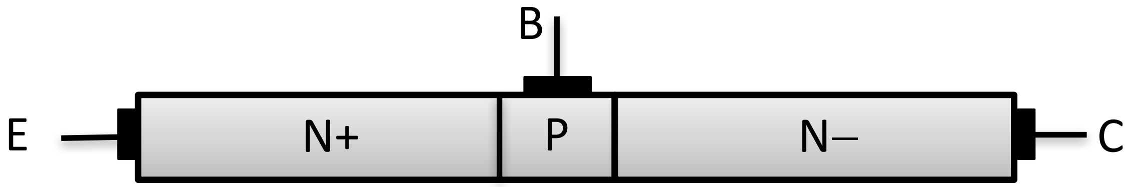
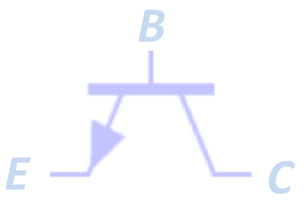
Chapter 5

Electronics I - Physics of Bipolar Transistors





Fall 2017

Types of Bipolar Transistors

source: Sedra & Smith

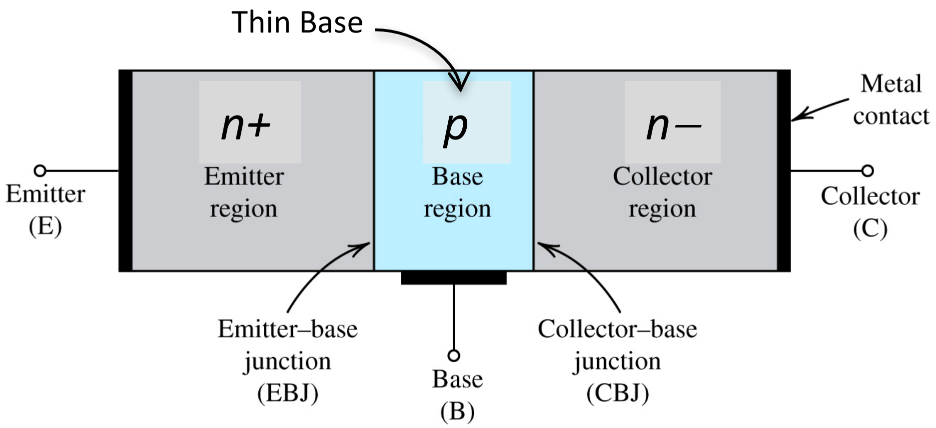


Figure - A simplified structure of the npn transistor

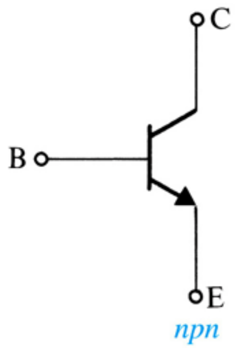


Figure – Symbol of the npn transistor

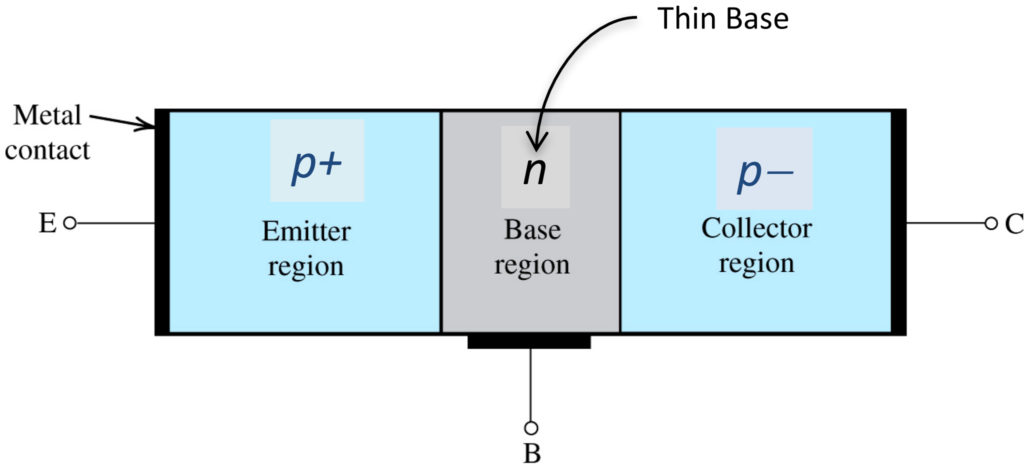


Figure - A simplified structure of the pnp transistor.

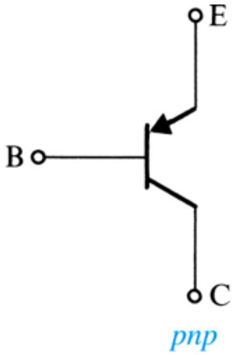


Figure – Symbol of the pnp transistor

Physical structure of an npn BJT

source: Sedra & Smith

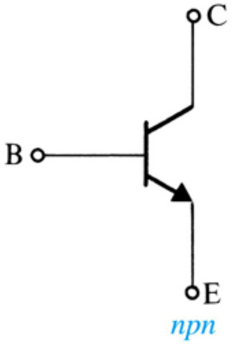


Figure - npn BJT symbol

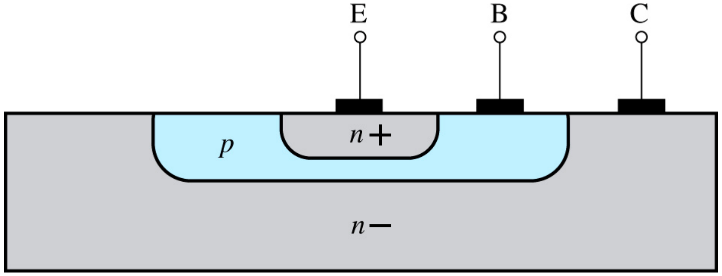
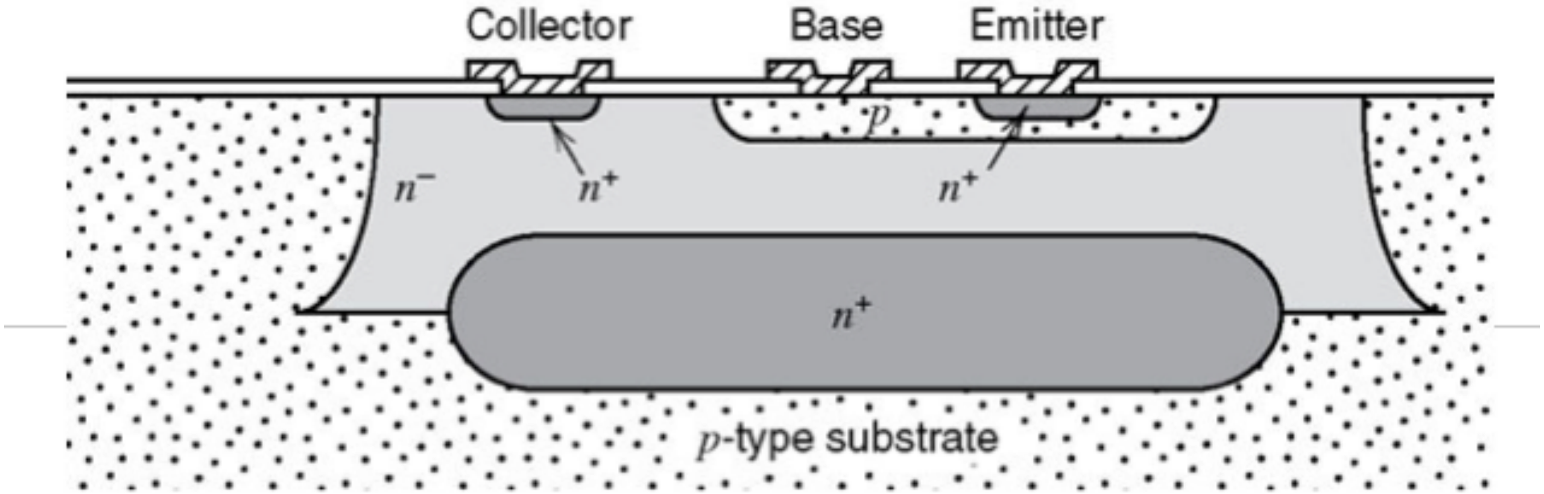


Figure - Simplified Cross-section of an npn BJT.

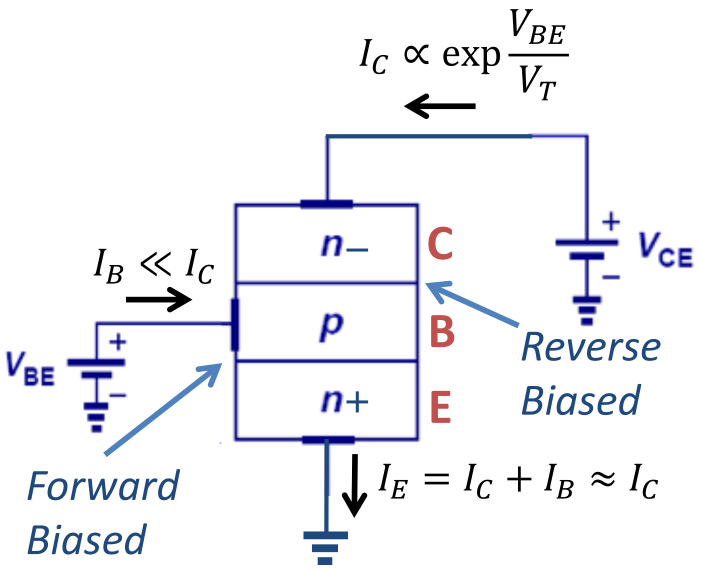
source: Gray & Meyer



NPN BJT operating in “Forward” **Active Mode**

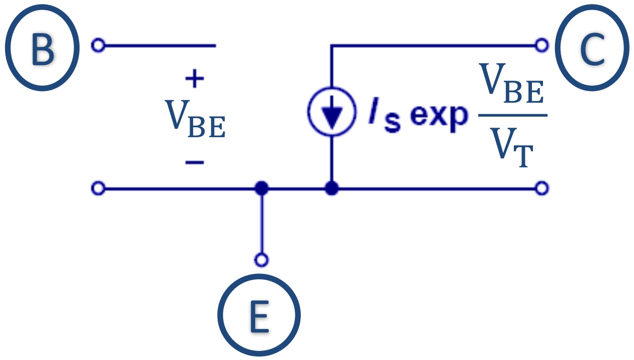
source: B. Murmann

Conceptual View:

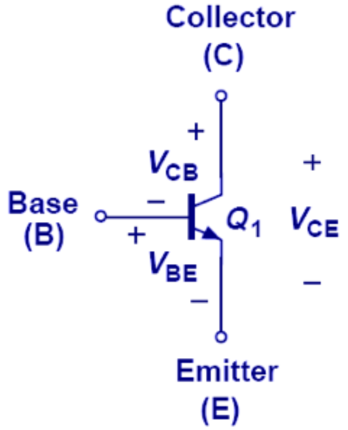


$$V_{CB} = V_{CE} - V_{BE}$$

- Device acts as a voltage controlled current source
  - V_{BE} controls I_C

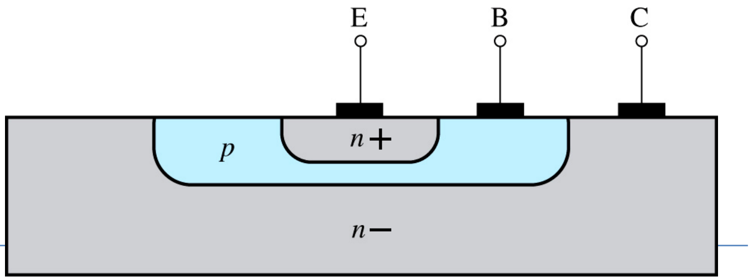


- The BE junction is forward biased (V_{BE} > 0) and the BC junction is reverse biased (V_{BC} < 0 ←→ V_{CB} > 0)



- The device is built such that:
  - The BASE region is very thin
  - The EMITTER doping is much higher than the BASE doping (N_E (donors) >> N_B(acceptors))
  - The COLLECTOR doping is much lower than the BASE doping (N_B (acceptors) >> N_C (donors))

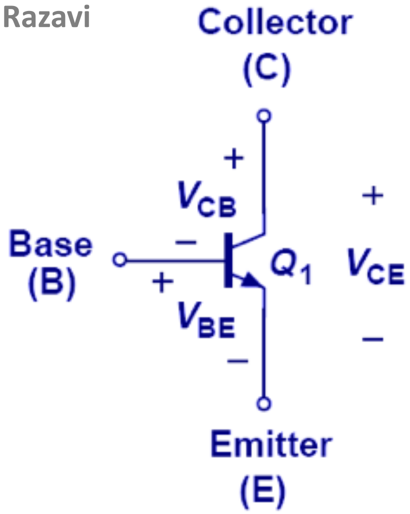
Outline of discussion for NPN BJT in Active mode



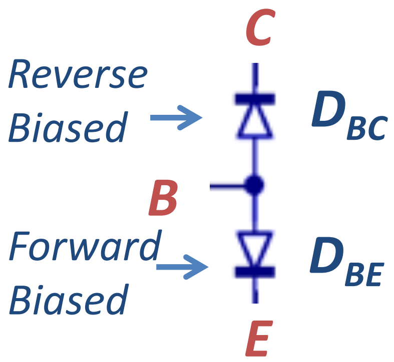
source: B. Murmann

- To understand the operation of the NPN BJT in active mode, we will to look at:
  - Properties of forward biased PN^+ junction (BE)
  - Properties of reverse biased PN^- junction (BC)
  - The idea of combining the two junctions by a very thin P-type region (B)

source: Razavi



Although the device contains two PN junctions it cannot be modeled as two back to back diodes.



