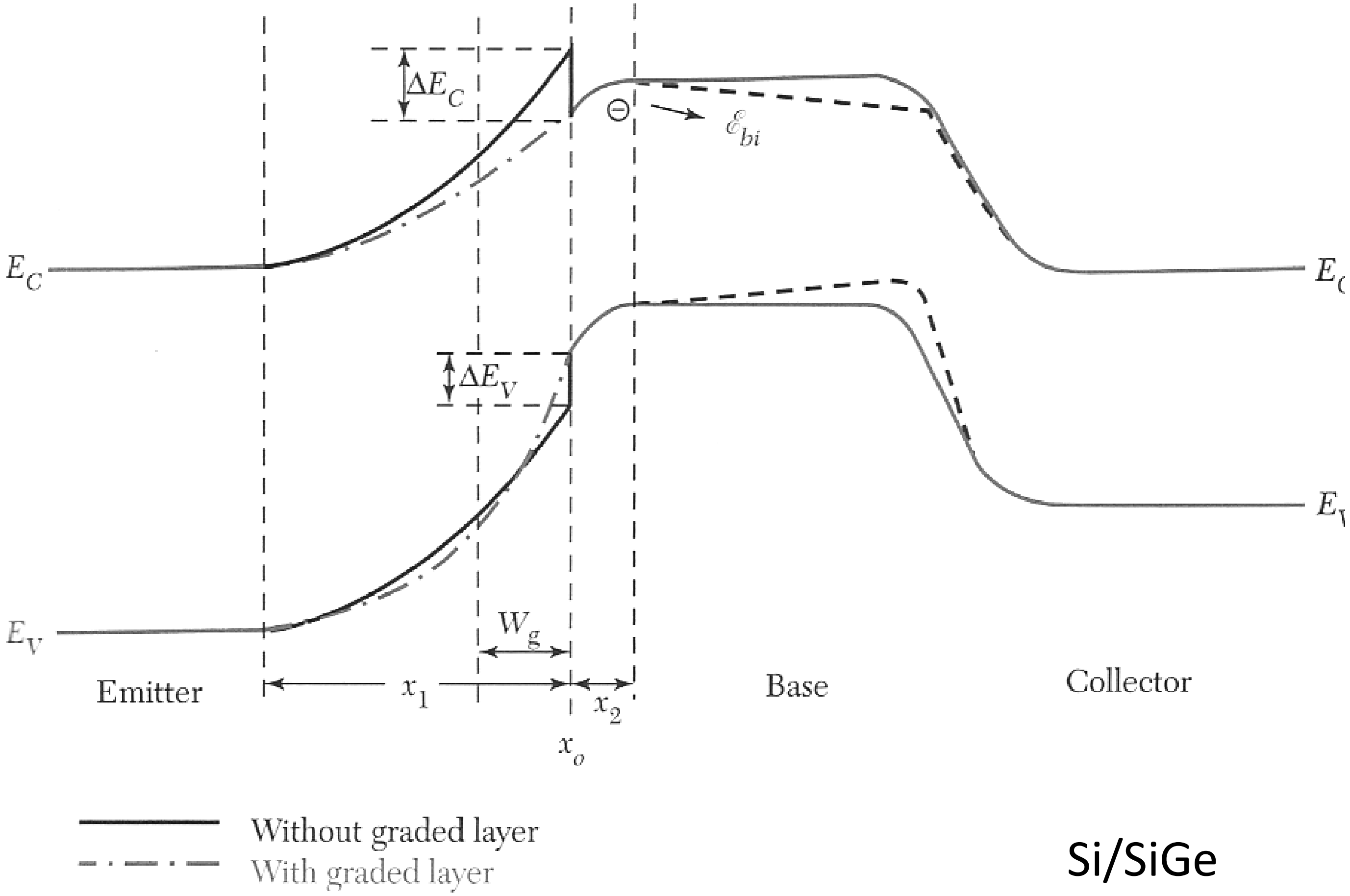
Higher base doping

- 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

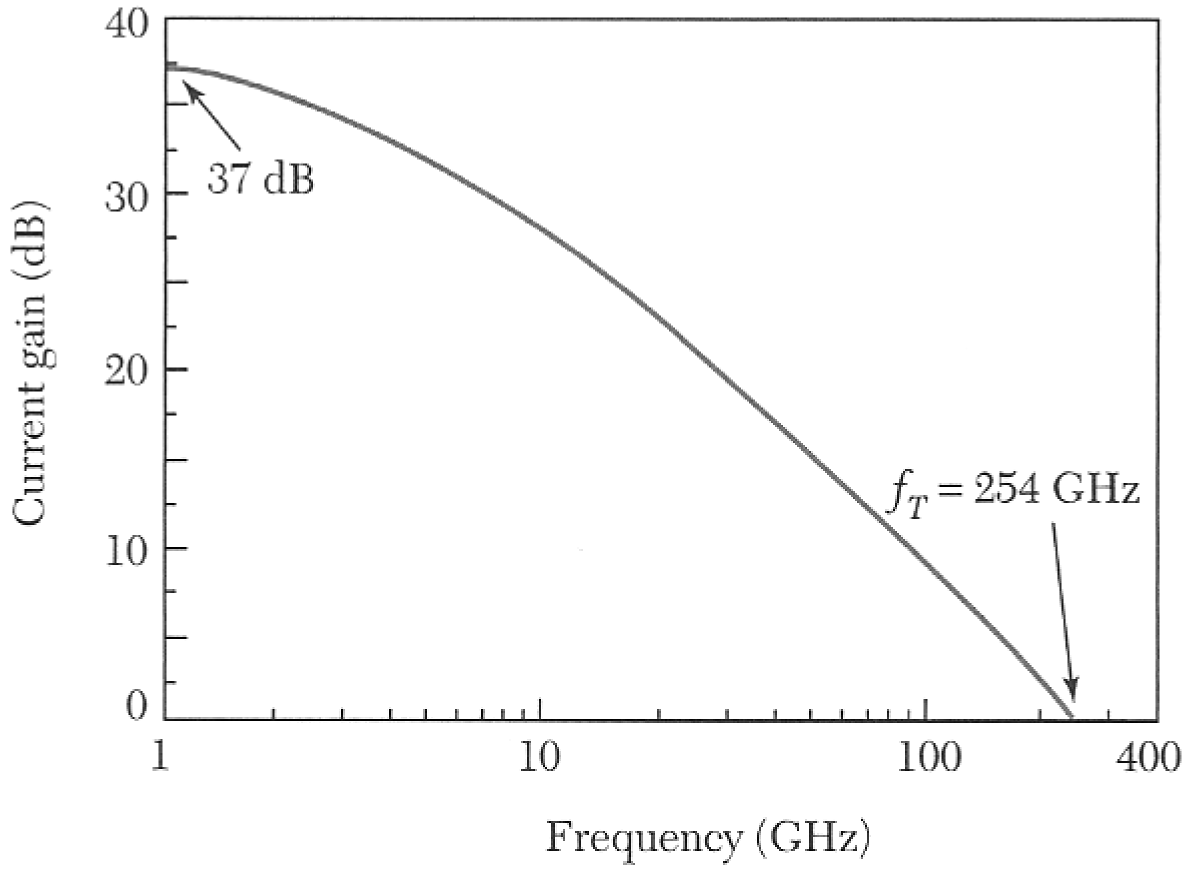
Heterojunction bipolar transistors

Higher doping in the base:

