Bipolar Junction Transistors (BJT)

Ideal Transistor

Bipolar Transistor - Terminals

NPN Bipolar Transistor Physics

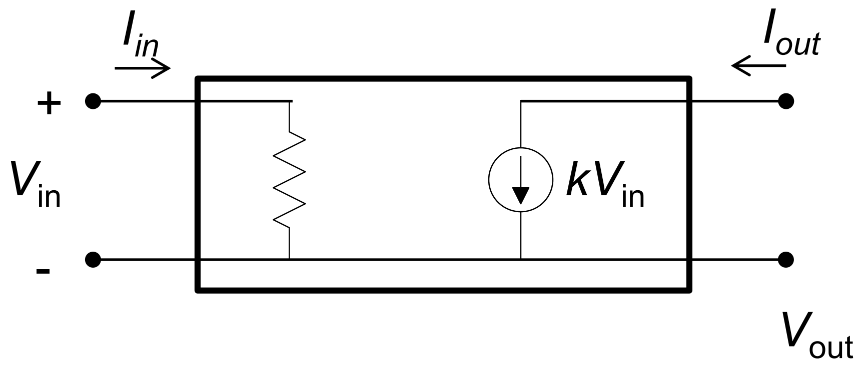
Large Signal Model

Early Effect

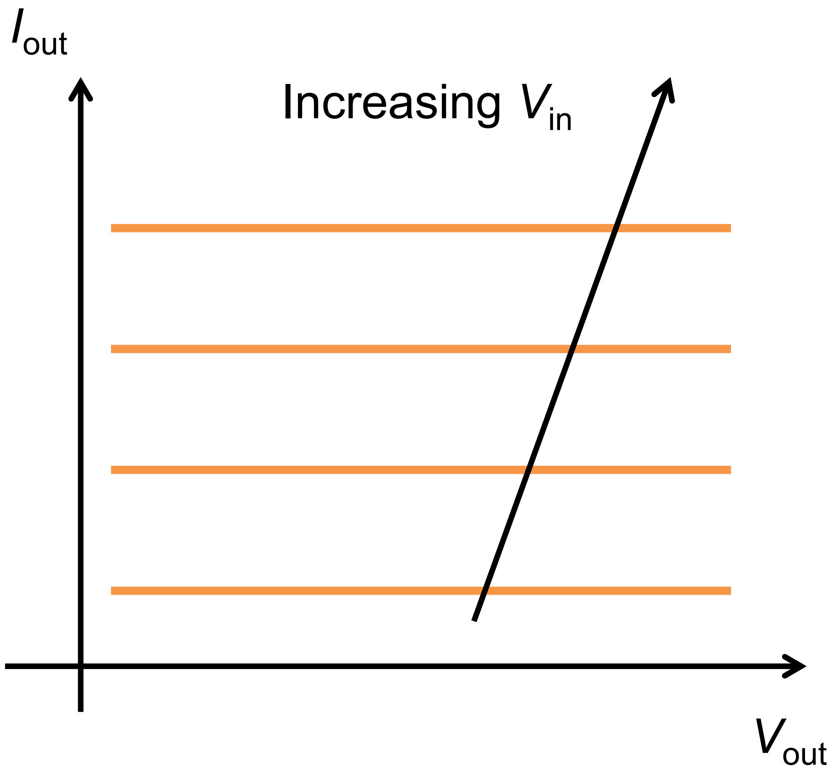
Small Signal Model

Reading: (Sedra, Smith, 7th edition)
4.1 - 4.2
6.2.2 (small signal model)
9.2.2 small signal model with capcitances

Ideal Transistor - characteristics



current source controlled by a voltage (V_{in})



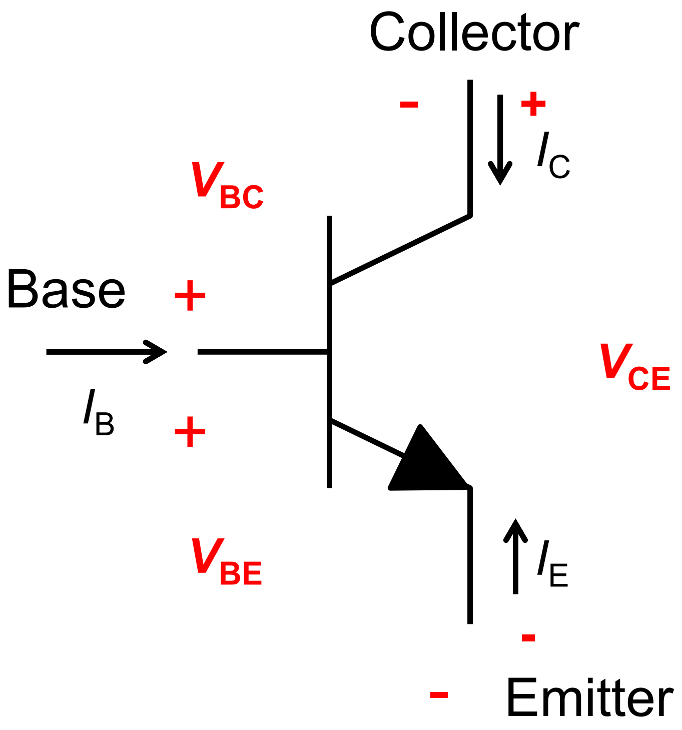
I_{out} independent of V_{out}!
I_{in} independent of V_{out}!