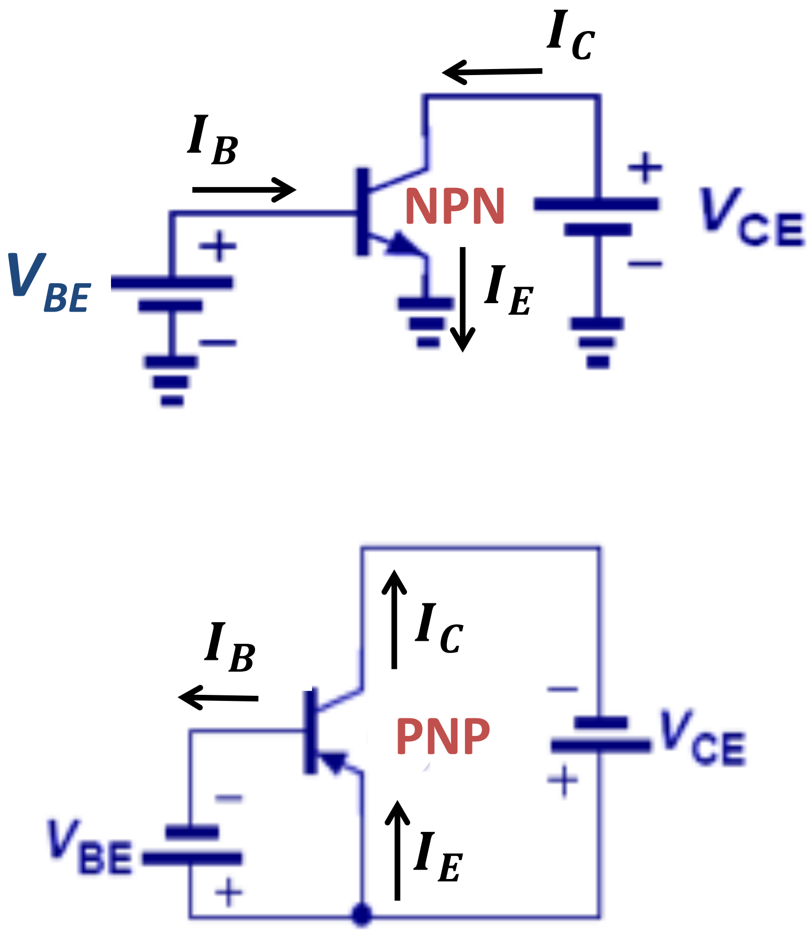
The doping levels and dimensions of E and C are quite different ($N_E >> N_C$ and $A_C >> A_E$). The device is not symmetric: E and C cannot be interchanged

Main idea

- Make the P-region (B) of the PN+ junction (BE junction) very thin and forward bias it
  - This way the electrons injected from the N^+ side (E) into the P side (B) cannot recombine much
- Attach an N^- region (C) to the P-region (B) and reverse bias the resulting PN^- junction (BC junction)
  - This way most of the electrons injected into the P-region (B) are swept into the N^- region (C) before there is any significant amount of recombination occurring
- Final Result: most of the electrons emitted in E will make it through B and get collected in C

Voltage polarities for BJTs in active mode

source: Razavi



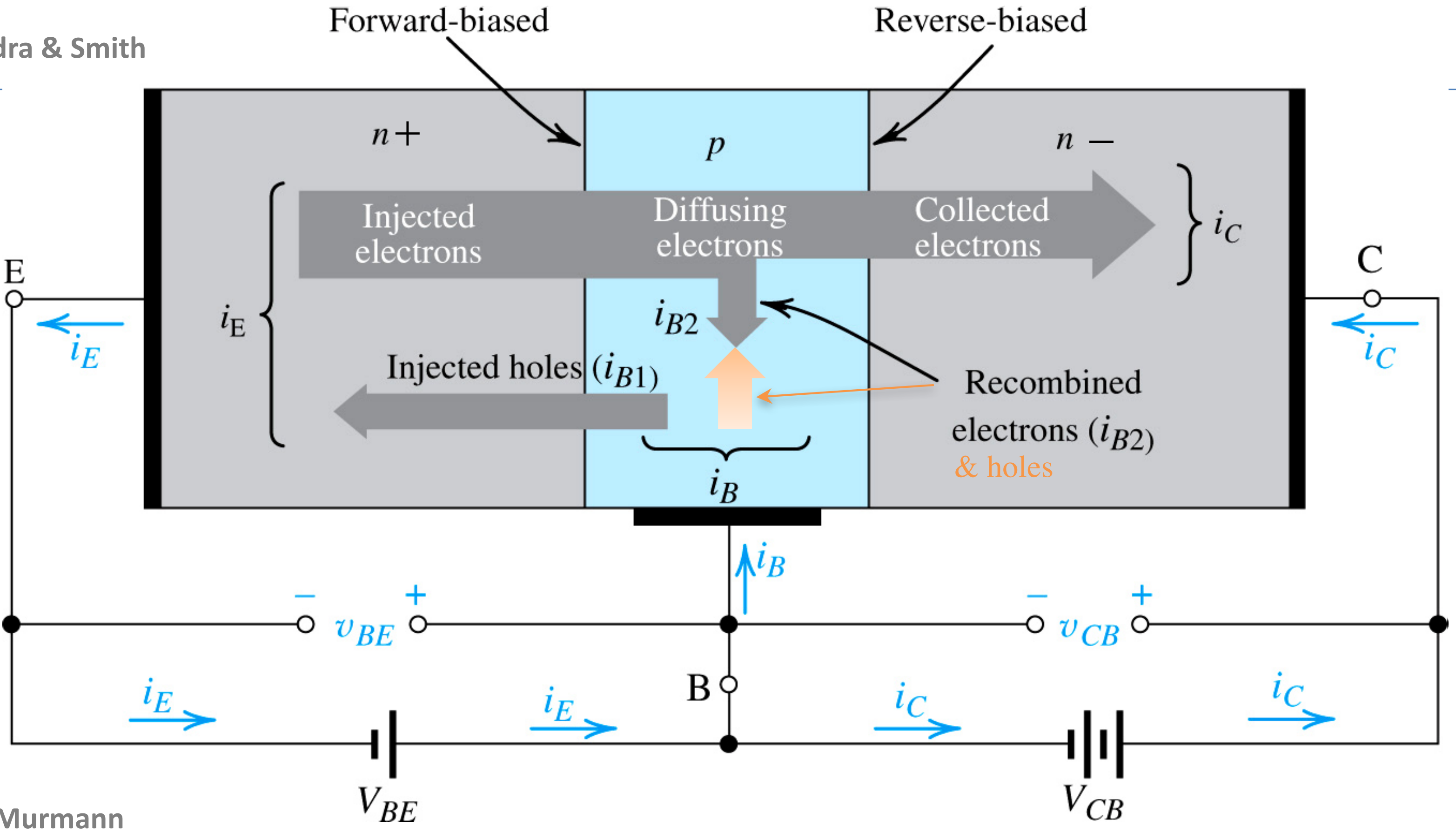
$$\begin{cases} V_{BE} \geq V_{BE,ON} \\ V_{CE} > V_{CE,SAT} \end{cases}$$

$$\begin{cases} V_{EB} \geq V_{EB,ON} \\ V_{EC} > V_{EC,SAT} \end{cases}$$

Figure – Voltage polarities and current flow in bipolar transistors biased in the active mode

Currents for NPN BJT in active mode

source: Sedra & Smith

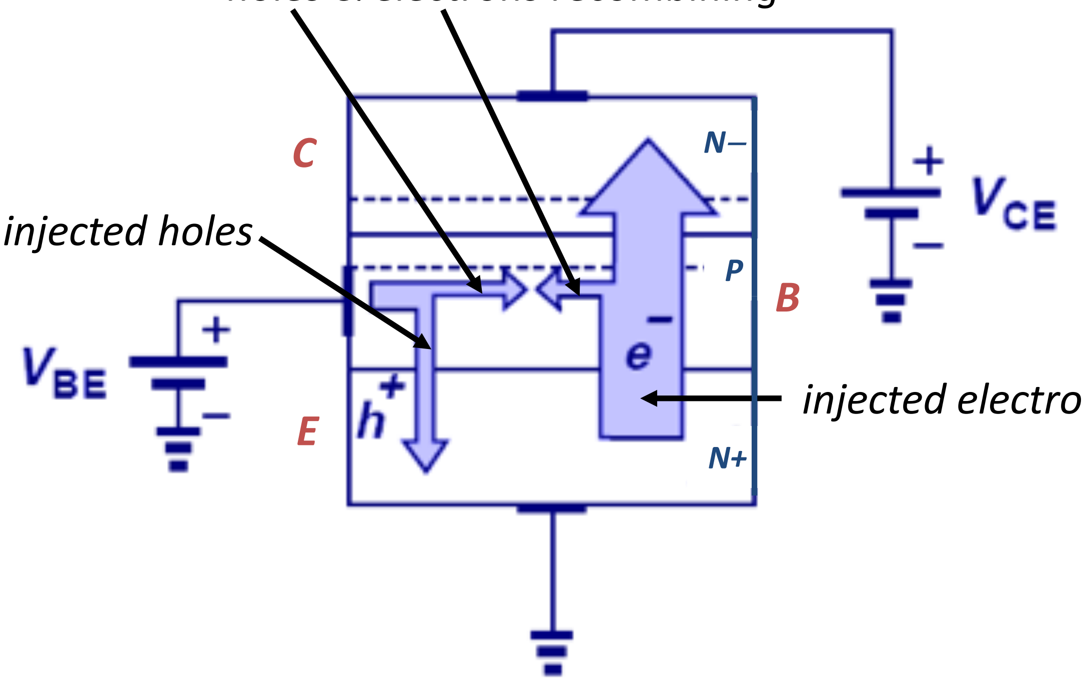


source: B. Murmann

- Primary current is due to electrons captured by the collector
- Two (undesired) base current components
  - Hole injection into emitter (→ 0 for infinite emitter doping)
  - Recombination in base (→ 0 for base width approaching 0)

Currents for NPN BJT in active mode

source: Razavi

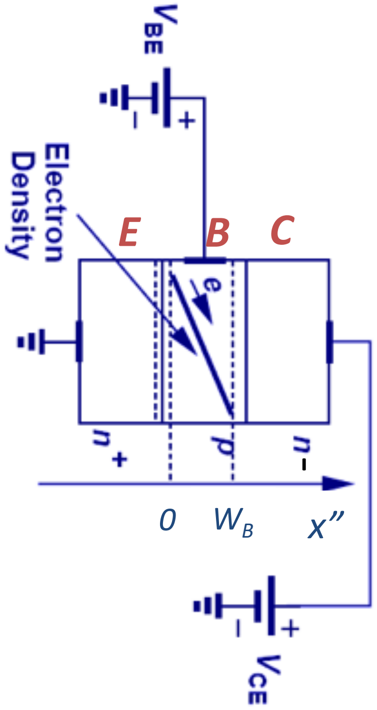


holes & electrons recombining

injected holes

injected electrons

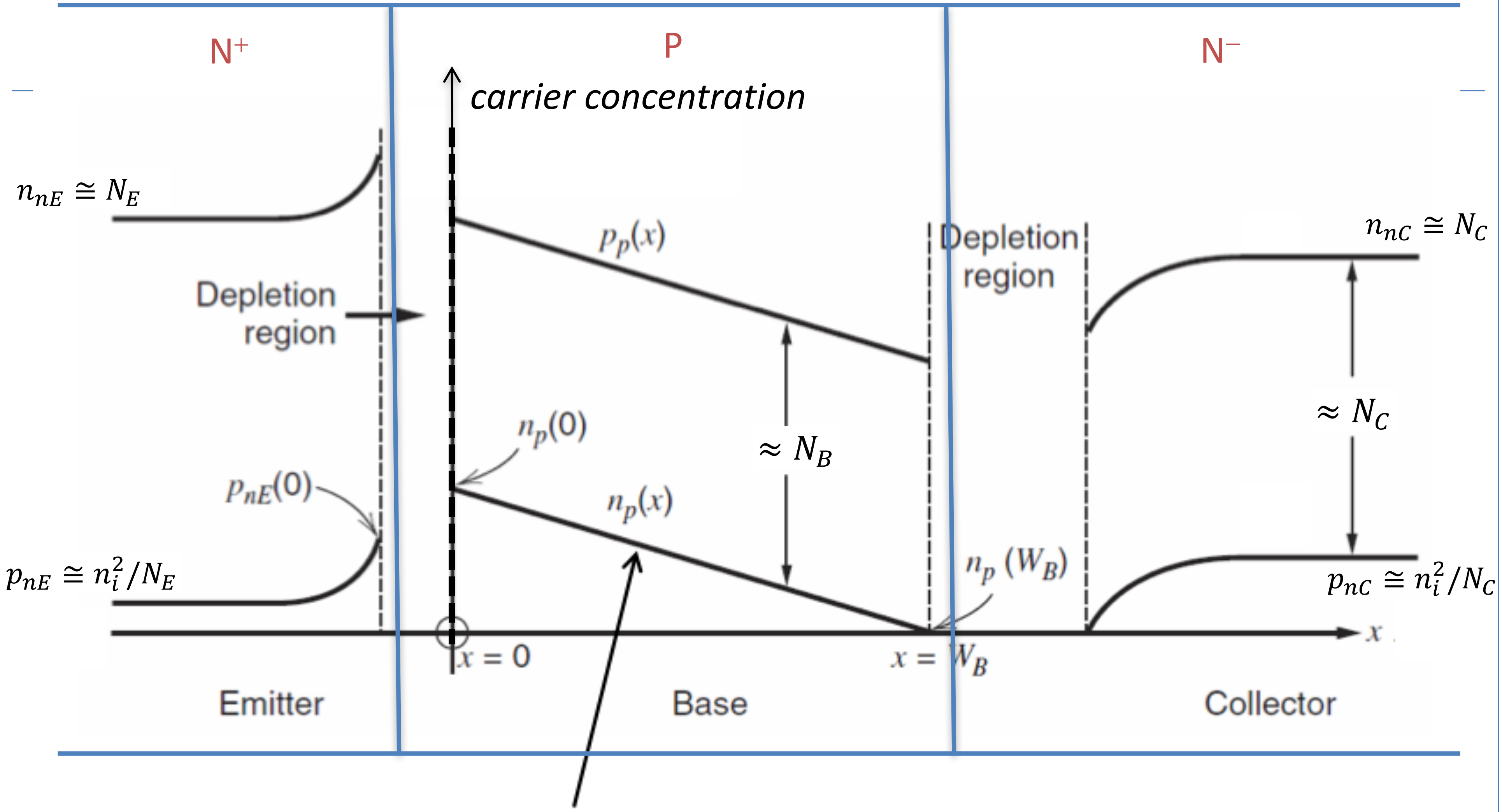
Electrons diffusing in P region



- There a lot of electrons injected into the P region, not that many holes injected in N+ region ($N_E >> N_B$)
- The electrons injected in the P region causes a diffusion current decaying in the x” direction due to recombination (recombination necessitate a flow of holes to balance out the flow of electrons)