allows for

- a thinner base without punch through
- lower base resistance

→ higher frequency operation

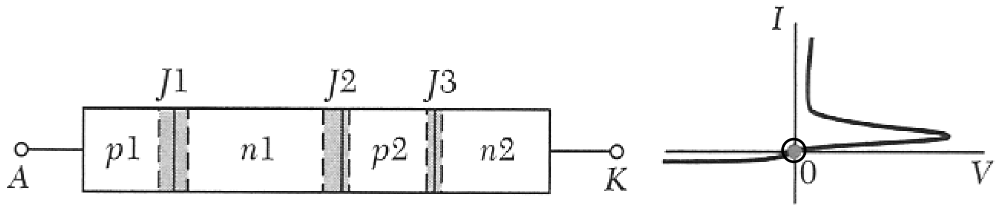


fastest InP/InGaAs HBT's have an f_T of 710 GHz

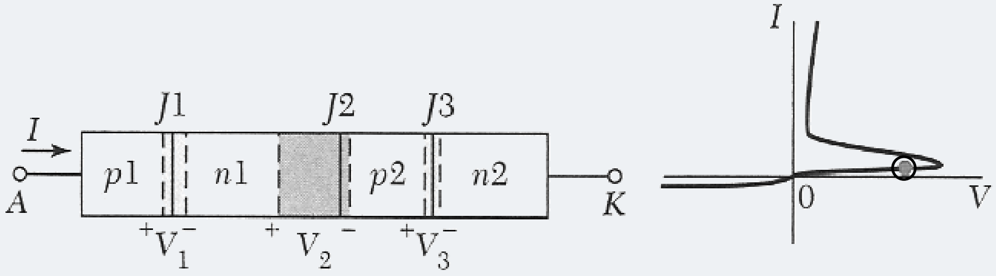
microwave engineering

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

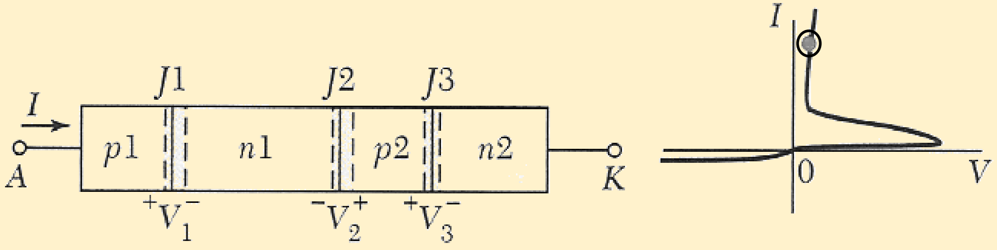
Thyristors



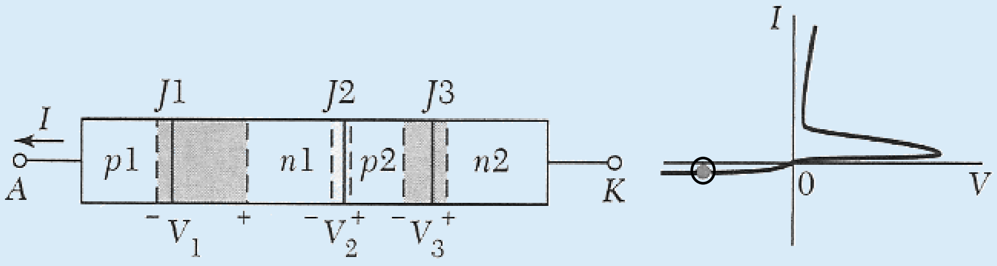
Forward blocking



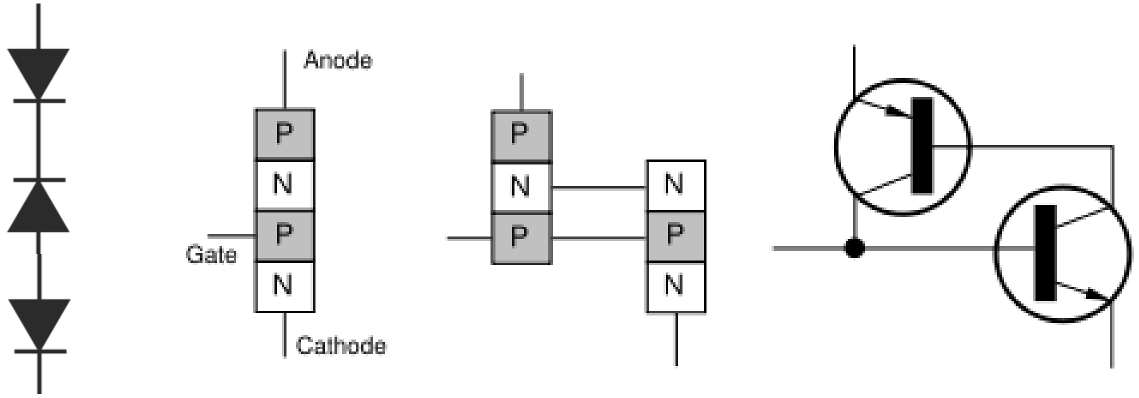
Forward conducting



Reverse blocking

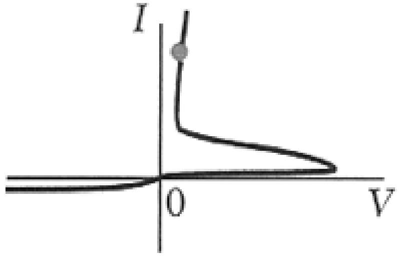