Two main transistor types:

Bipolar Transistors (Power Amplifiers, HighSpeed AD/DA converters)

Field Effect Transistors (99.999% - mainly integrated circuits / digital)

Bipolar Transistor - npn



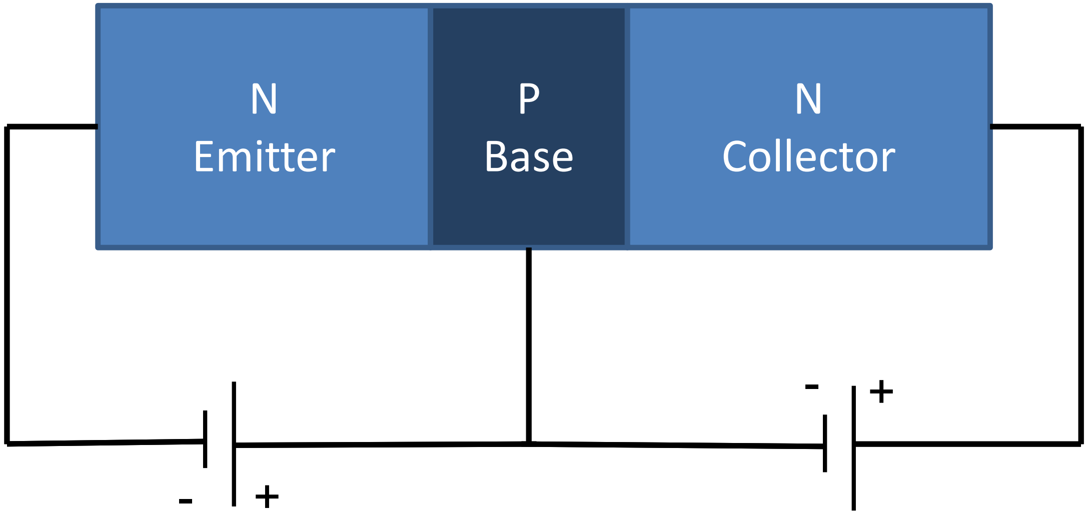
Sign convention: $V_{xy}=V_x-V_y$

I_B – base current

I_C – collector current

I_E – emitter Current = $-(I_C+I_B)$

Bipolar Transistor - npn in active mode



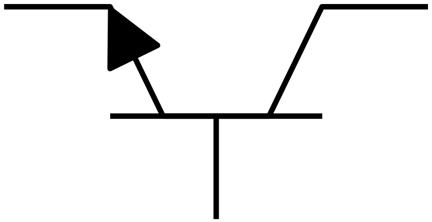
$V_{BE} > 0$

$V_{BC} < 0$

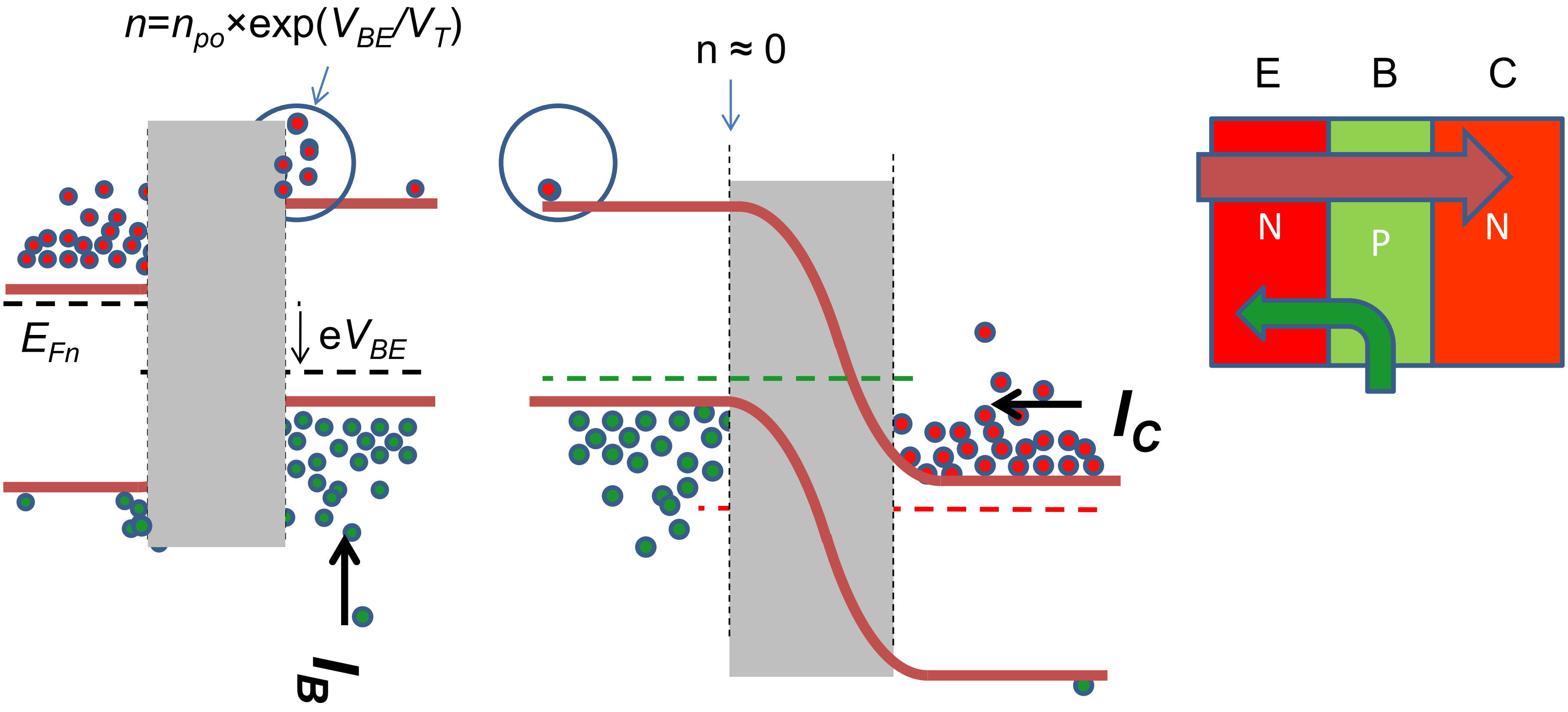
Forward biased PN junction

Reverse biased PN junction

npn



Bipolar transistor: band structure



Forward biased emitter-base junction injects electrons

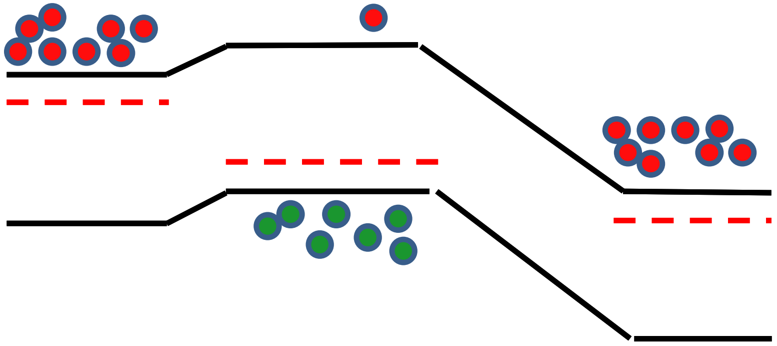
Reverse biased base-collector junction sweeps away electrons (independent of V_{BC})