Carrier Concentrations

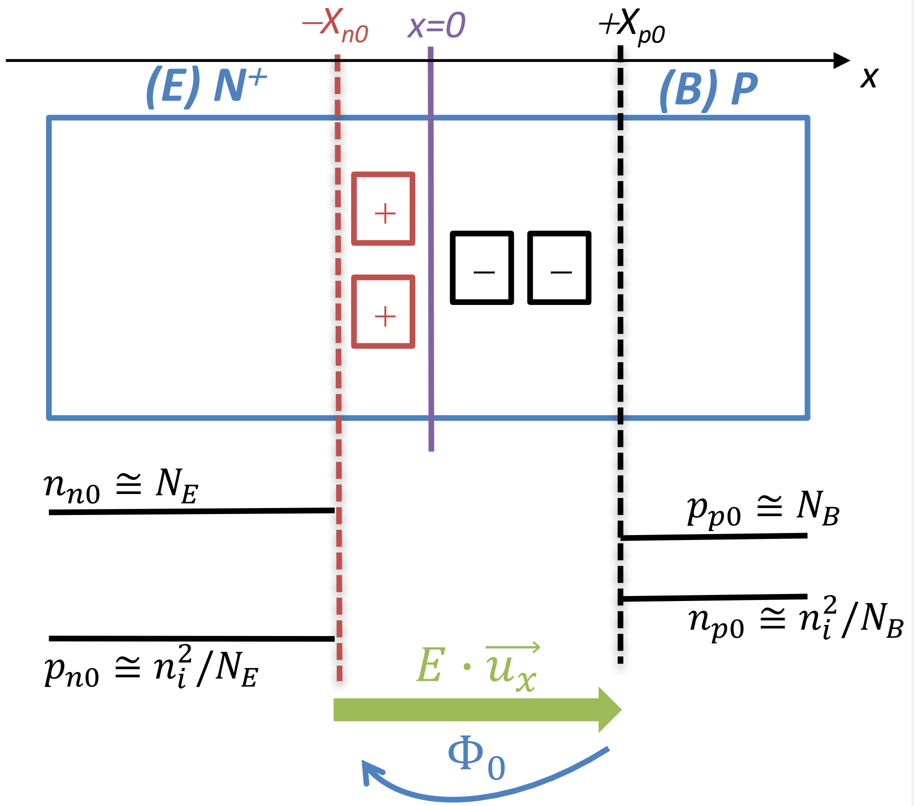
source: Gray & Meyer



Straight line because base is thin; negligible recombination ("short base" electron profile)

BE (PN$^+$) junction

- *Built-in Potential (PN+ junction at equilibrium: $V_{BE}=0$)*



electrons want to diffuse

holes want to diffuse

electrostatic force prevents e$^-$ from diffusing

electrostatic force prevents h$^+$ from diffusing

Electrostatic force and diffusion balance out:

$$(drift)\quad \cancel{q}\mu_p p E = \cancel{q} D_p \frac{dp}{dx} \quad \text{(diffusion)}$$

$$\updownarrow$$

$$\underbrace{-\int_{V(-X_{no})}^{+V(X_{p0})} dV}_{\equiv \Phi_0} = \underbrace{\frac{D_p}{\mu_p}}_{\equiv V_T} \int_{p_{n0}}^{p_{p0}} \frac{dp}{p}$$

$$\updownarrow$$

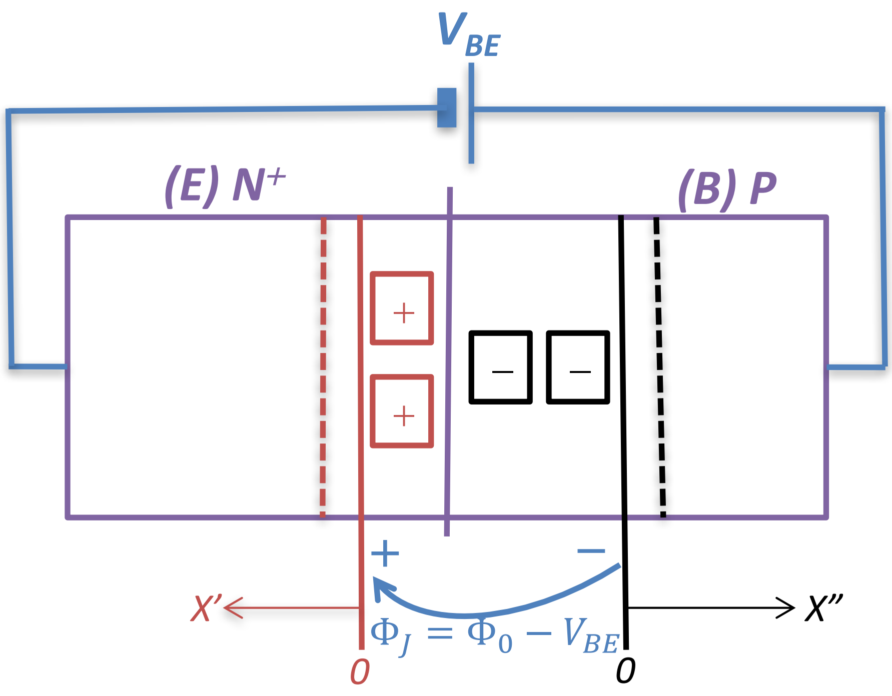
$$\boxed{\frac{p_{p0}}{p_{n0}} = exp\left(\frac{\Phi_0}{V_T}\right) = \frac{n_{n0}}{n_{p0}}}$$

$$\Phi_0 = V_T \cdot ln\left(\frac{n_{n0}}{n_{p0}}\right) = V_T \cdot ln\left(\frac{p_{p0}}{p_{n0}}\right) \approx$$

$$\approx V_T \cdot ln\frac{N_E N_B}{n_i^2}$$

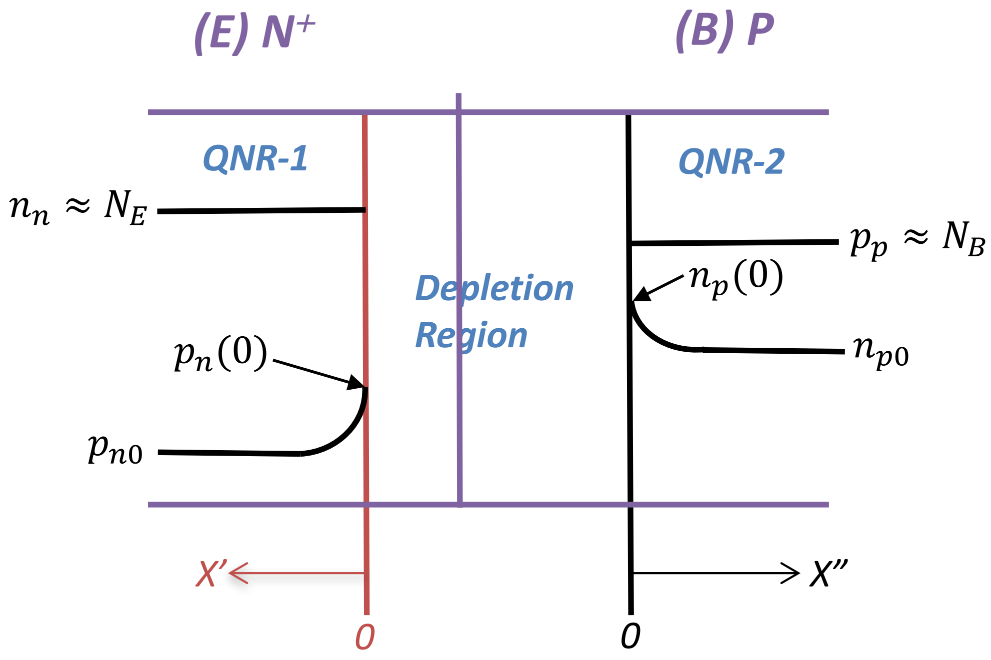
BE (PN^+) junction with forward bias

- The depletion region narrows and diffusion processes are no longer balanced by electrostatic forces



- With a forward bias applied some electrons can now diffuse from the N+ side (where they are majority carriers) to the P side (where they become minority carriers). Similarly, some holes diffuse from the P side into the N+ side
- This migration of carriers from one side to another is called INJECTION
- As a result of injections the concentration of minority carriers at the edges of the depletion region (x'=0 and x"=0) is "significantly" increased

BE (PN$^+$) junction with forward bias



- *Important result to remember*
  - Forward Bias increases the concentration of electrons at the P side's edge of depletion region by a factor $\exp(V_{BE}/V_T)$ (*Law of the Junction*)

$$n_p(0) = \frac{n_{n0}}{\exp\left(\frac{\Phi_0 - V_{BE}}{V_T}\right)} = $$

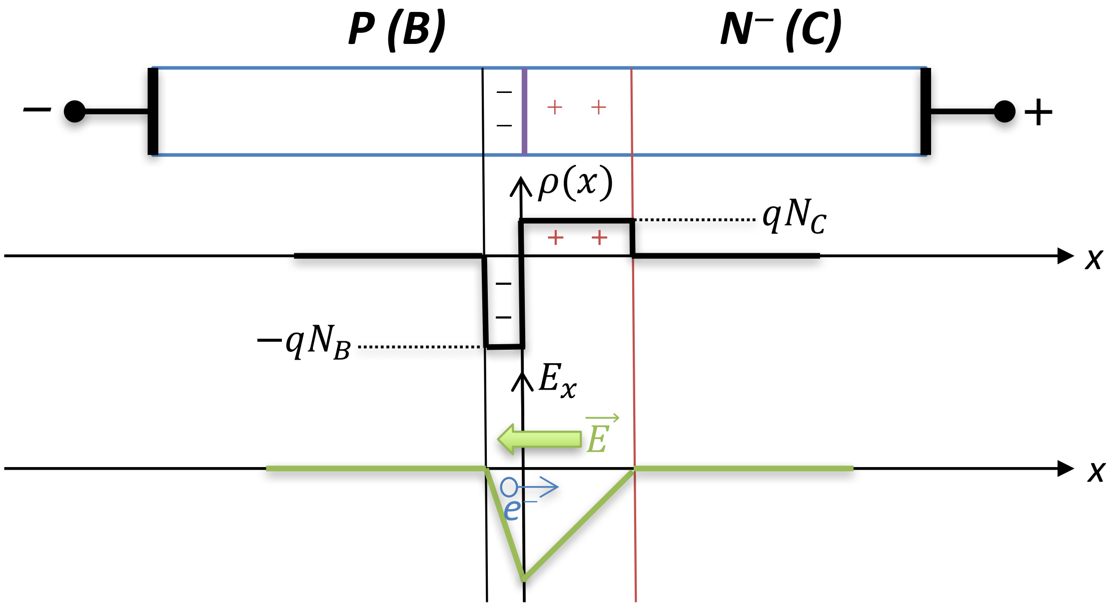
$$= \frac{n_{n0}}{\exp(\Phi_0/V_T)} \exp\left(\frac{V_{BE}}{V_T}\right) \approx$$

$$\boxed{\approx n_{p0} \cdot \exp\left(\frac{V_{BE}}{V_T}\right) \approx \frac{n_i^2}{N_B} \exp\left(\frac{V_{BE}}{V_T}\right)}$$

- Since outside the depletion region there must be charge neutrality, the concentrations of the majority carriers at the edges of the depletion region must also increase of the same amount the minority carriers increased
- However if we assume low level of injection the increase in majority carriers in not significant and can be neglected
- The carriers injected would like to diffuse into the neutral regions, but quickly fall victim of recombination
- The number of minority carriers decay exponentially and drops to 1/e at the so called diffusion length (L_p and L_n are on the order of microns)