Thyristors

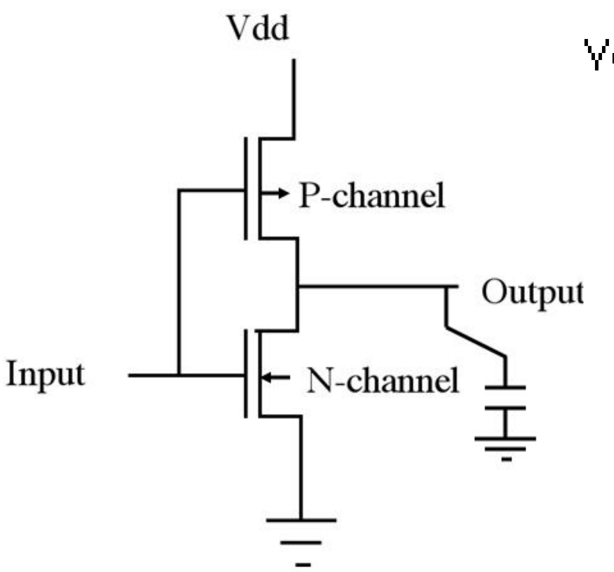


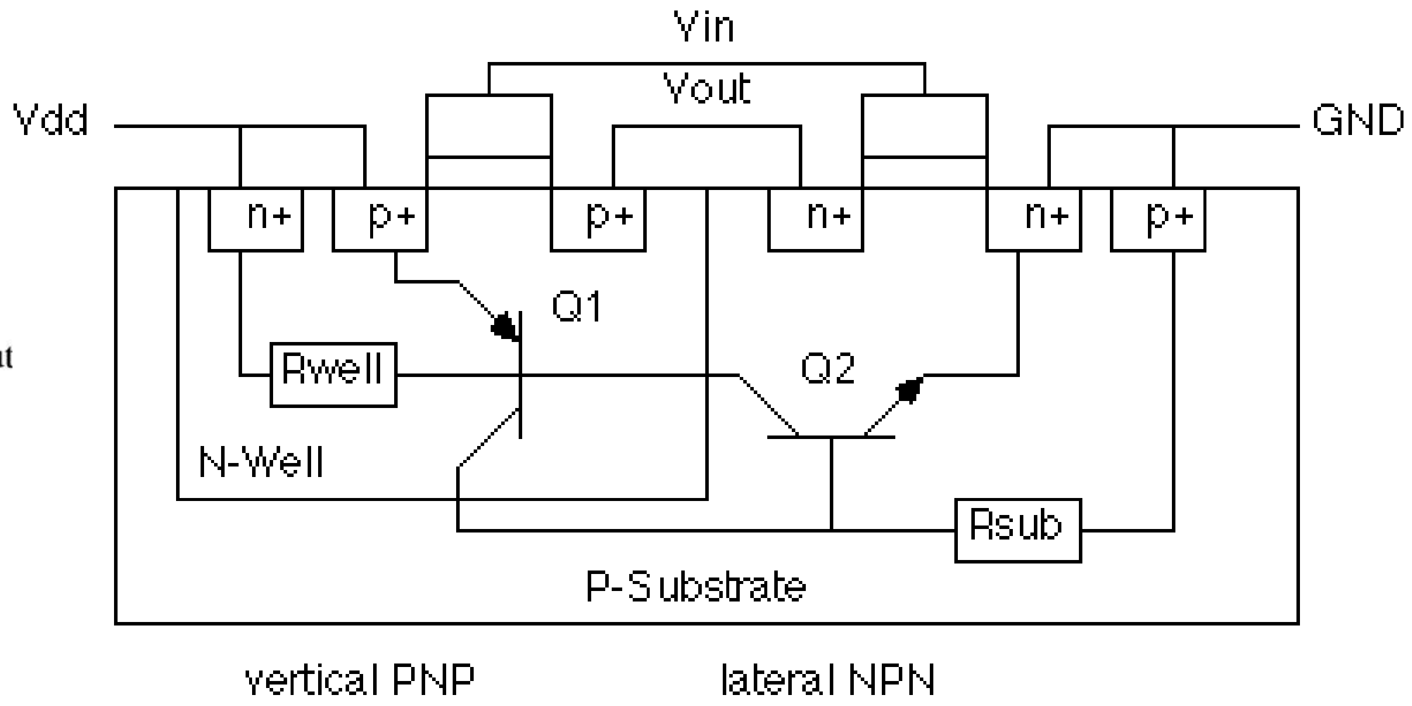
$\beta_1 * \beta_2 > 1$

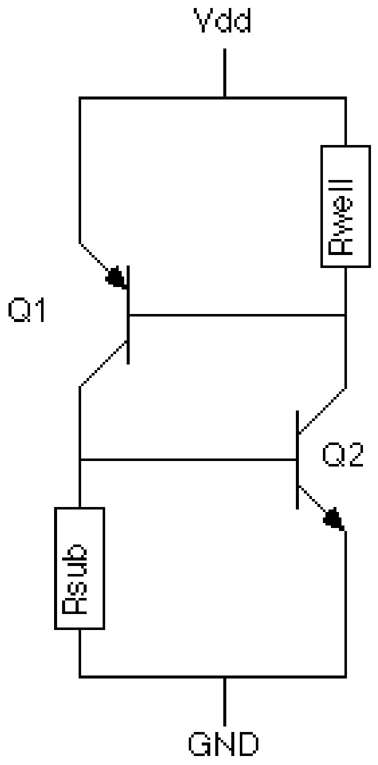
Used for switching high currents or voltages



Latch-up



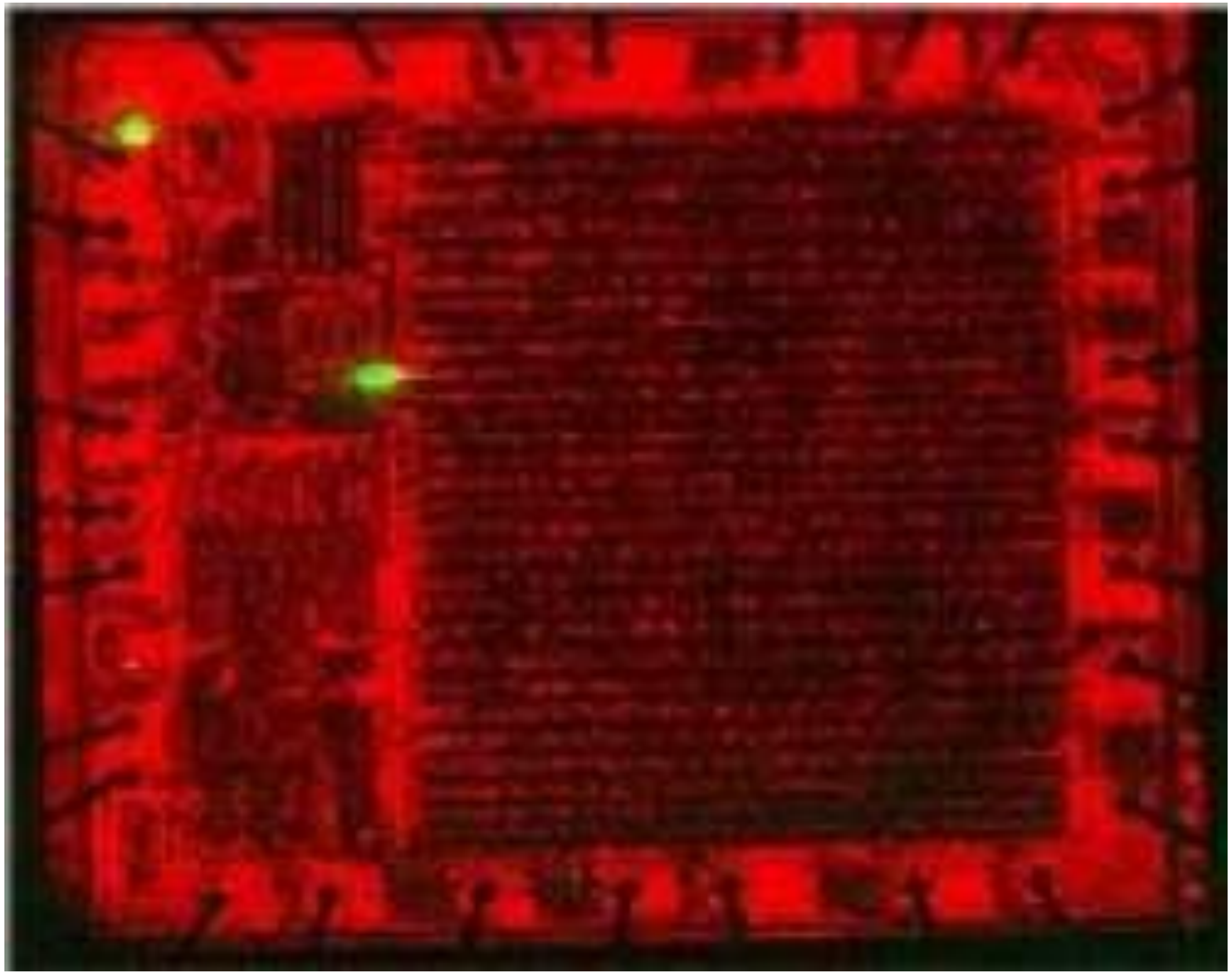




Both BJT's conduct, creating a low resistance path between V_{dd} and GND. The product of the gains of the two transistors in the feedback loop, is greater than one. The result of latchup is at the minimum a circuit malfunction, and in the worst case, the destruction of the device.