Operating modes

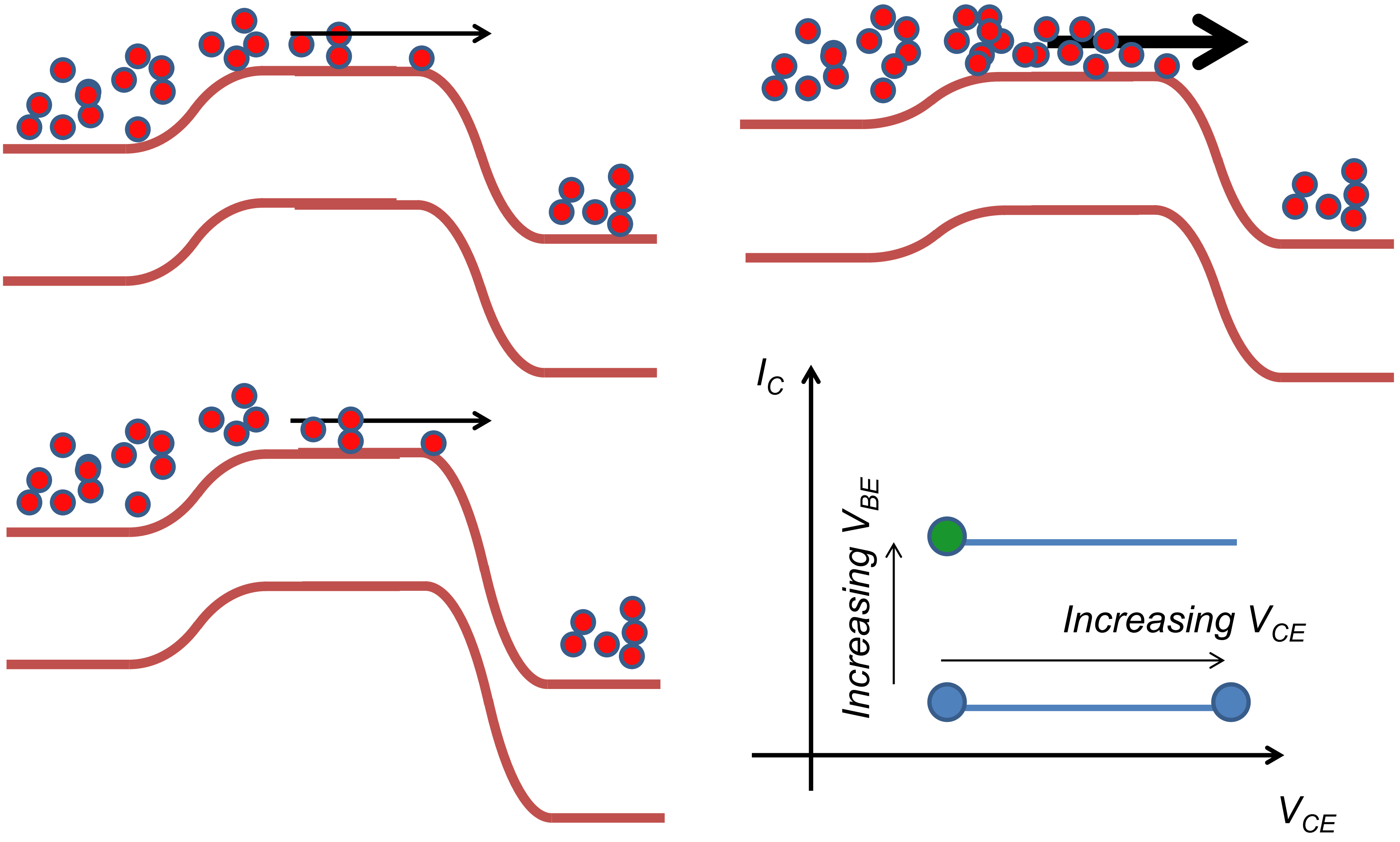
[redacted]