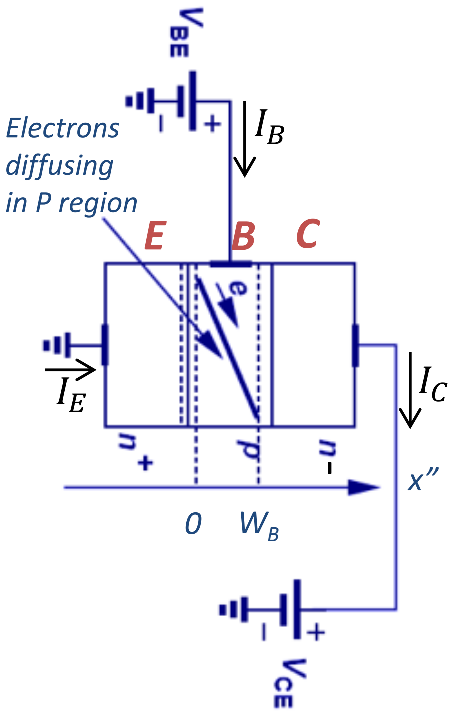
Reverse Biased BC (PN^-) junction

- Reverse bias increases the width of the depletion region and increases the electric field
- Depletion region extends mostly in N^- side
- Any electron that "somehow" make it into the depletion region is swept through by the electric field, into the N- region



Collector Current for an NPN BJT in active mode

source: Razavi



- First order expression:
  - The electrons injected from the emitter into base diffuse through base and then get swept into collector:

$$J_n = qD_n \left.\frac{dn_p}{dx}\right|_0 \cong qD_n \frac{\Delta n_p}{\Delta x} = qD_n \frac{n_p(0)-n_{p0}}{0-W_B} =$$

$$= -\frac{qD_n}{W_B} n_{p0}\left(e^{V_{BE}/V_T}-1\right) \approx -\frac{qD_n}{W_B}\frac{n_i^2}{N_B} e^{V_{BE}/V_T}$$

  - Multiplying by the emitter area and changing the sign to obtain the conventional current

$$I_C \approx A_E \frac{qD_n}{W_B}\frac{n_i^2}{N_B} e^{\frac{V_{BE}}{V_T}} = I_S \cdot e^{\frac{V_{BE}}{V_T}}$$

I_{SE} *to be picky*

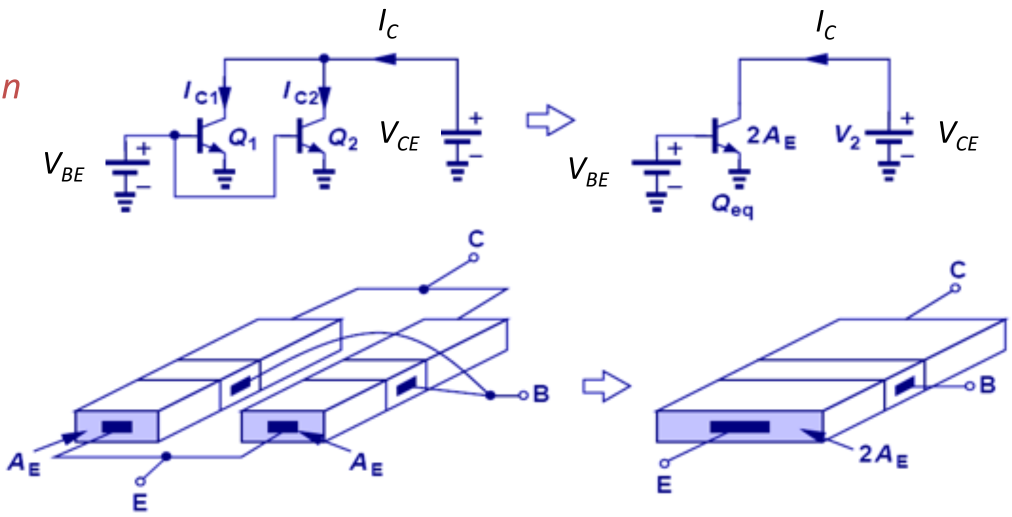
The device operates as a voltage controlled current source (it performs voltage-current conversion)

Relation between collector current and emitter area

source: Razavi

- When two transistors are put in parallel and experience the same potential across all three terminals, they can be thought of as a single transistor with twice the emitter area.

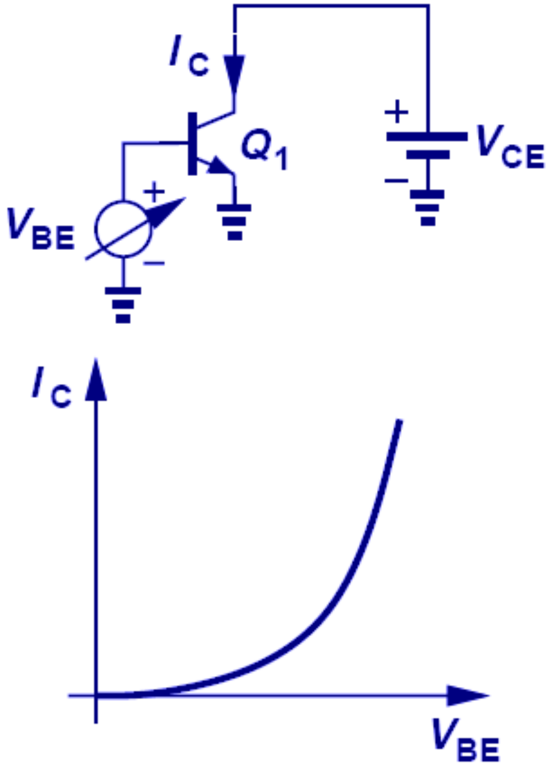
Parallel combination of two transistors



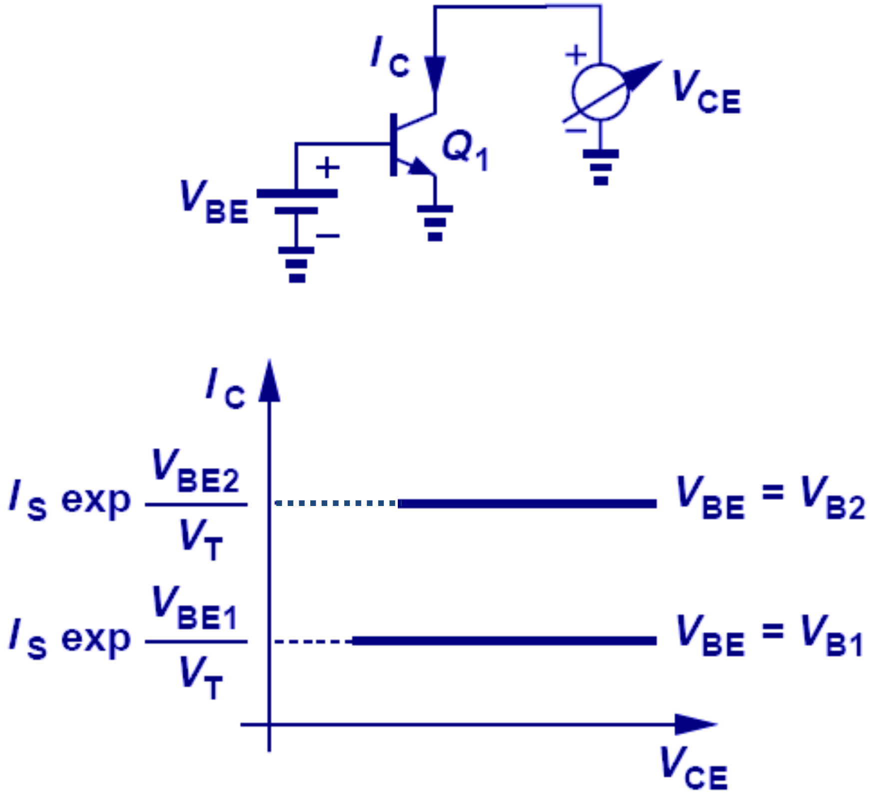
$$I_C \cong 2A_E \times \frac{qD_n}{W_B}\frac{n_i^2}{N_B} e^{\frac{V_{BE}}{V_T}}$$

Characteristics of NPN BJT in active mode

source: Razavi



(a)

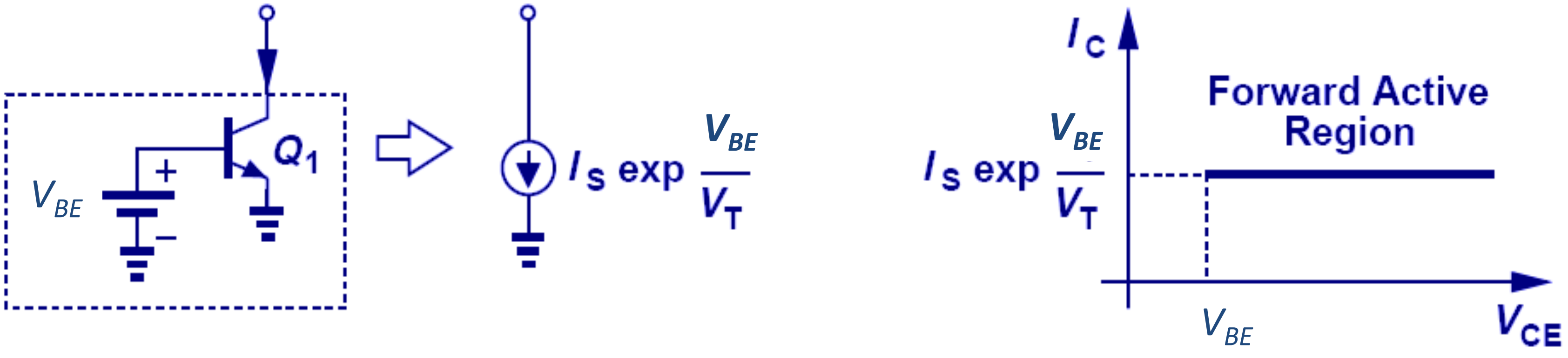


(b)

NPN BJT in active mode behaves as a constant current source

- **Ideally**, the collector current does not depend on the collector to emitter voltage. This property allows the transistor to behave as a constant current source when its base-emitter voltage is fixed.

source: Razavi



(a) (b)

NOTE:

don't forget the BC (PN$^-$) junction must be reverse biased ($V_{BC} \leq 0$):

$$V_{CB} = V_{CE} - V_{BE} \leftrightarrow V_{BC} = V_{BE} - V_{CE}$$

so V_{CE} must not go below V_{BE}

Effect of temperature on I_C vs. V_{BE} characteristics for NPN BJT in active mode

source: Sedra and Smith

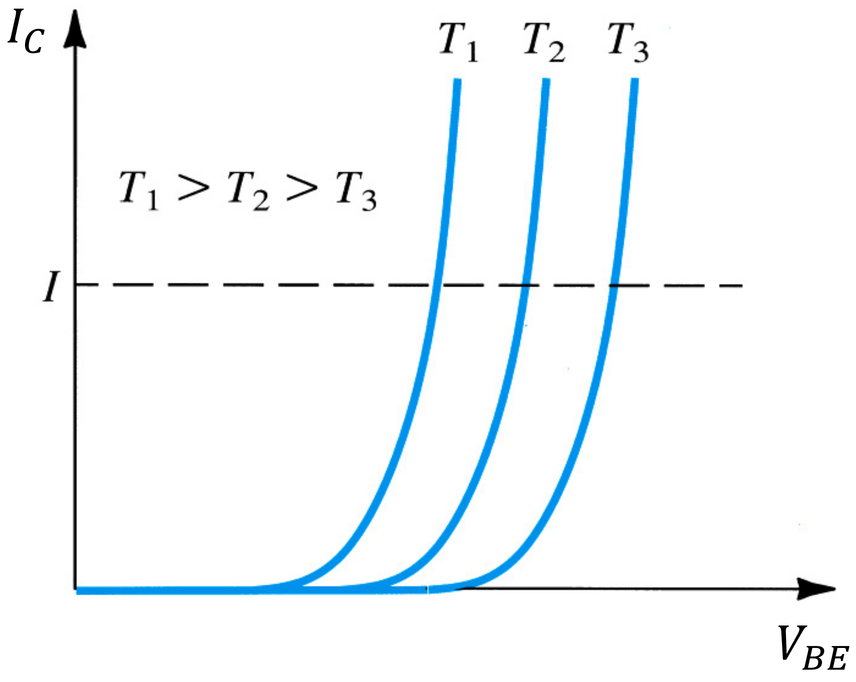
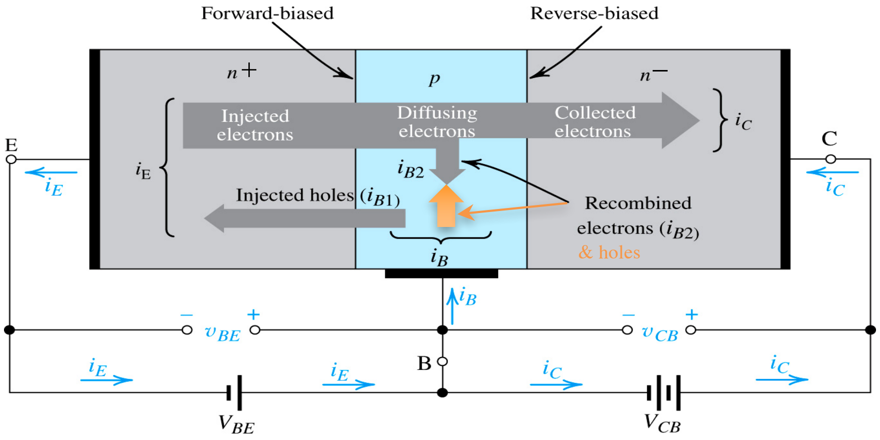


Figure - Effect of temperature on the I_C-V_{BE} characteristics. At constant I_C the V_{BE} changes by about –2mV/Celsius

Base current for NPN BJT in active mode (1)