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

emission microscope



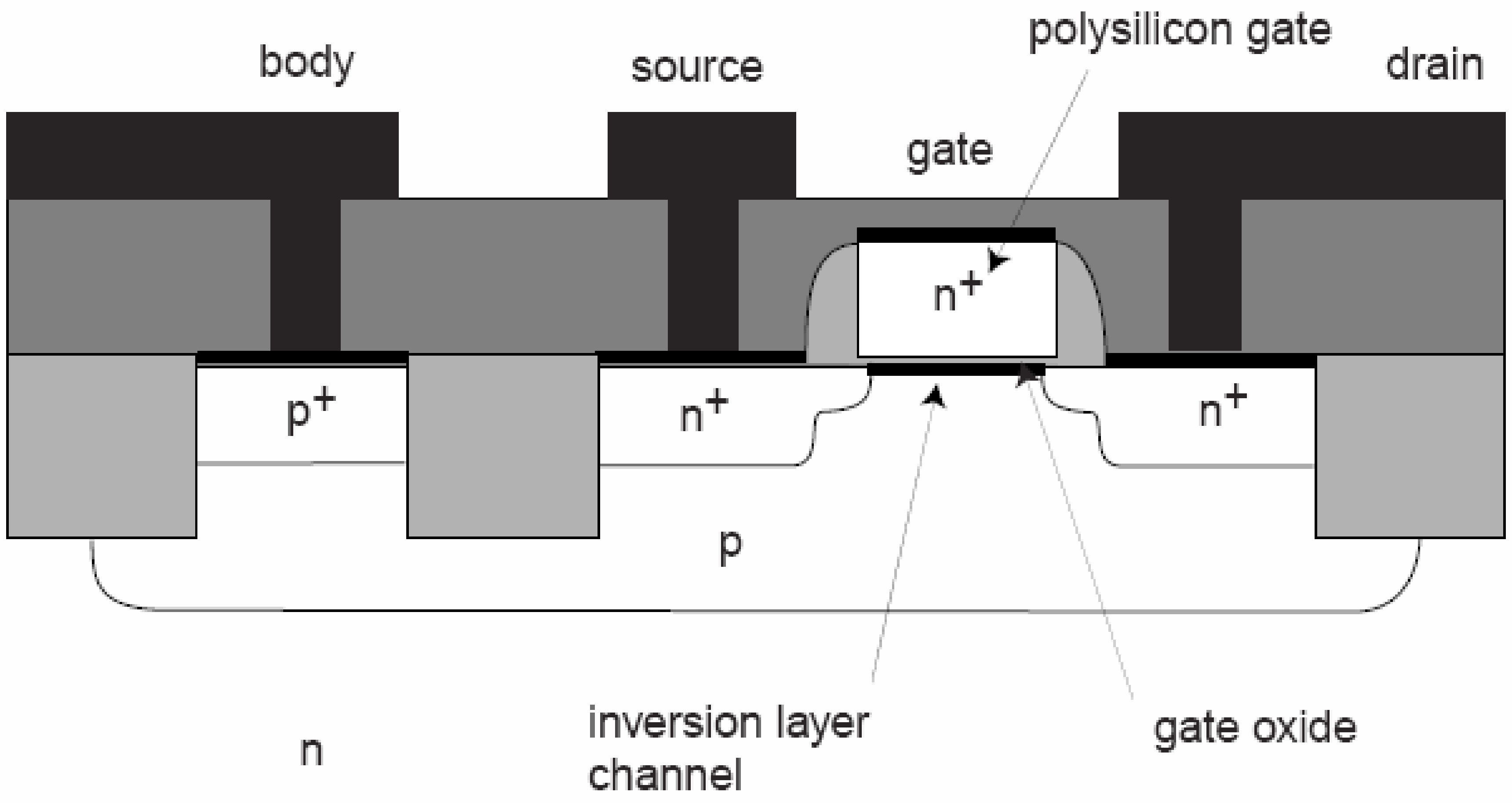
Forward biased diodes emit light. (BJT)
Defects often emit light.

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

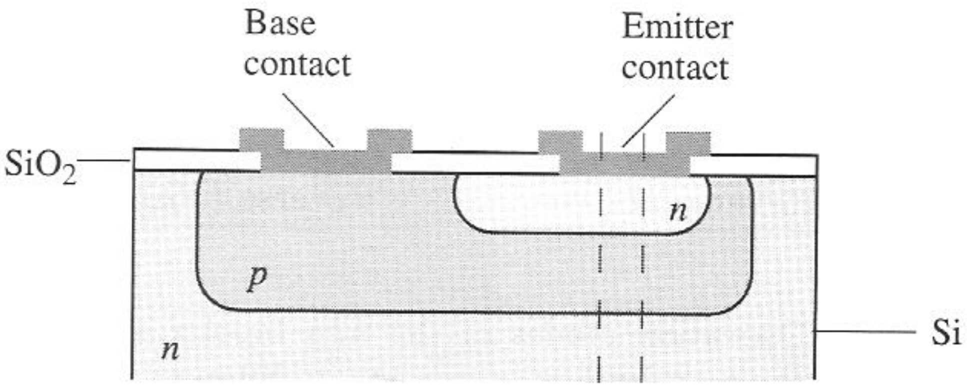
When does it emit light?

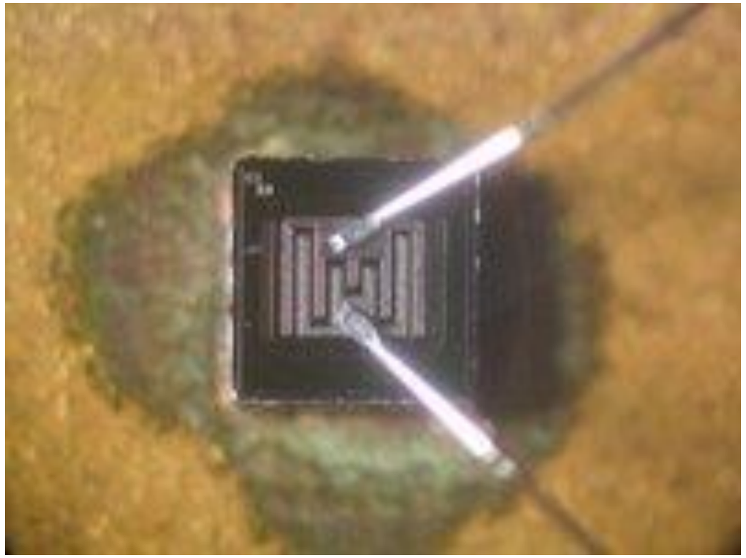
- Thyristor
- Bipolar junction transistors
- MOSFET
- JFET
- Si diode

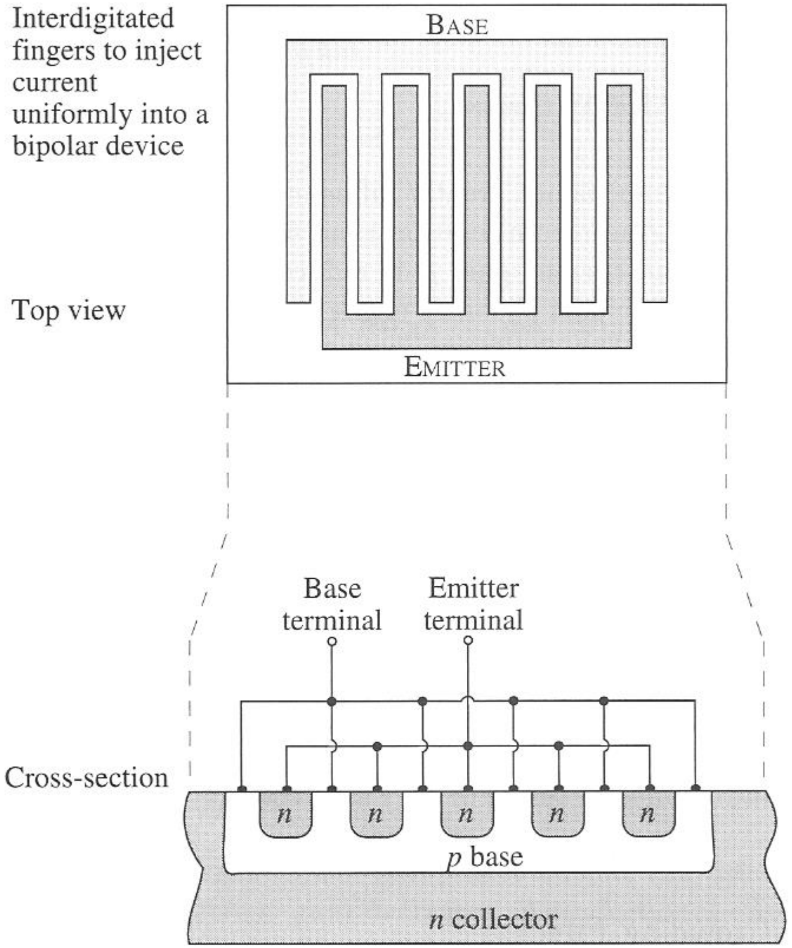
Can you operate like a BJT ?