Active

EBJ: forward / CBJ: reverse

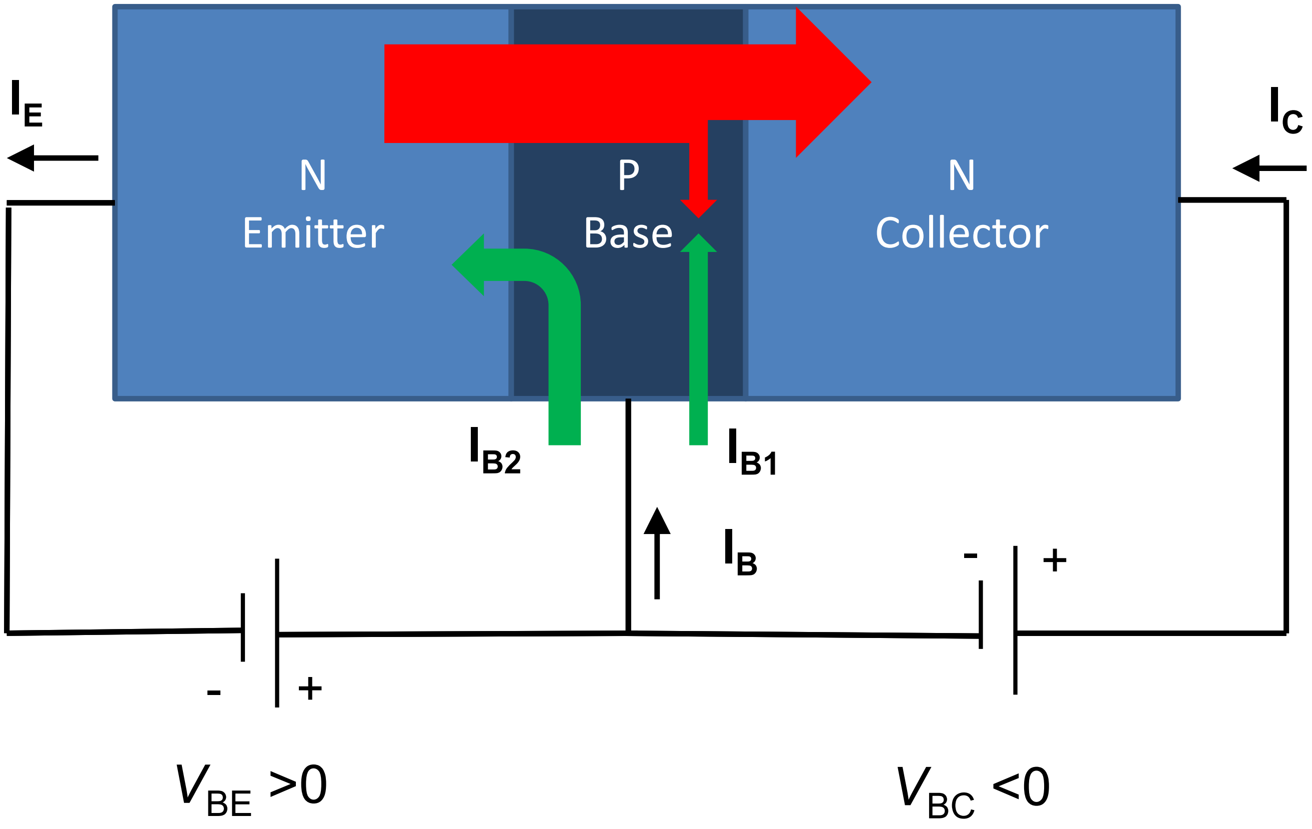


Electron diffusion currents – active mode



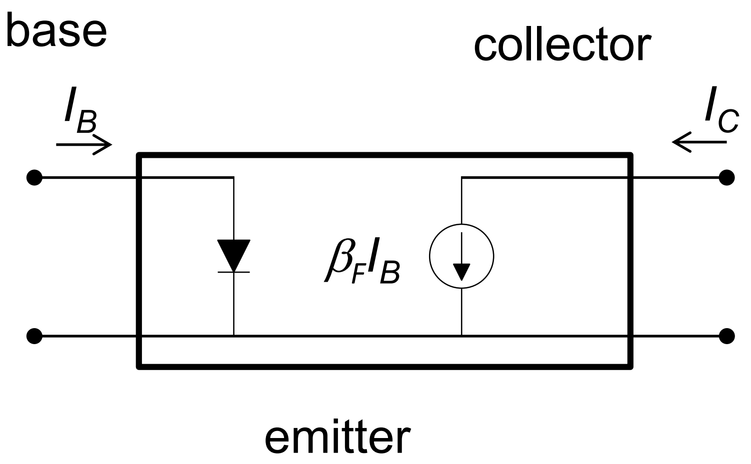
Currents in active mode

$$I_E + I_{B1} + I_{B2} + I_C = 0$$



On whiteboard: calculate I_C, I_{B1}, I_{B2} and the gain β

Large Signal Model – active mode

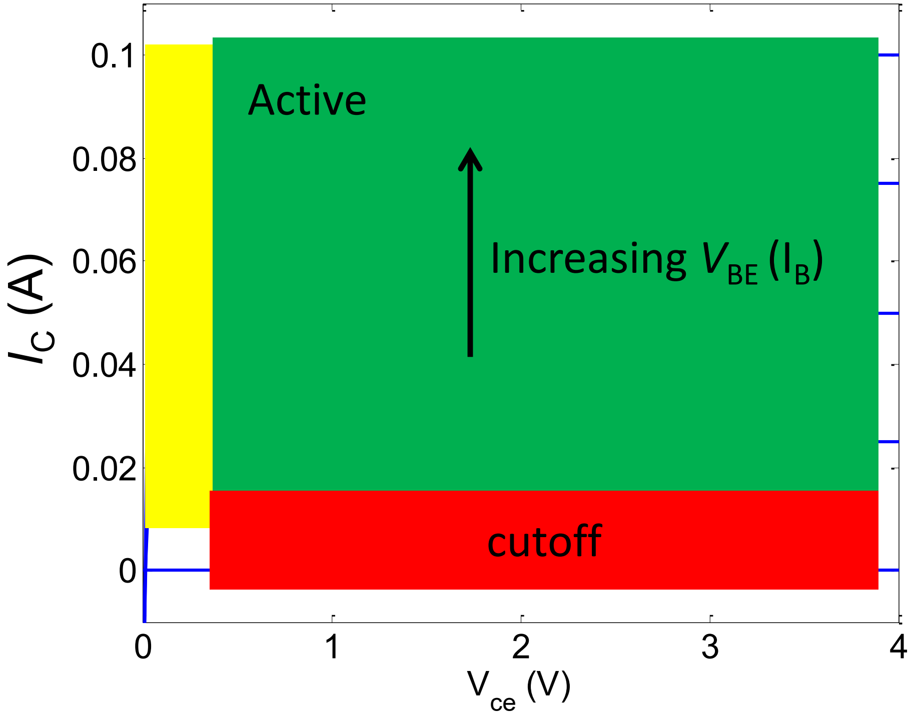


$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

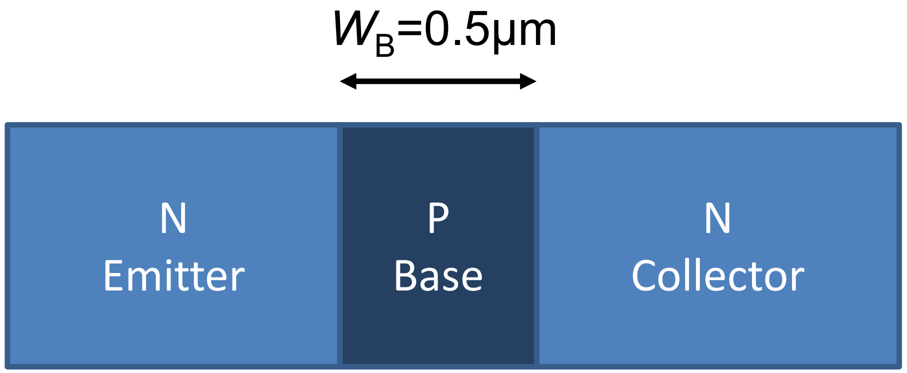
$$I_B = \frac{I_C}{\beta}$$

$V_{BE} > 0.6\text{V}$
$V_{BC} < 0.4\text{V}$
$V_{CE} < V_{BR}$

β : current gain



Example – typical Si NPN Transistor



Area: 200µm^2

N_D=1×10^{19} cm^{-3} (emitter doping)