- Primary current is due to electrons captured by the collector
- Two (undesired) base current components
  - Hole injection into emitter (→ 0 for infinite emitter doping)
  - Recombination in base (→ 0 for base width approaching 0)

source: Sedra & Smith

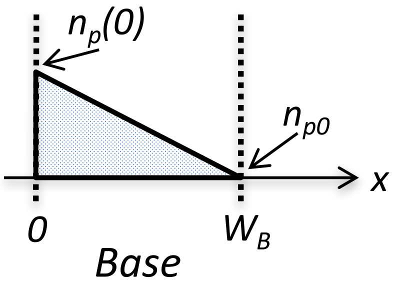


holes injected in emitter

recombination in base

In modern narrow-base transistors $I_{B1} >> I_{B2}$

$$I_B = I_{B1} + I_{B2} \approx I_{B1}$$



Charge of minority carriers (electrons) in BASE

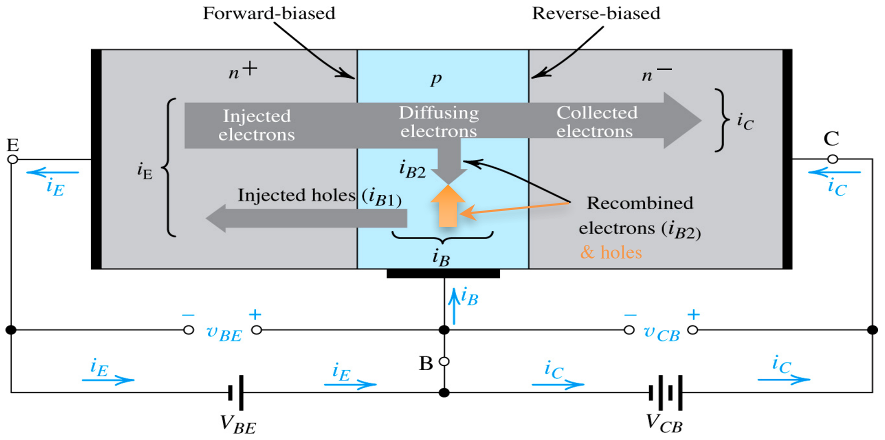
$$I_{B2} = \frac{Q_{e,BASE}}{\tau_{BASE}} \approx \frac{\frac{1}{2} n_p(0) q A_E W_B}{\tau_n} \cong \frac{1}{2} \frac{q A_E W_B}{\tau_n} \frac{n_i^2}{N_B} e^{V_{BE}/V_T}$$

life time electrons

$$n_p(0) - n_{p0} \cong n_p(0)$$

Base current for NPN BJT in active mode (2)

source: Sedra & Smith



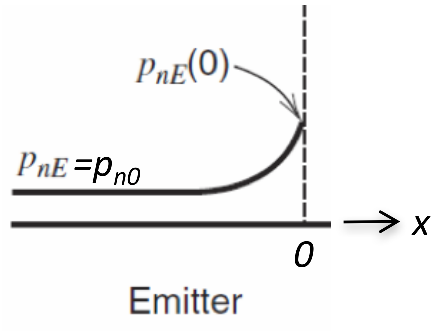
- Primary current is due to electrons captured by the collector
- Two (undesired) base current components
  - Hole injection into emitter (→ 0 for infinite emitter doping)
  - Recombination in base (→ 0 for base width approaching 0)

holes injected in emitter

recombination in base

In modern narrow-base transistors $I_{B1} >> I_{B2}$

$$I_B = I_{B1} + I_{B2} \approx I_{B1}$$



current due to holes diffusing in emitter

$$I_{B1} = -qA_E D_p \left.\frac{dp_n(x)}{dx}\right|_0 \cong -qA_E D_p \frac{d}{dx}\left(\frac{n_i^2}{N_E} e^{\frac{V_{BE}}{V_T}} e^{\frac{-x}{L_p}}\right)\Bigg|_0 =$$

$$= qA_E \frac{D_p}{L_p} \frac{n_i^2}{N_E} e^{\frac{V_{BE}}{V_T}}$$

Base current for NPN BJT in active mode (3)

holes injected in emitter

recombination in base

In modern narrow-base transistors $I_{B1} >> I_{B2}$

$$I_B = I_{B1} + I_{B2} \approx I_{B1}$$

current due to holes diffusing in emitter

recombination current in base

$$I_B = I_{B1} + I_{B2} = \left(qA_E \frac{D_p}{L_p} \frac{n_i^2}{N_E} + \frac{1}{2} \frac{qA_E W_B}{\tau_n} \frac{n_i^2}{N_B} \right) e^{\frac{V_{BE}}{V_T}}$$

$$I_C \approx A_E \frac{qD_n}{W_B} \frac{n_i^2}{N_B} e^{\frac{V_{BE}}{V_T}} = I_S \cdot e^{\frac{V_{BE}}{V_T}}$$

$$\beta_F = \frac{I_C}{I_B} = \frac{1}{\frac{W_B^2}{2\tau_n D_n} + \frac{D_p}{D_n} \frac{W_B}{L_p} \frac{N_B}{N_E}}$$

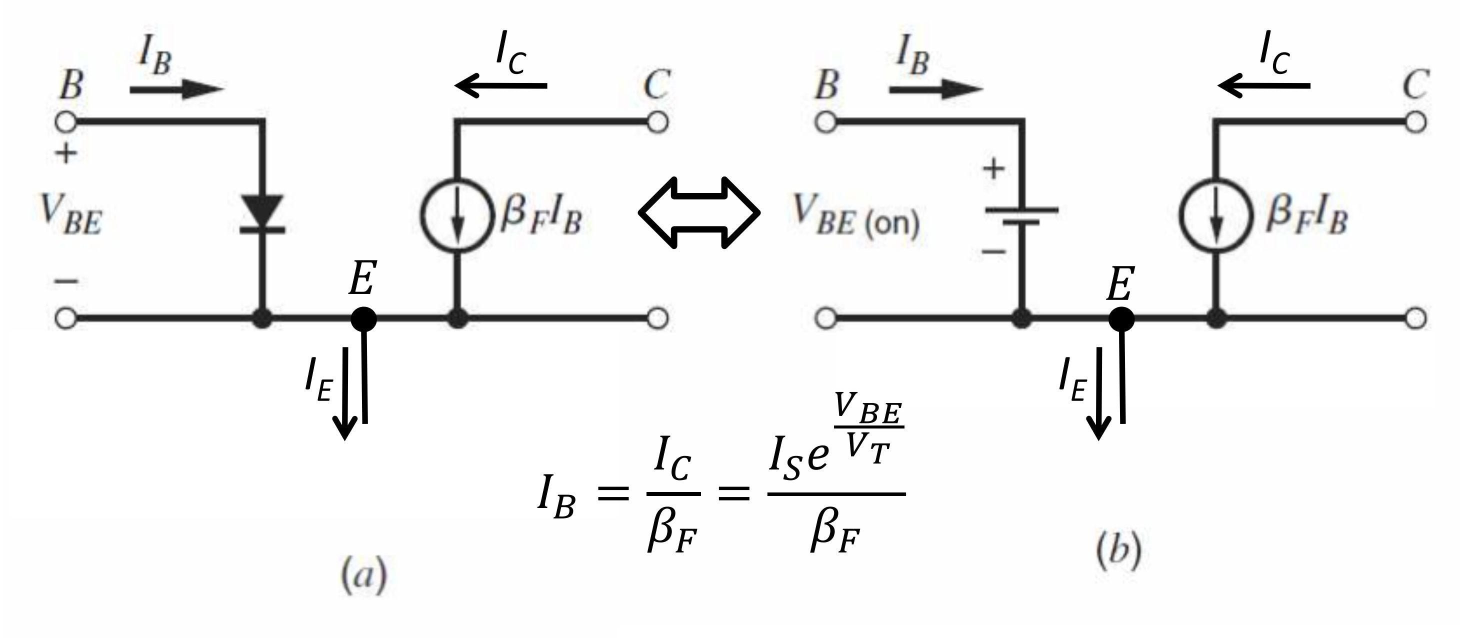
- Primary current is due to electrons captured by the collector
- Two (undesired) base current components
  - Hole injection into emitter (→ 0 for infinite emitter doping)
  - Recombination in base (→ 0 for base width approaching 0)

As expected:
β_F is maximized by minimizing W_B and maximizing N_E/N_B

Important result: I_B is a constant fraction of I_C (----> $\beta_F = I_C/I_B$)

Large signal (DC) model of NPN BJT in active region

source: Gray and Meyer



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

Figure - Simplified model; very useful for bias point calculations (assuming e.g. VBE(on) = 0.8V)

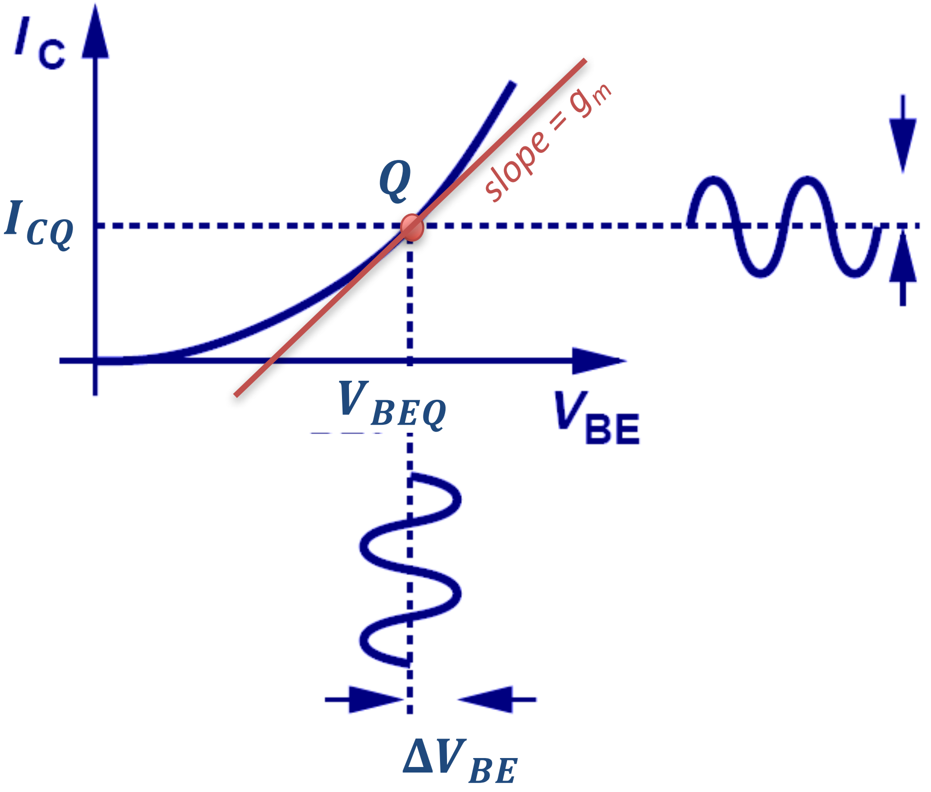
$$\beta_F \therefore \frac{I_C}{I_B}$$ (ideally infinite: I_B=0)

$$\alpha_F \therefore \frac{I_C}{I_E} = \frac{I_C}{I_B + I_C} = \frac{\beta_F}{\beta_F + 1}$$ (ideally one)

- The subscript “F” indicates that the device is assumed to operate in the forward active region (BE junction forward biased, BC reverse biased, as assumed so far)
    - More on other operating regions soon …

Small signal (AC) model of NPN BJT in active mode

source: Razavi

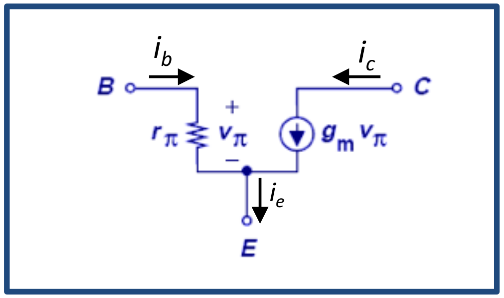


$$\Delta I_C \cong g_m \, \Delta V_{BE}$$

- The *transconductance* g_m expresses the "strength of the device (how well the controlling voltage is converted in a current)

$$g_m = \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}}\left(I_S e^{\frac{V_{BE}}{V_T}}\right) = \frac{I_C}{V_T}$$

$$g_\pi = \frac{dI_B}{dV_{BE}} = \frac{d(I_C/\beta_F)}{dV_{BE}} = \frac{g_m}{\beta_f}$$



Common notations:

$\Delta V_{BE} \equiv v_{be} \equiv v_\pi$

$\Delta I_C \equiv i_c$

$\Delta I_B \equiv i_b$

$\Delta V_{CE} \equiv v_{ce}$

$r_\pi = 1/g_\pi \equiv h_{ie}$

$\beta_f \equiv h_{fe} \cong \beta_F \equiv h_{FE}$

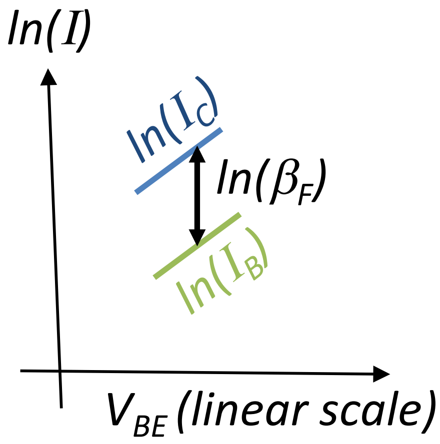
Flavors of β (with BJT in forward active mode)

$$\frac{I_C}{I_B} \equiv \beta_F \equiv h_{FE} \leftarrow DC \ \ beta$$

$$\frac{\Delta I_C}{\Delta I_B} \equiv \beta_f \equiv h_{fe} \leftarrow AC \ \ beta$$

To first order we assume $\beta_{DC} \approx \beta_{AC}$

In other words we assume β_F is constant
(we'll see later that is not always accurate)