interdigitated contacts in power transistors

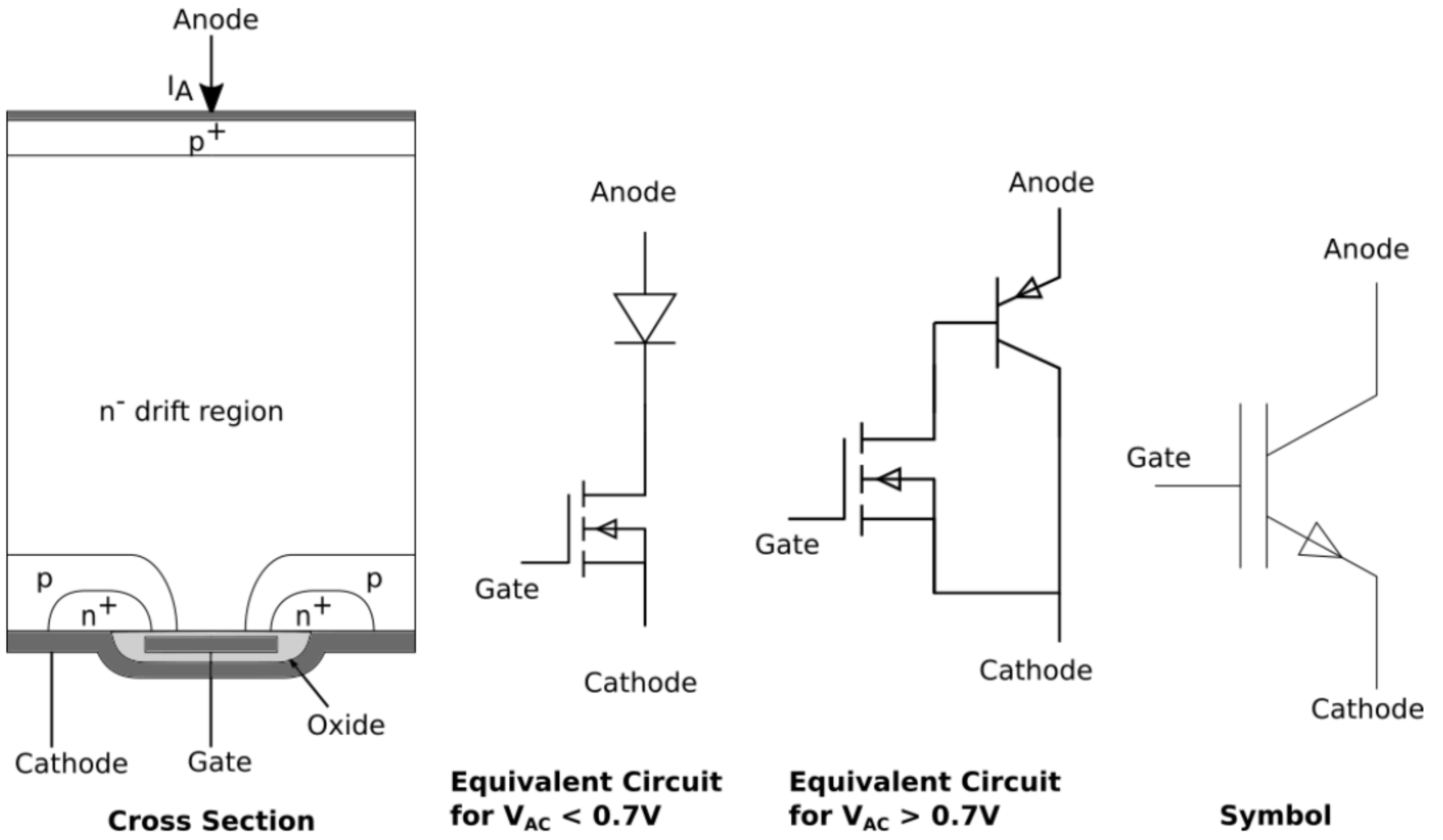






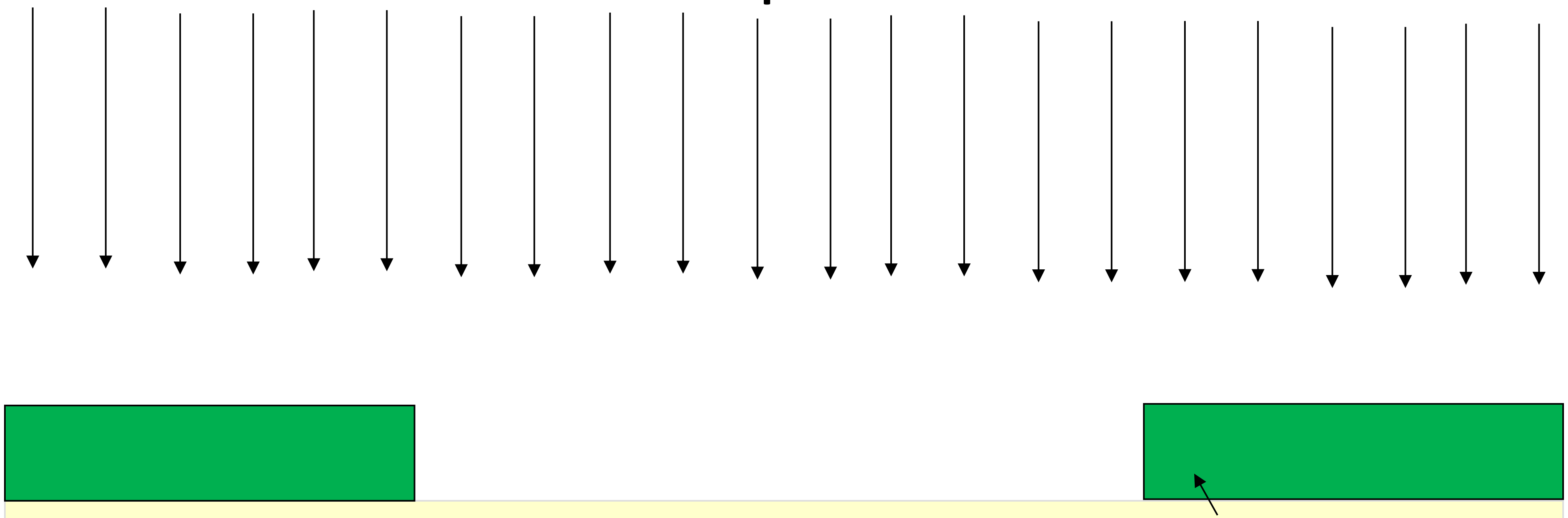
Insulated Gate Bipolar Transistor (IGBT)