D_p=1 cm^2/s (hole diffusion constant)
L_p=0.5µm (diffusion length)

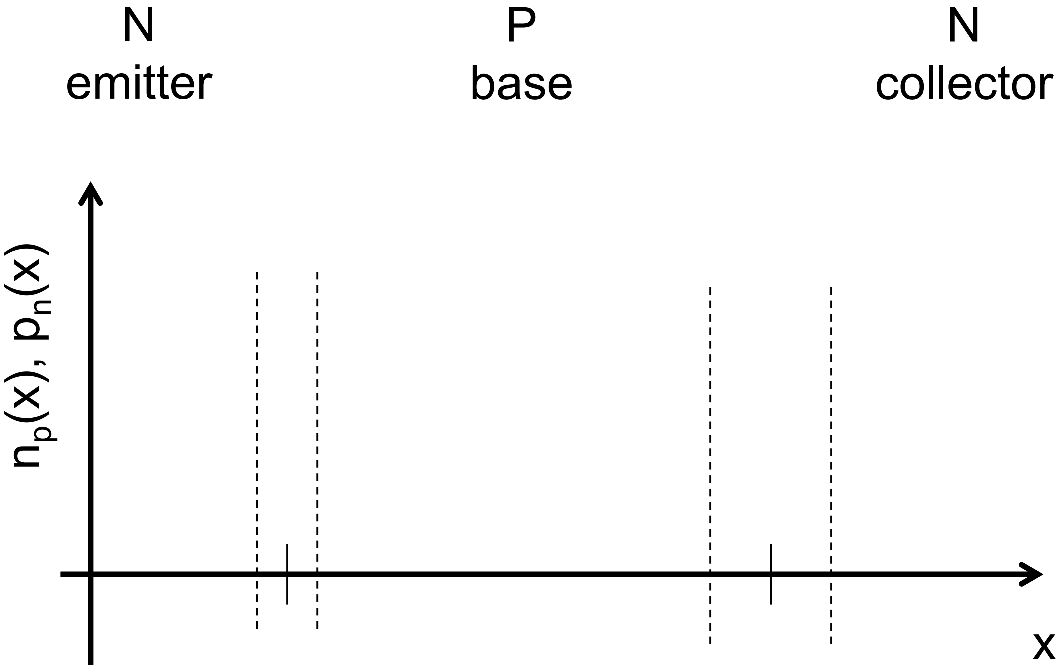
N_A=2×10^{17} cm^{-3} (base doping)
D_n=15 cm^2/s (electron diffusion constant)
τ_b=1 µs (minority carrier lifetime)

Calculate β and I_S

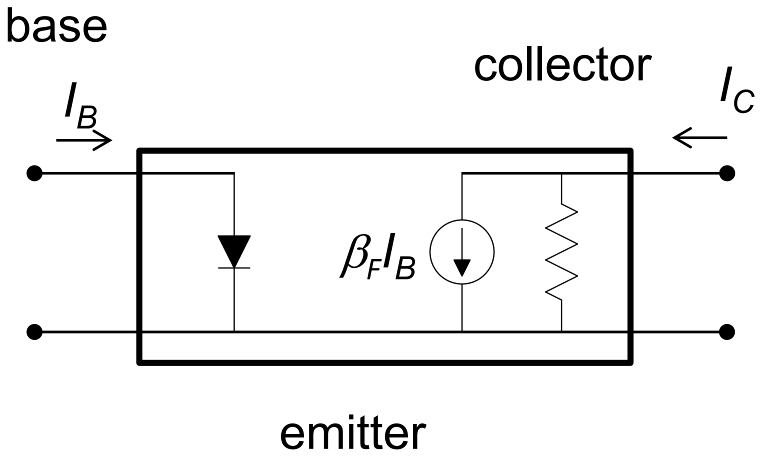
2 min excersise – Early effect (4.2.3)

Ideally I_C should not increase with V_{CE}, however the width of a pn-junction depends on applied voltage!

1. How does the base-collector depletion region change for increasing V_{CE}?
2. Sketch the <u>minority</u> carrier distribution in the base with V_{CE} applied?
3. How does I_C change with V_{CE} in this case?