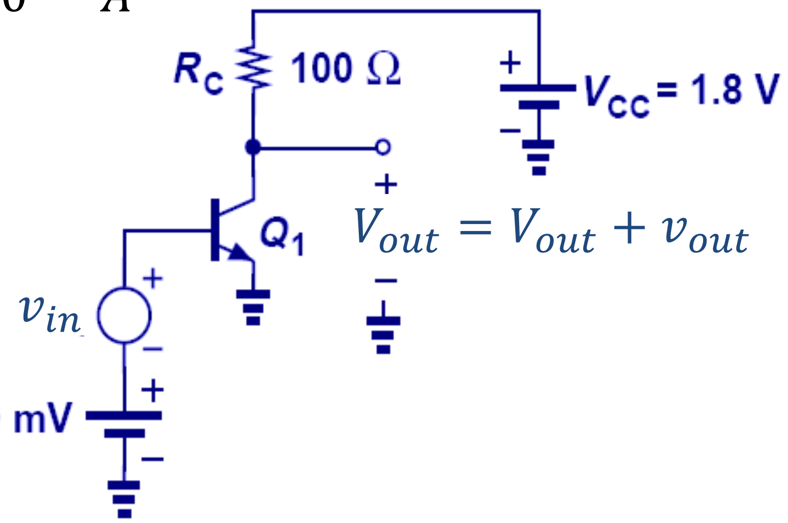


Let’s finally build an amplifier !

source: Razavi

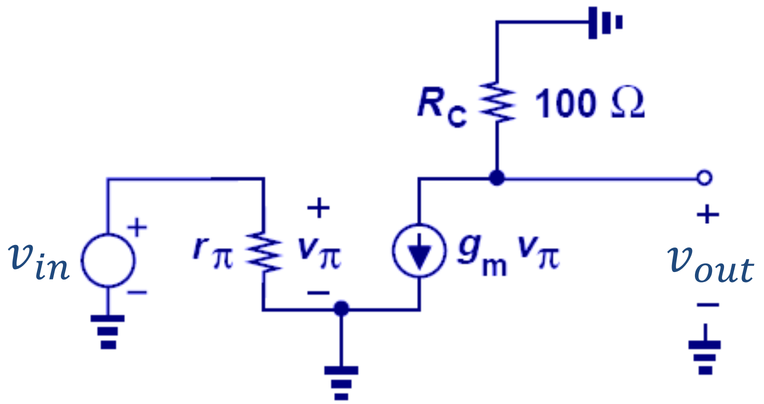
$I_S = 3\times10^{-16}A$

$\beta = 100$



$V_{out} = V_{out} + v_{out}$

$V_{BE} =$ 800 mV



$$I_C = I_S e^{\frac{V_{BE}}{V_T}} \cong 6.92\ mA$$

$$g_m = \frac{I_C}{V_T} \cong 266\ \ mS$$

$$r_\pi = \frac{\beta}{g_m} \cong 376\ \Omega$$

$$A_V = \frac{v_{out}}{v_{in}} = -g_m R_c \cong -26.6$$

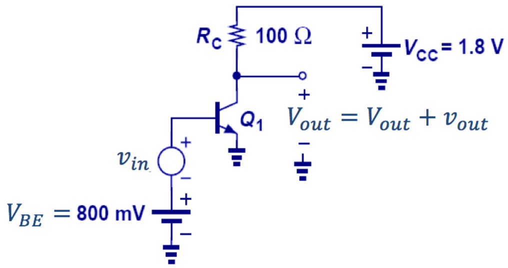
It looks like by increasing R_C
we can get whatever gain we want.
This sounds too good to be true !
There must be limitations we are
missing !

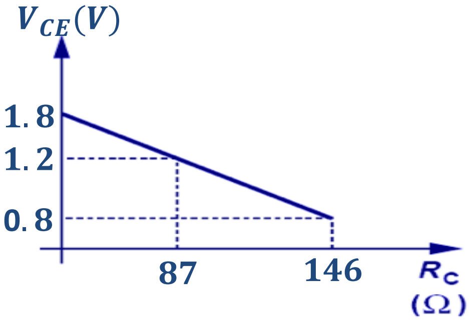
Practical Limitations

- First of all for the device to behave as a voltage controlled current source we must operate in forward active mode (BE must be forward biased and BC reverse biased)
  - As R_C increases, V_{CE} drops and eventually forward biases the collector-base junction. This will force the transistor out of forward active region.
  - Therefore, there exists a maximum tolerable collector resistance

$$V_{CE} = V_{CC} - R_C I_C \geq V_{BE}$$

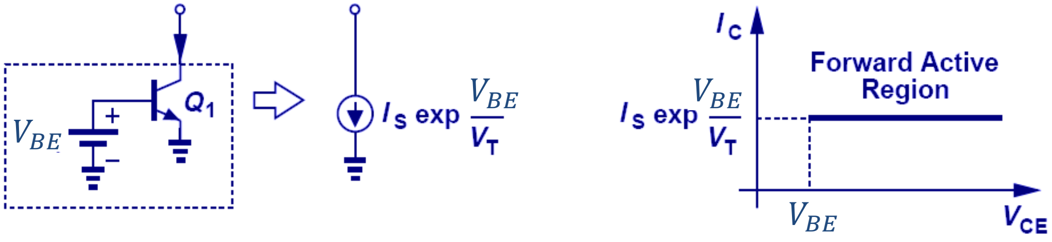
$$R_C \leq \frac{V_{CC} - V_{BE}}{I_C} \therefore R_{C,MAX}$$





- Second, I am very skeptical we can build anything that behave exactly as an **ideal** current source

source: Razavi

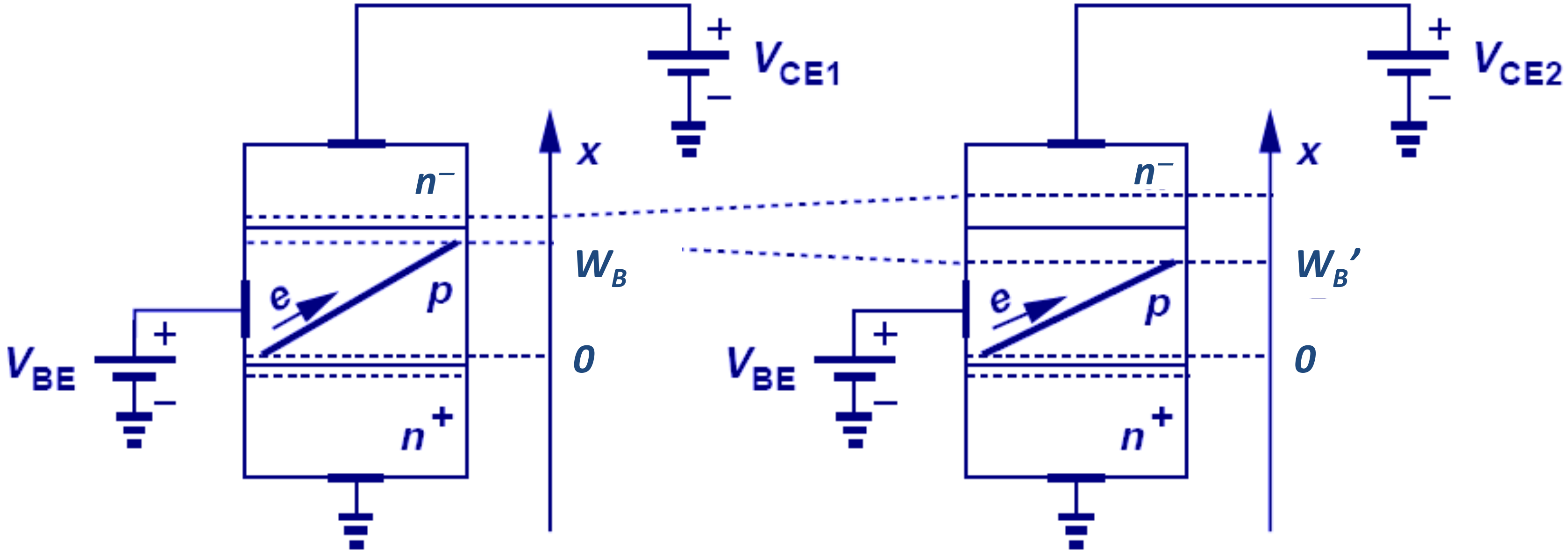


(a) (b)

$$I_C \approx A_E \frac{qD_n}{W'_B}\frac{n_i^2}{N_B} e^{\frac{V_{BE}}{V_T}} = I_S \cdot e^{\frac{V_{BE}}{V_T}} \cdot \left(1+\frac{V_{CE}}{V_A}\right)$$

Early Effect (1)

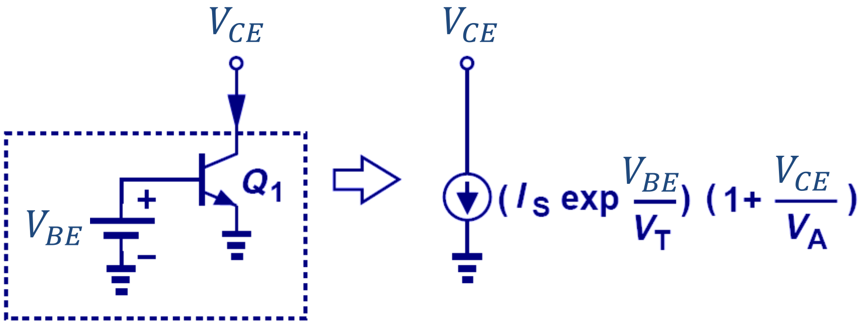
source: Razavi

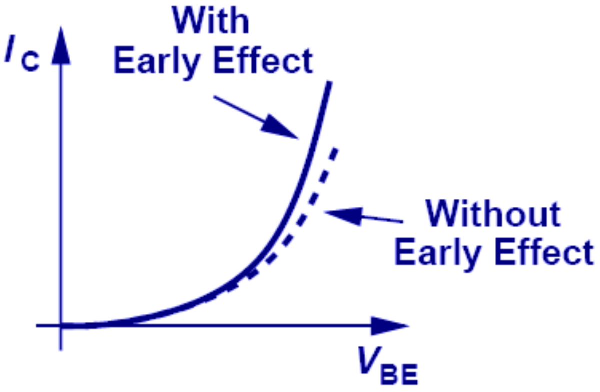


- The claim that collector current does not depend on V_{CE} is not accurate
- As V_{CE} increases, the depletion region between base and collector increases. Therefore, the effective base width decreases, which leads to an increase in the collector current.

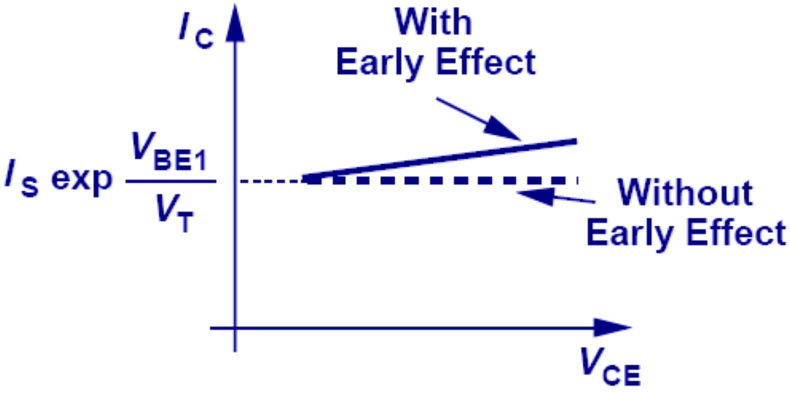
Early Effect (2)

source: Razavi





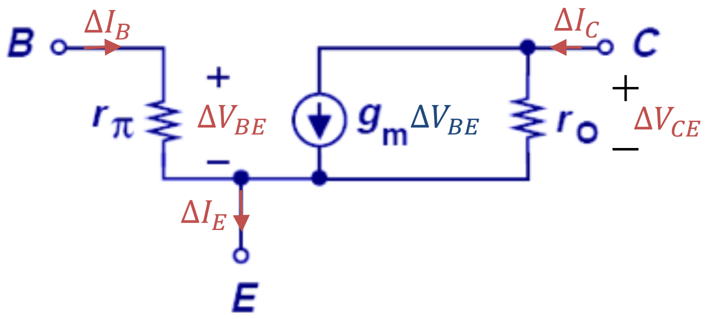
(a)



(b)