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



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

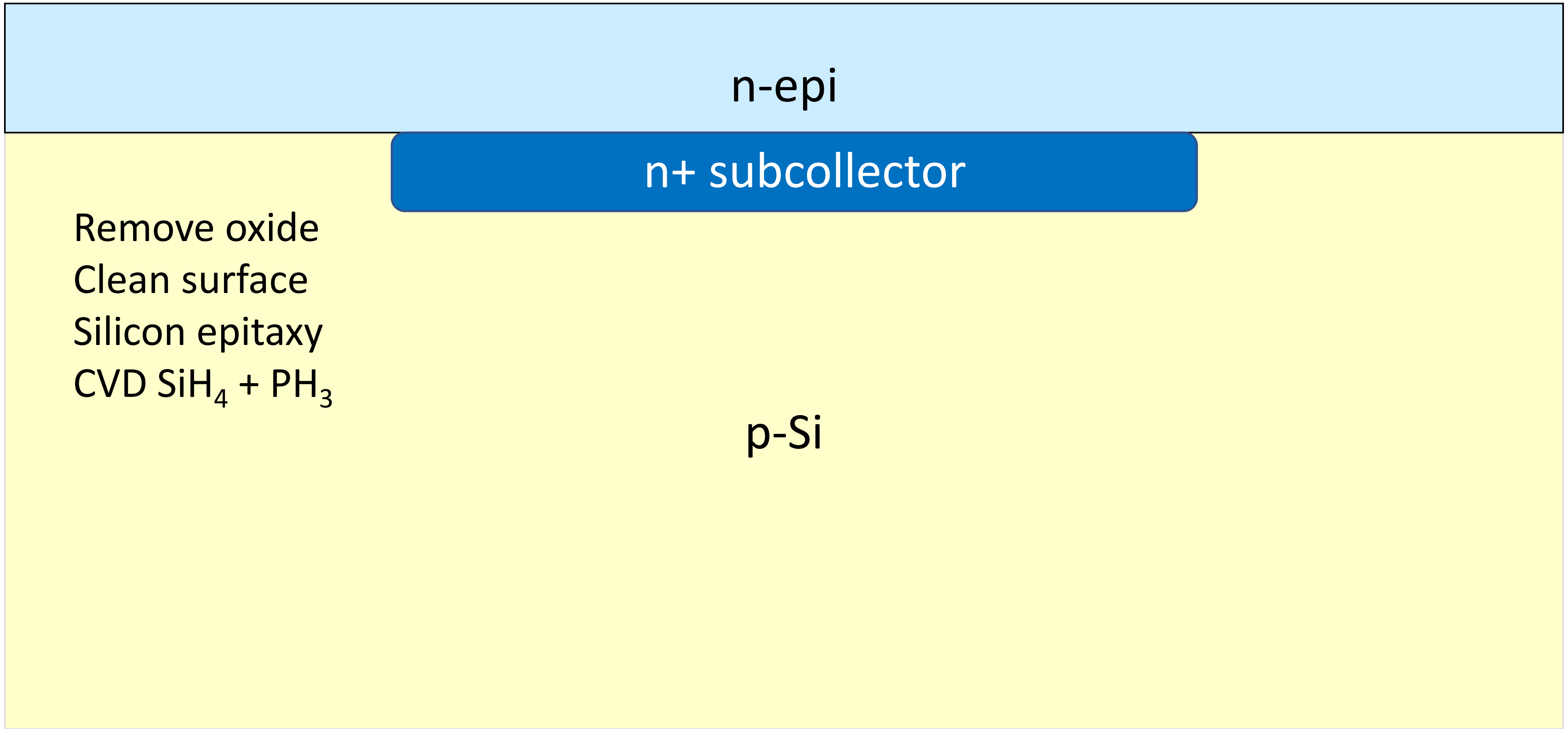
http://lampz.tugraz.at/~hadley/psd/L13/igbt.html



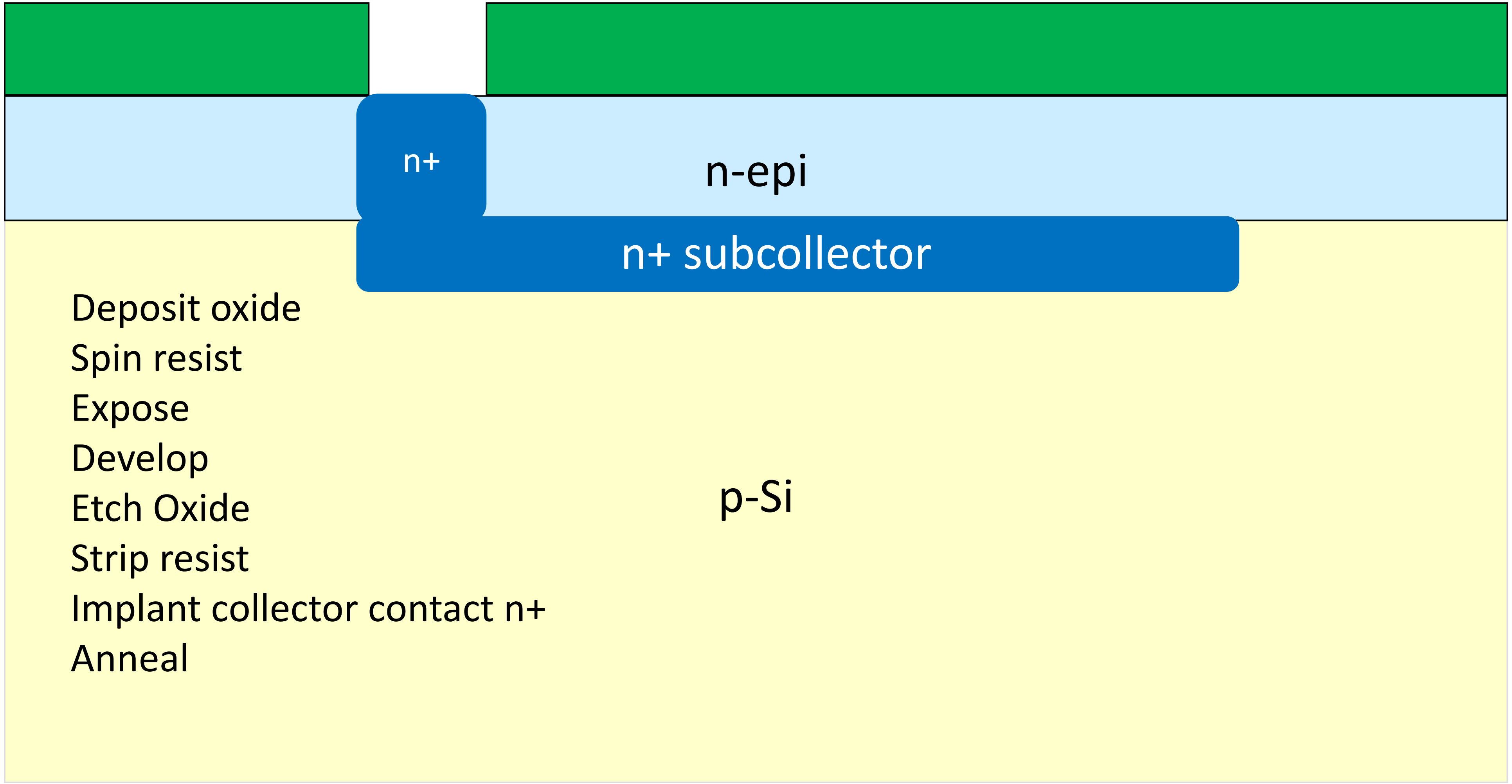
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant subcollector n+