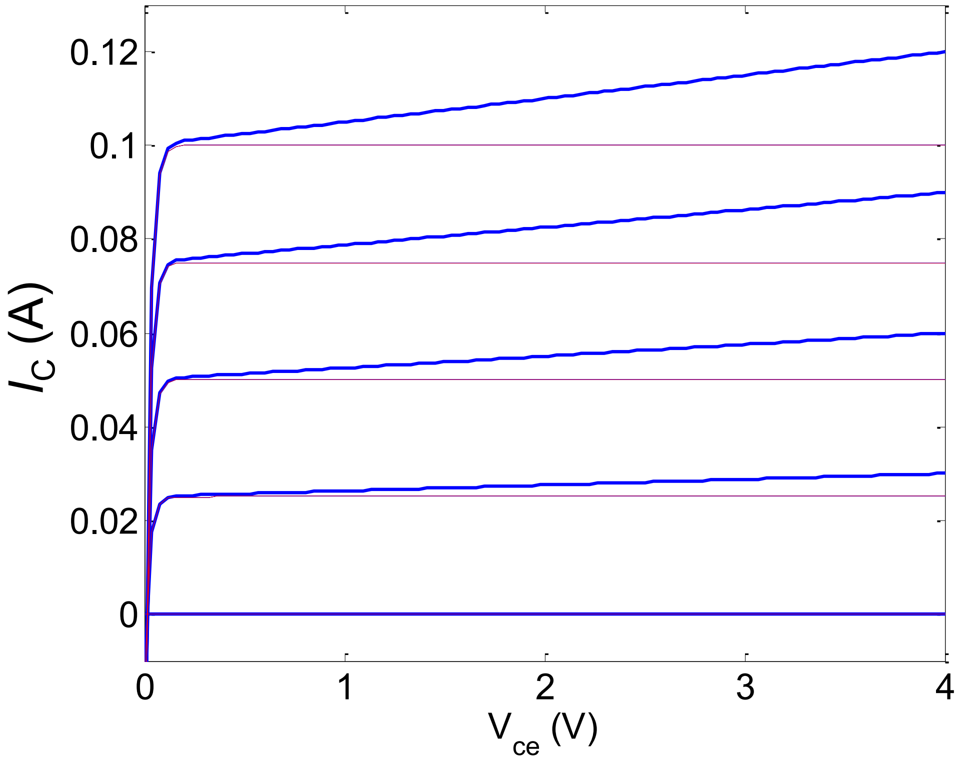


Large Signal Model – Early Effect (4.2.3)



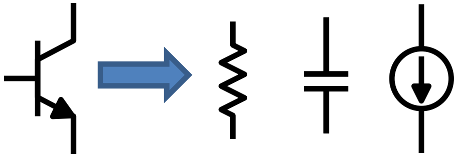
$$I_C = I_S\left(1+\frac{V_{CE}}{V_A}\right)e^{\frac{V_{BE}}{V_T}}$$

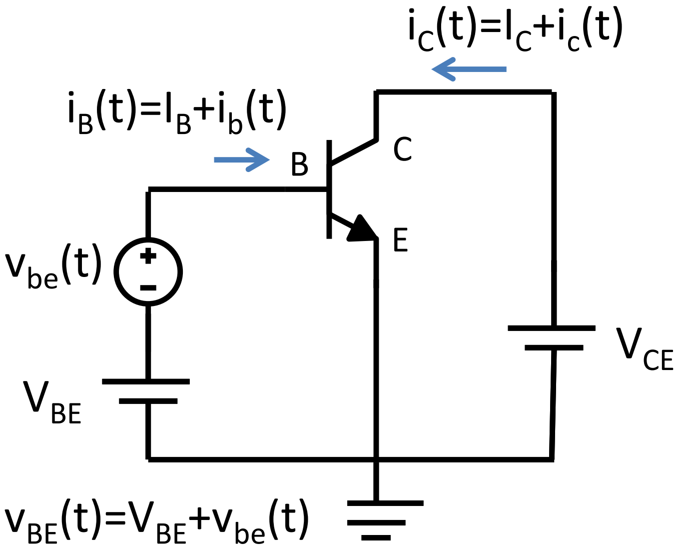
$$I_B = \frac{I_C}{\beta_F} = \frac{I_S\left(1+\frac{V_{CE}}{V_A}\right)e^{\frac{V_{BE}}{V_T}}}{\beta_F}$$