Small-signal model including Early effect

source: Razavi



$$g_o = \frac{1}{r_o} = \frac{dI_C}{dV_{CE}} = \frac{d}{dV_{CE}}\left(I_S \cdot e^{\frac{V_{BE}}{V_T}} \cdot \left(1+\frac{V_{CE}}{V_A}\right)\right) = I_S \cdot e^{\frac{V_{BE}}{V_T}} \cdot \frac{1}{V_A} = \frac{I_C}{\left(1+\frac{V_{CE}}{V_A}\right)} \cdot \frac{1}{V_A} \overset{\overset{V_{CE} \ll V_A}{\downarrow}}{\cong} \frac{I_C}{V_A}$$

$$g_m = \frac{dI_C}{dV_{BE}} \cong \frac{I_C}{V_T}$$

$$g_\pi = \frac{dI_B}{dV_{BE}} = \frac{d(I_C/\beta_F)}{dV_{BE}} \cong \frac{I_C/\beta_f}{V_T} = \frac{g_m}{\beta_f}$$

$$r_\pi = 1/g_\pi \equiv h_{ie}$$

$$g_o = 1/r_o \equiv h_{oe}$$

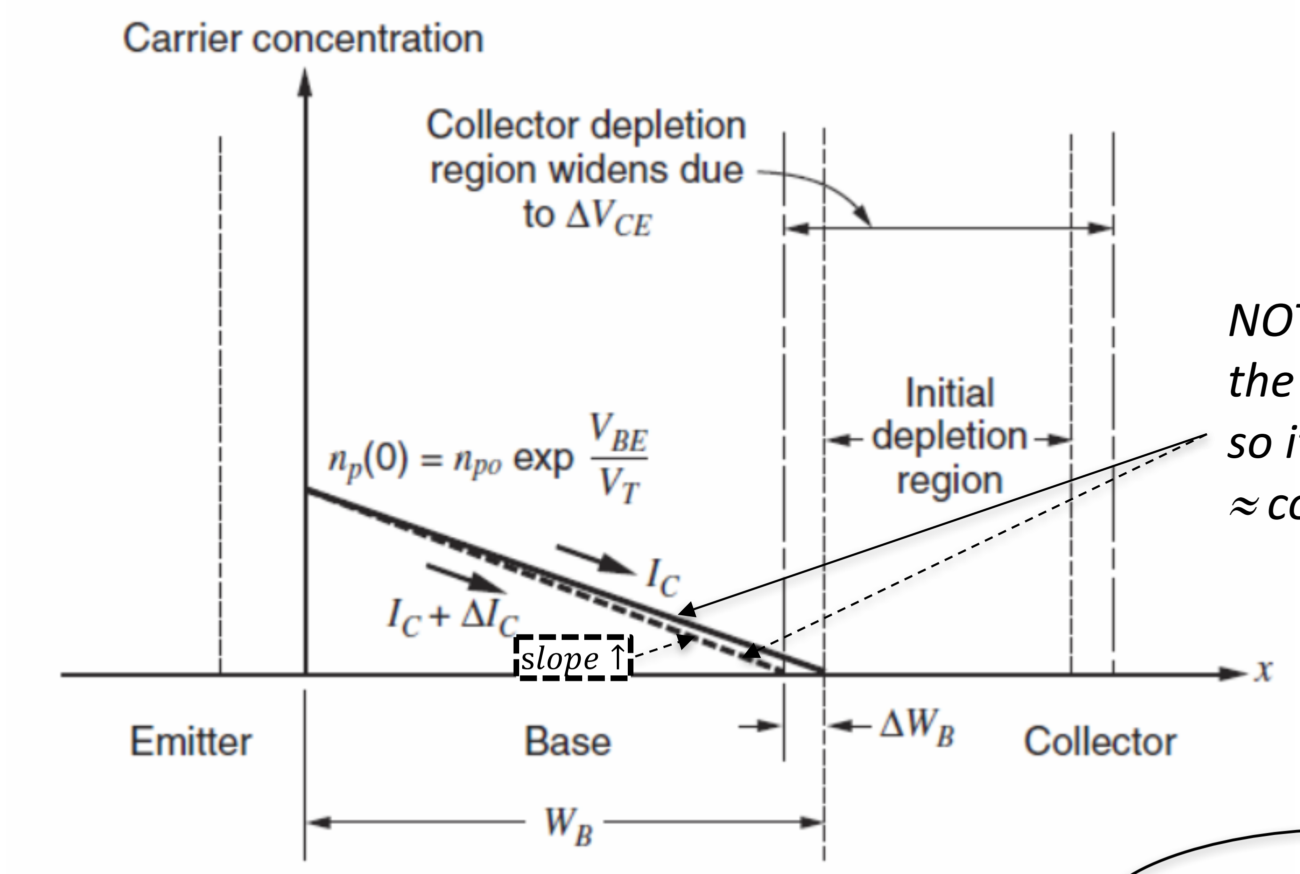
$$\beta_f \equiv h_{fe} \cong \beta_F \equiv h_{FE}$$

$\textit{intrinsic gain} \therefore g_m r_0 \approx \frac{V_A}{V_T} \longleftarrow$ *max gain the device can provide*

Base modulation and Early voltage

source: Gray & Meyer

I_C = diffusion current of electrons in base ∝ gradient of electrons in base = $\Delta n_p(x)/\Delta x$



NOTE:
the slope changes very little,
so it is reasonable to assume it
≈ constant)

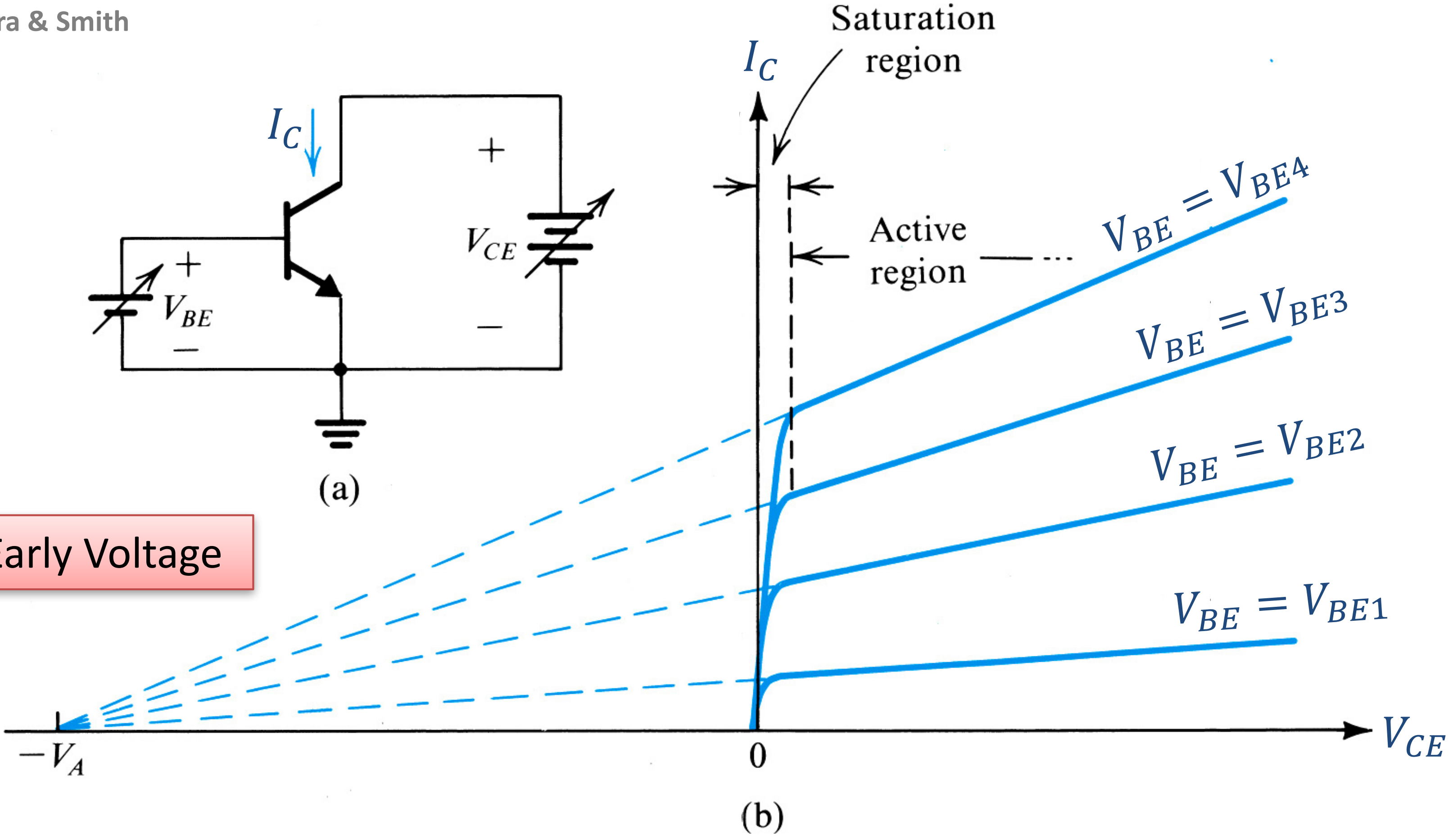
since ΔW_B is negative
we need a minus
sign in the equation

$$\Delta V_{CE} \uparrow \Longrightarrow \Delta I_C \uparrow \Longrightarrow \Delta W_B \downarrow$$

$$V_A \therefore \frac{I_C}{\frac{\partial I_C}{\partial V_{CE}}} = -\frac{W_B}{\frac{dW_B}{dV_{CE}}} \approx const.$$

Dependence of I_C on V_{CE}

source: Sedra & Smith



V_A = Early Voltage

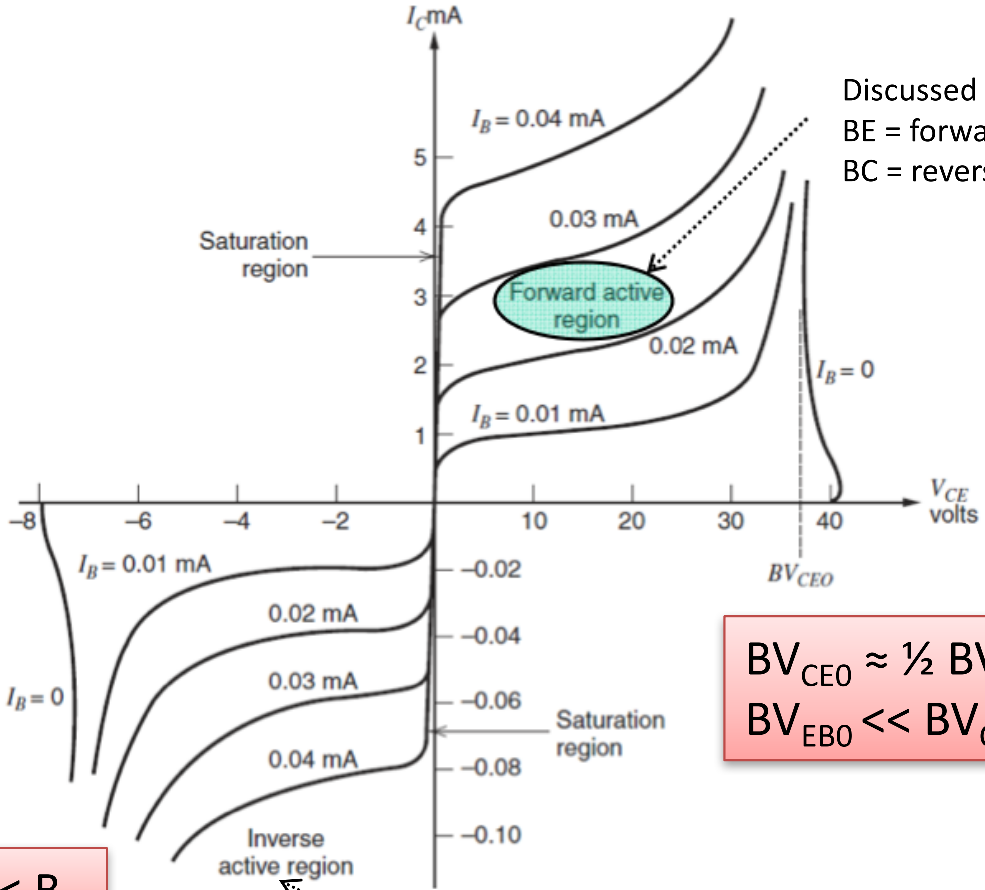
In Forward active region: $I_C \approx A_E \frac{q D_n n_i^2}{W'_B N_B} e^{\frac{V_{BE}}{V_T}} = I_S \cdot e^{\frac{V_{BE}}{V_T}} \cdot \left(1 + \frac{V_{CE}}{V_A}\right)$

Model Extensions

- Complete picture of BJT operating regions
- Dependence of β_F on operating conditions