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

Epi-growth

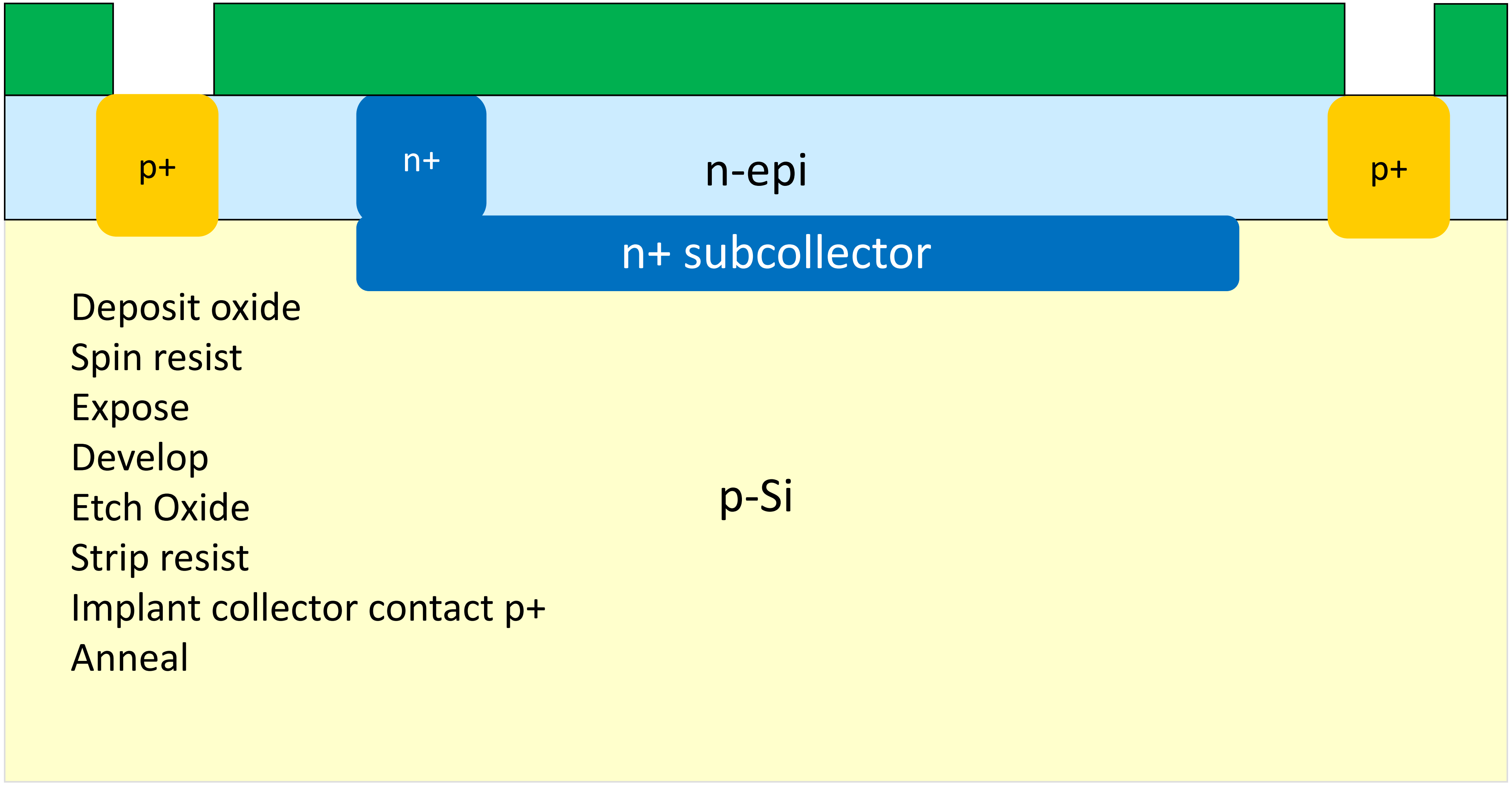

n-epi
n+ subcollector
Remove oxide
Clean surface
Silicon epitaxy
CVD $SiH_4 + PH_3$
p-Si

Collector Contact



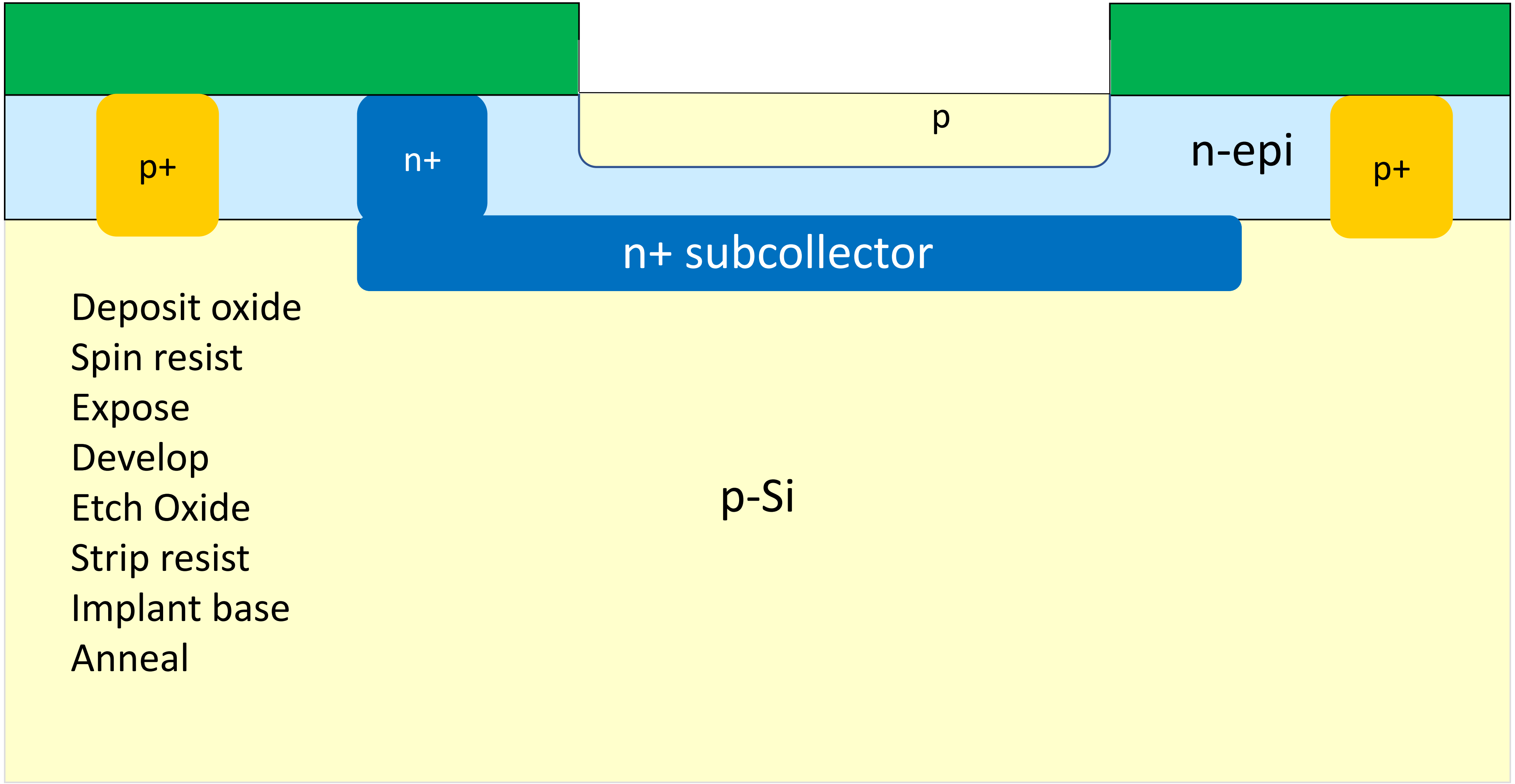
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant collector contact n+
Anneal