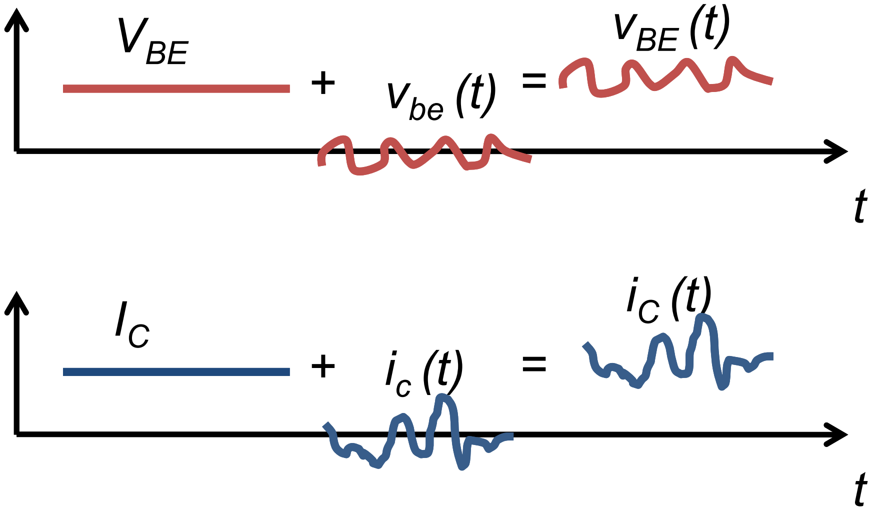


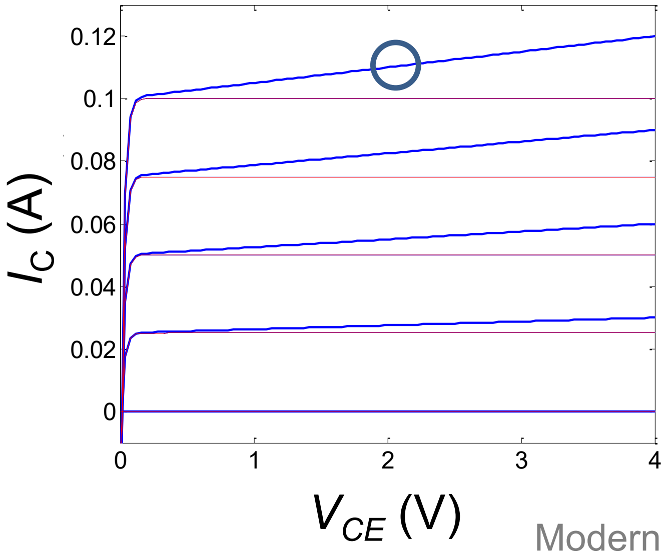
V_A – Early voltage
15-100V

Small Signals– Taylor Expansion









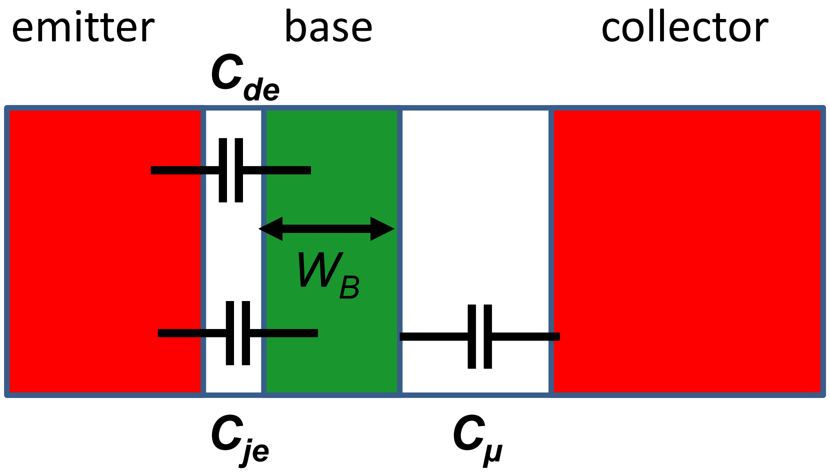
1st order Taylor expansion - linearization

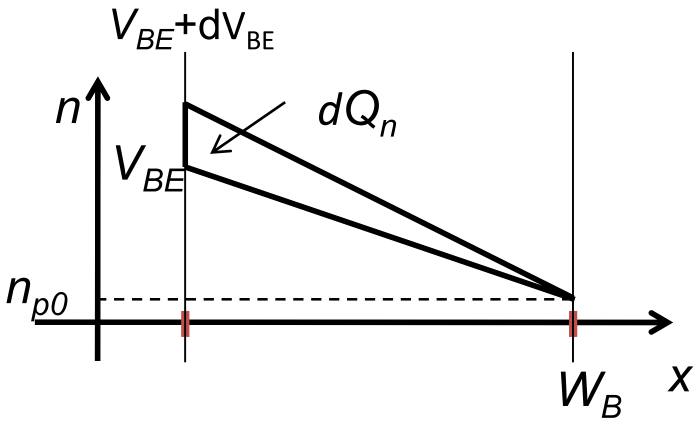
$$f(x_0+\delta x) \approx f(x_0) + \left.\frac{df(x)}{dx}\right|_{x=x_0} \delta x + \ldots$$

$$i_C(V_{BE}+v_{be}) \approx i_C(V_{BE}) + g_m \cdot v_{be}$$

$$i_C(V_{CE}+v_{ce}) \approx i_C(V_{CE}) + \frac{1}{r_0} \cdot v_{ce}$$

capacitances: C_μ, C_{je}, C_{de} *(9.2.2 (partially))*





C_{je}, C_μ : junction capacitances (small).

C_{de} : diffusion (base charging) capacitance (only forward biased pn-junction). Change in V_{BE} give change in charge in base (Q_n) -> capacitance

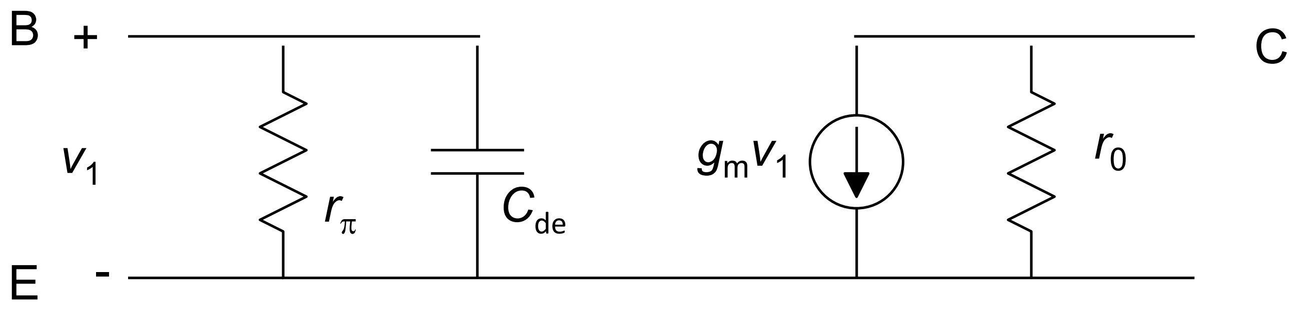
Capacitances become important for high-frequencies

$$C_{de} = \frac{dQ_n}{dv_{BE}} = \tau_F \frac{di_C}{dv_{BE}} = \tau_F g_m$$

τ_F: base transit time, average time for a carrier to cross base

$\tau_F = W_B^2/2D_n$

(simple) small Signal Model – Active Mode



Transconductance – controls the current source

$$g_m = \frac{I_C}{V_T}$$

Remember:
V_T=kT/q

Input resistance – I_B change with V_{BE}

$$r_\pi = \frac{\beta_F}{g_m}$$

Output resistance – Early effect

$$r_0 = \frac{V_A}{I_C} = \frac{V_A}{g_m V_T}$$

Diffusion (base charging) capacitance – forward biased BE junction

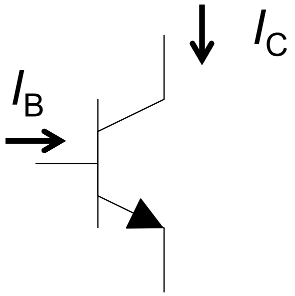
$$C_{de} = \tau_F g_m$$

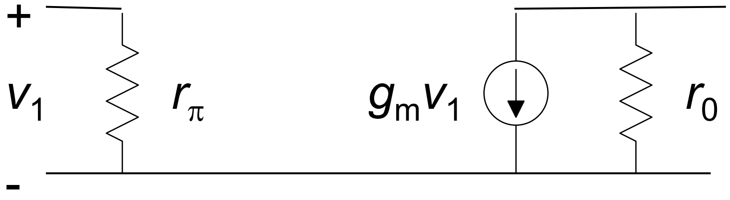
Example – low f model

A BJT is biased so that I_C=5mA.
Low frequency -> capacitances are "open circuit"