Guard ring

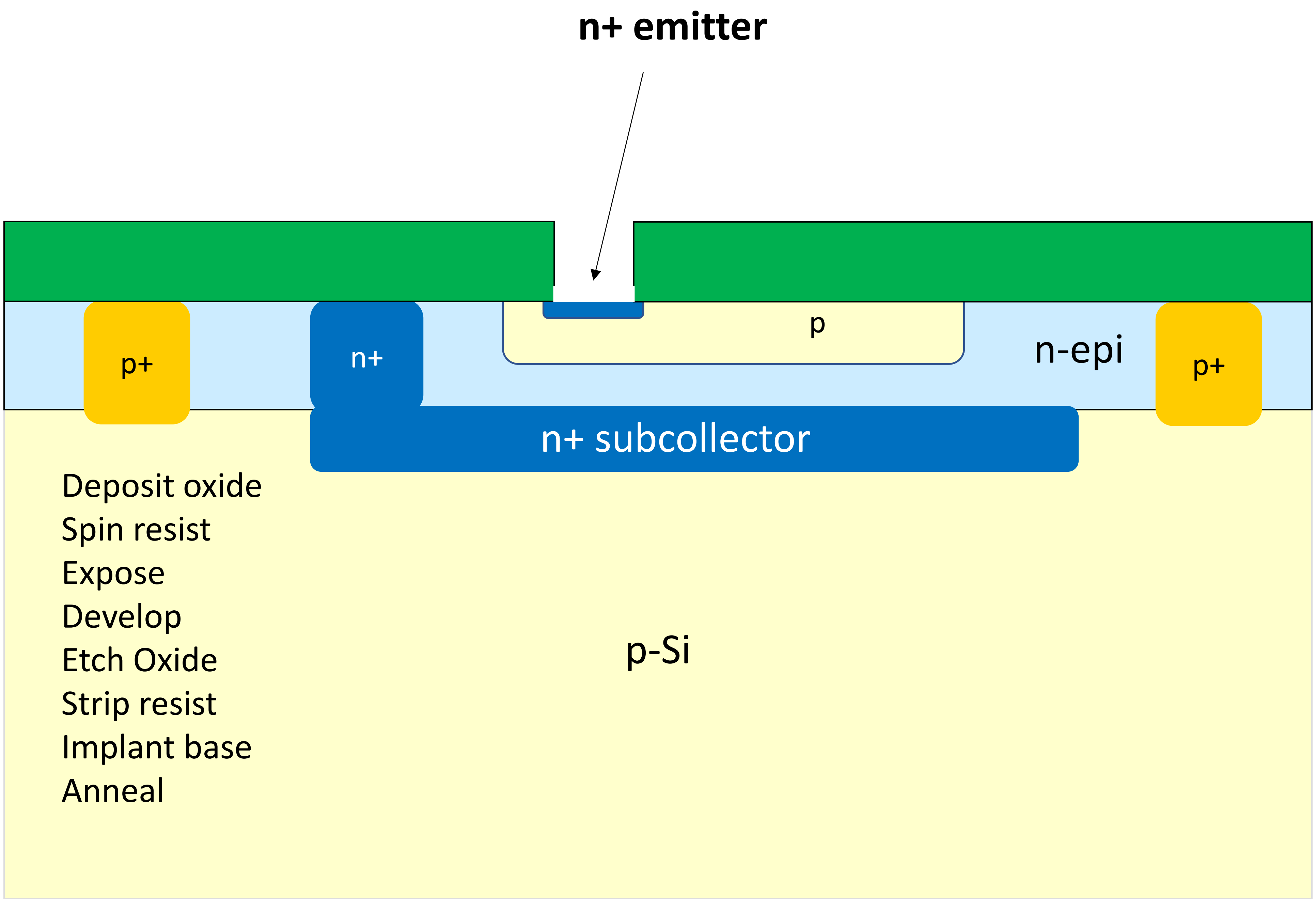


Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant collector contact p+
Anneal

p-well



p+
n+
p
n-epi
p+
n+ subcollector
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal
p-Si


n+ emitter
p
p+
n+
n-epi
p+
n+ subcollector
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal
p-Si

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

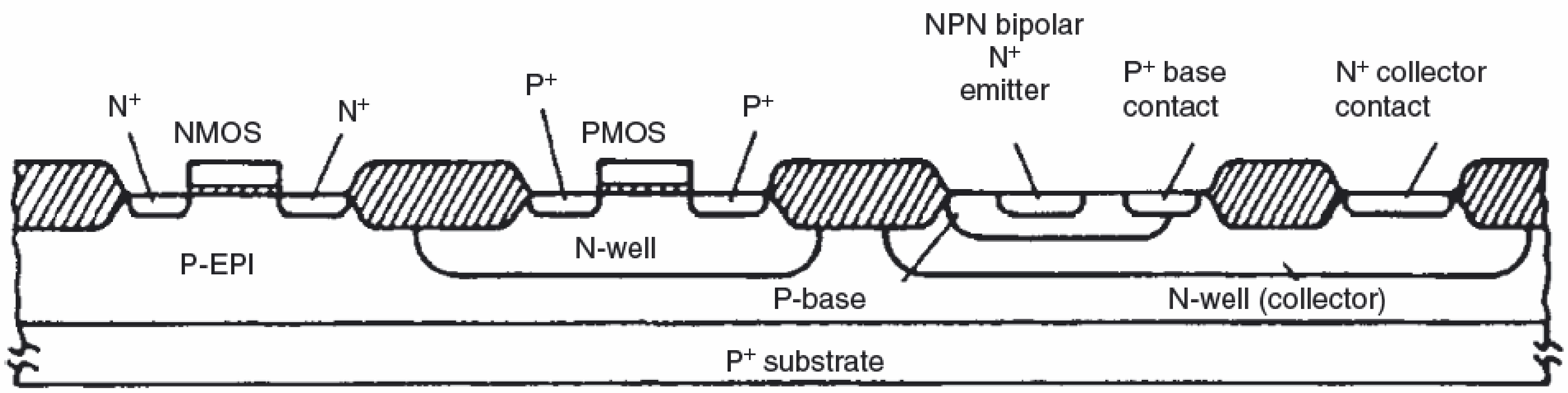
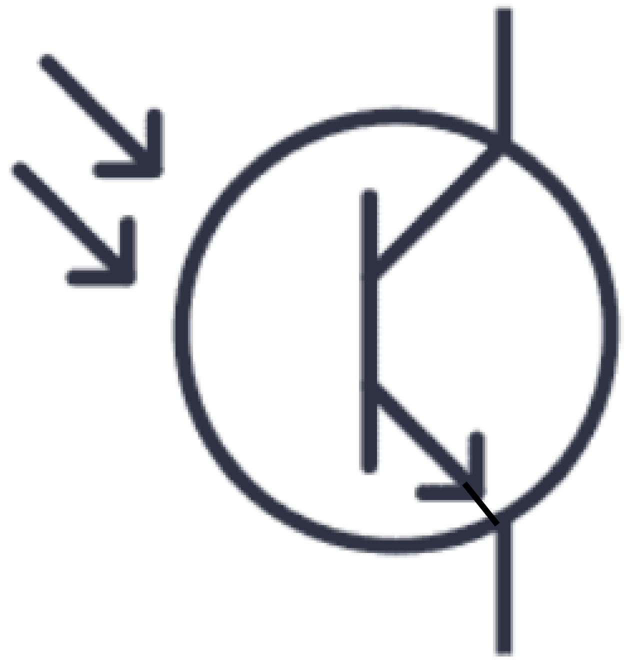


Figure 27.6 Simple BiCMOS technology: triple diffused-type bipolar transistor added to a CMOS process with minimal extra steps: only p-base diffusion mask is added to CMOS process flow. Reproduced from Alvarez (1989) by permission of Kluwer

See: Fransila

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?