Parameters:
$\beta = 500$
$V_A = 100$ V
$V_T = 25.9$ mV

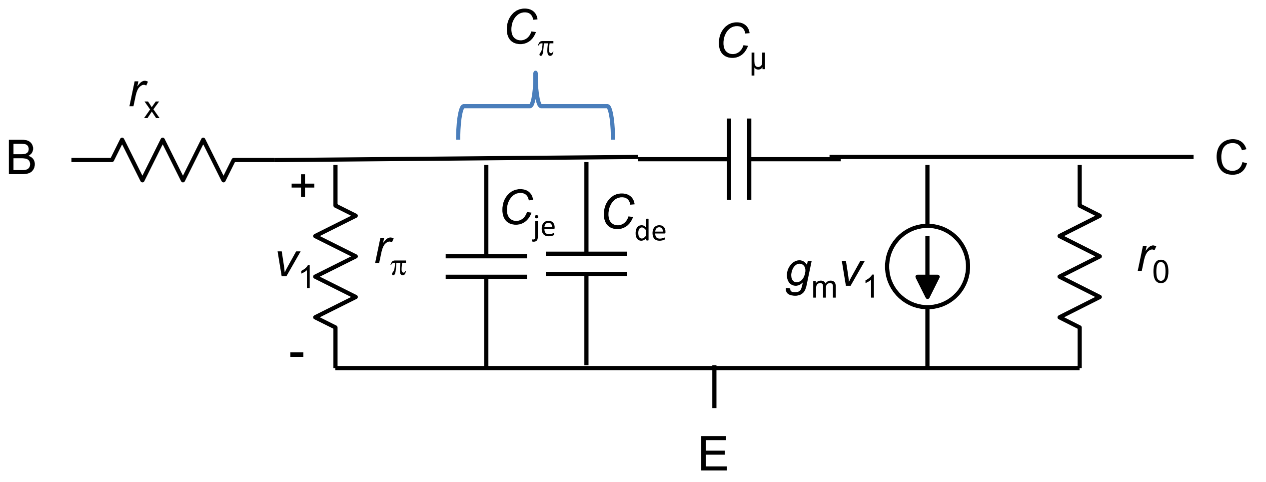
Calculate I_B and the corresponding small signal model.





Small Signal Model – more advanced

- Add junction capacitances C_μ (BC junction) and C_{je} (BE junction).
- Sum capacitances $C_\pi = C_{je} + C_{de}$.
- Add series resistances in base (r_x).



r_x, C_{je} and C_μ: Depends on exact transistor geometry.

Summary - BJTs

- NPN or PNP. NPN is faster due to higher electron mobility

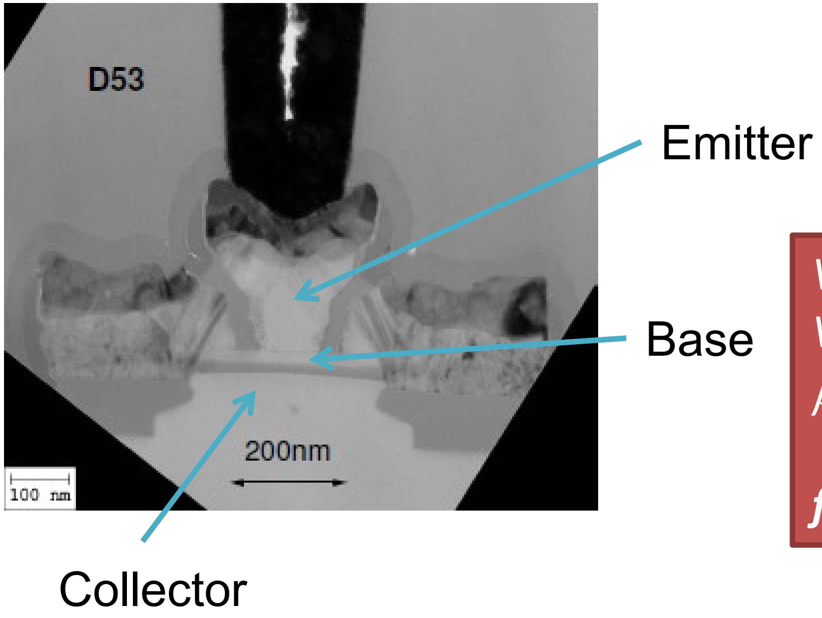
- Active mode (used for amplifiers):
  - Emitter-base junction is forward biased (injects minority carriers into base)
  - Collector-base junction is reverse biased (removes minority carriers from base)

- Early effect: increasing V_{CE} extends the collector-base depletion region narrowing the base resulting in a higher diffusion current I_C.

- Small signal model:
  - Input resistance (r_π) due change in base current (I_B) when changing V_{BE}.
  - Output resistance (r_0) due to Early effect.
  - Base charging capacitance (C_{de}) due to change in charge in base region when changing V_{BE}.
  - Can add more capacitances and resistances to get more accurate (and complicated) model.

State-of-the Art: SiGe Bipolar Transistor

- Vertical device
- Not symmetric – high emitter doping, lower in collector
- Heterostructure with graded E_g to enable high dopning in base (low resistance) without backinjection into emitter.



Emitter

Base

Collector

V_{BR} ~ 1.5V
$V_{ce,sat}$ ~ 0.3V
β_F ~ 600

f_t=300 GHz