NPN BJT operating regions

source: Gray & Meyer



Discussed so far:
BE = forward biased
BC = reverse biased

$BV_{CE0} \approx ½ \, BV_{CB0}$
$BV_{EB0} << BV_{CB0}$

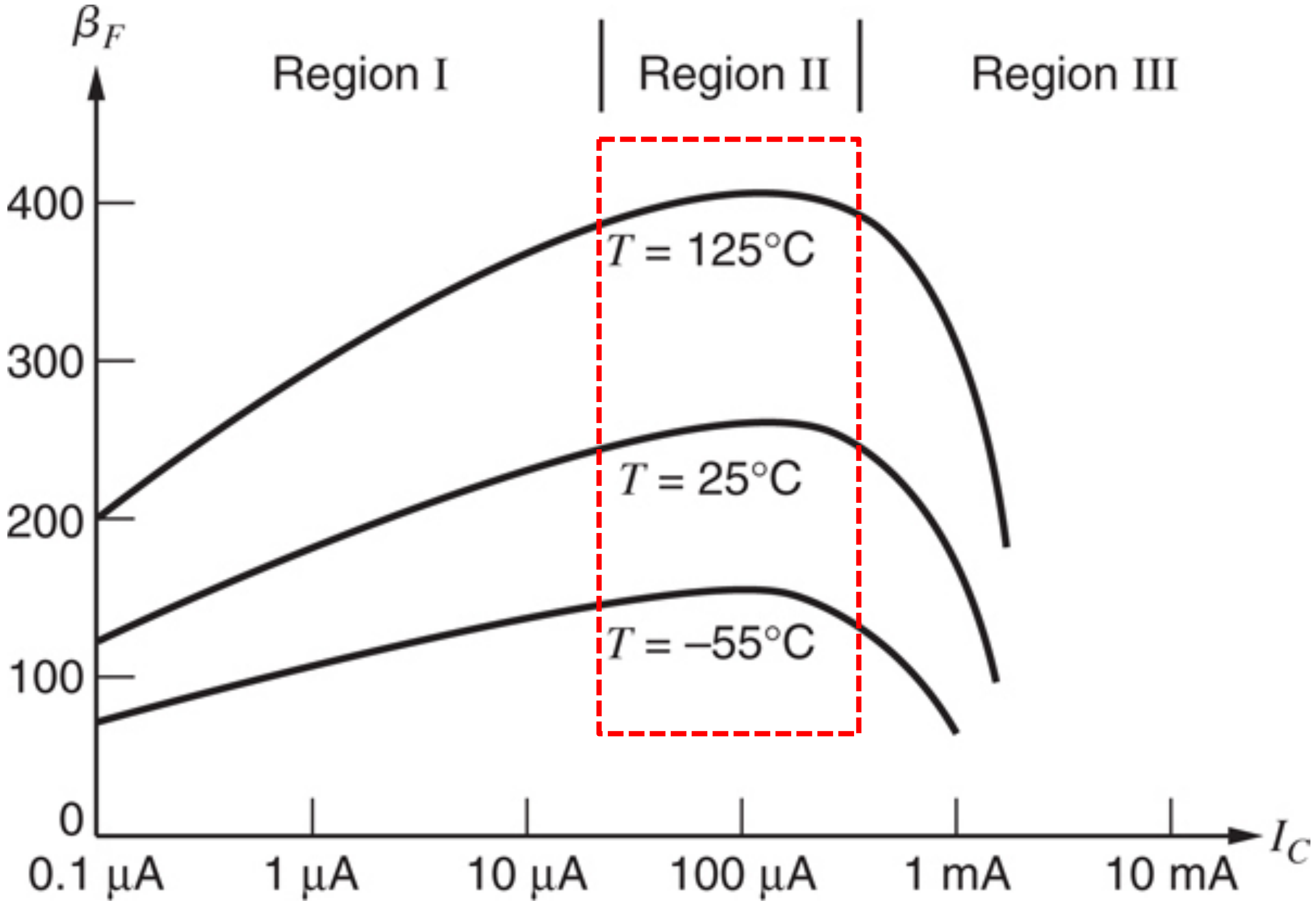
$\beta_R << B_F$

BE = reverse biased, BC = forward biased
the collector injects electrons in base and
the emitter collect them

Dependence of β_F on operating conditions (and temperature)

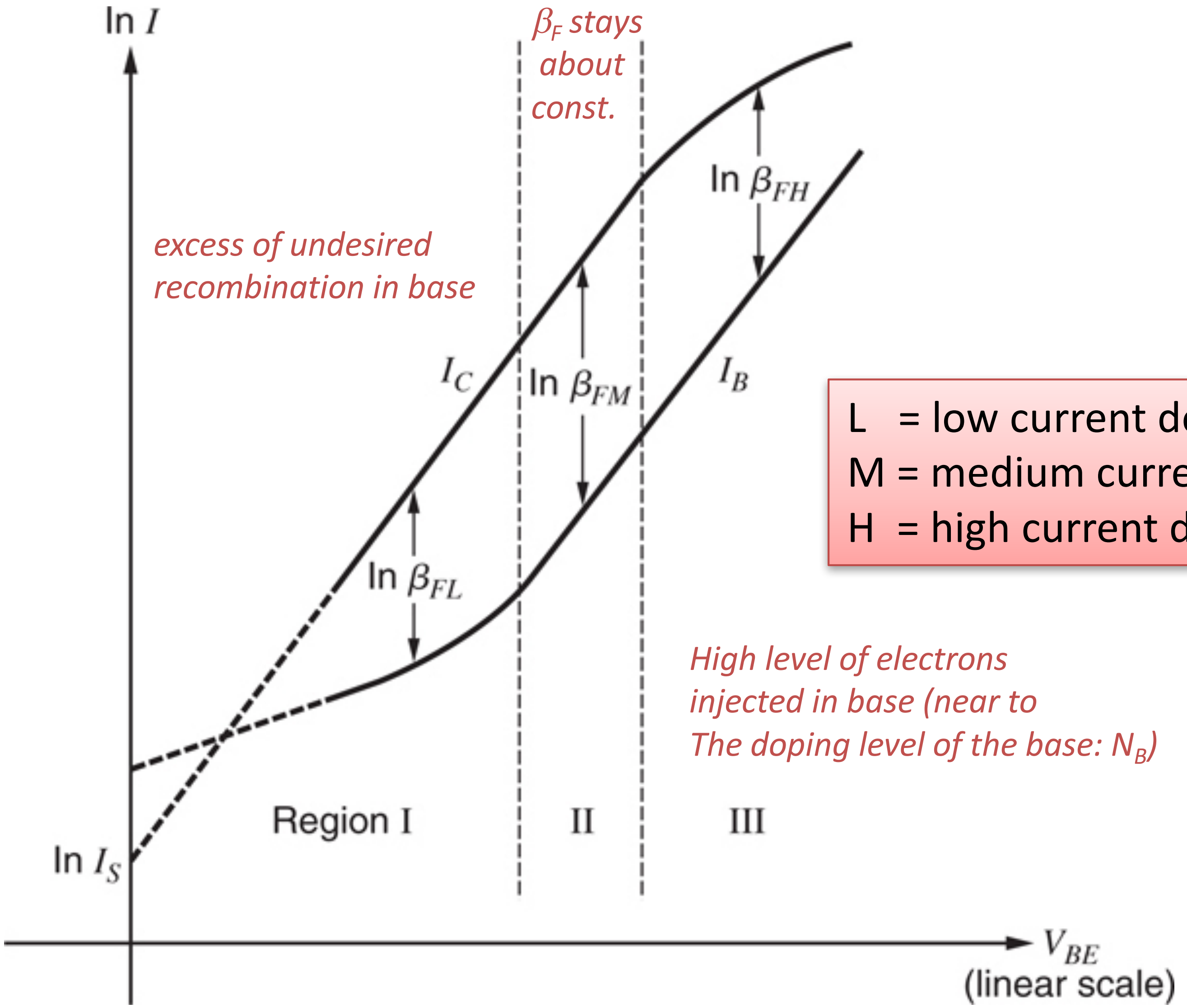
source: Gray & Meyer

A typical temperature coefficient for β_F is about +7000 ppm/℃



Gummel Plot (I_C and I_B vs. V_{BE})

source: Gray & Meyer



β_F stays about const.

excess of undesired recombination in base

High level of electrons injected in base (near to The doping level of the base: N_B)

L = low current density
M = medium current density
H = high current density

β_F fall-off

source: B. Murmann

- *Region II* (medium current density)
  β_F is about constant (as desired)

- *Region I* (low current density)
  there is an excess of undesired recombination in base

- *Region III* (high current density)
  the level of electrons injected in base is extremely high near the level of doping of the base (N_B). It can be shown that for this case:

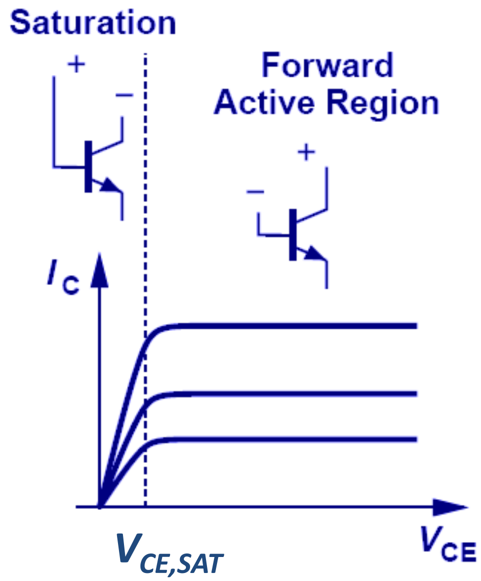
$$I_C \approx I_S e^{\frac{1}{2}\times\frac{V_{BE}}{V_T}}$$

NPN BJT in saturation mode

source: Razavi

saturation mode:

$$\begin{cases} V_{BE} \geq V_{BE,ON} \\ V_{CE} \leq V_{CE,SAT} \end{cases}$$



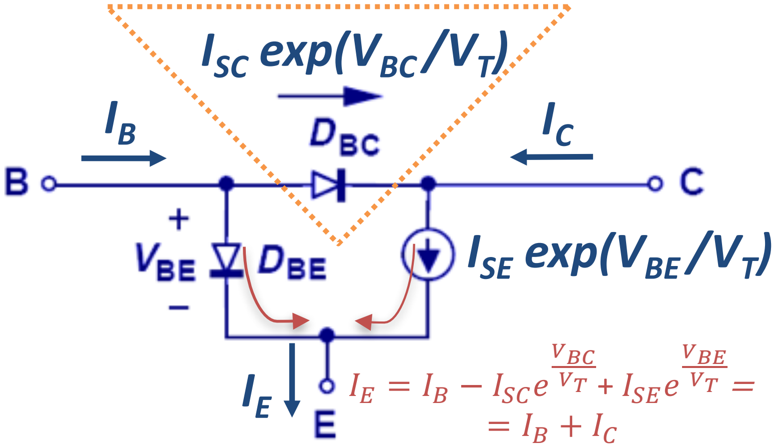
The term "*saturation*" is used because increasing the base current in this region of operation leads to little change in collector current (there is a significant drop in β compared to active mode)

- In active mode I_C is almost independent of V_{CE} (and V_{CB} ↔ $V_{CB} = V_{CE} - V_{BE}(on) \cong V_{CE} - 0.8$)
- In saturation not only the BE junction is forward biased, but also the BC junction is forward biased
  - As a result, I_C must also strongly depends on V_{CB} (and V_{CE} ↔ $V_{BC} = V_{BE}(on) - V_{CE} = 0.8 - V_{CE}$

NPN BJT in Saturation mode

source: Razavi

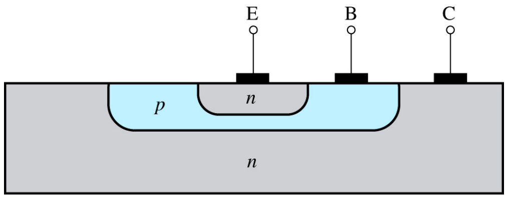
Add the BC forward diode to the previous model



$$I_E = I_B - I_{SC}e^{\frac{V_{BC}}{V_T}} + I_{SE}e^{\frac{V_{BE}}{V_T}} =$$
$$= I_B + I_C$$

I_{SC} = saturation current of the BC (PN^-) diode

$I_{SE} \equiv I_S$ = saturation current of the BE (PN^+) diode



$A_E < A_C \leftrightarrow I_{SC} > I_{SE}$

The BC junction area is larger than the BE junction area therefore the ON voltage of the BC diode is smaller than the ON voltage of the BE diode (typically $V_{BC,on} < V_{BE,on}$ by 0.4 V)

In saturation the *collector current is reduced* by $I_{SC}\cdot\exp(V_{BC}/V_T)$:

$$I_C = I_{SE}e^{\frac{V_{BE}}{V_T}} - I_{SC}e^{\frac{V_{BC}}{V_T}}$$

while the *base current is increased* by $I_{SC}\cdot\exp(V_{BC}/V_T)$:

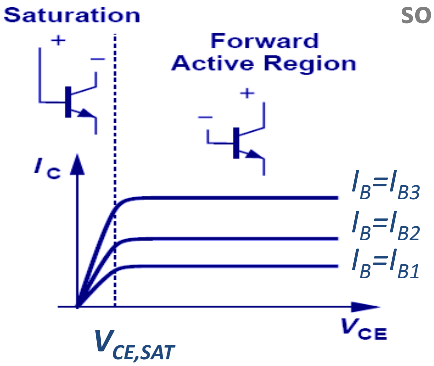
$$I_B = \frac{I_{SE}}{\beta_{active}}e^{\frac{V_{BE}}{V_T}} + I_{SC}e^{\frac{V_{BC}}{V_T}}$$

NPN BJT in Saturation mode

- Since in saturation I_C decreases and I_B increases the beta of the transistor decreases significantly:

$$\beta_{sat} \equiv \beta_{forced} = \left.\frac{I_C}{I_B}\right|_{sat} \le \beta \equiv \beta_{active}$$

- By adjusting V_{BC} (i.e. V_{CE}) the beta of a transistor in saturation (β_{forced}) can be set to any value lower than β_{active}



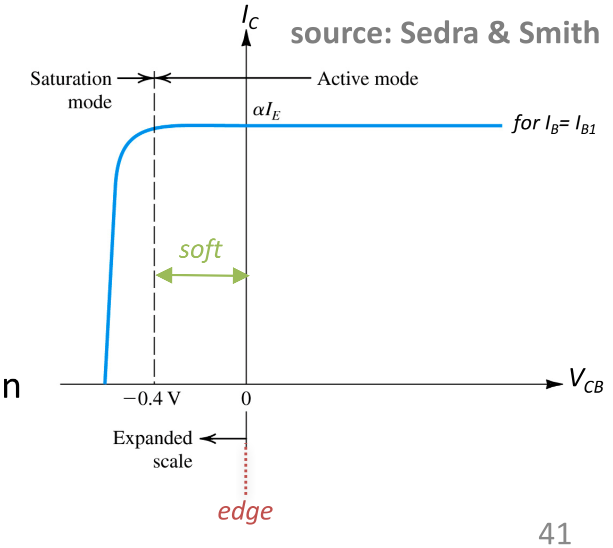
source: Razavi

"Soft" Saturation

source: Razavi

- For $V_{CE}=V_{BE}$, the BC junction sustain a zero voltage difference ($V_{BC}=V_{BE}-V_{CE}=0$), and its depletion region still absorbs most of the electrons injected by the emitter into the base
  - We consider this condition as the edge between active mode and saturation mode

- What happens if $V_{CE} < V_{BE}$, i.e. $V_{BC} > 0$?
  Not much until $V_{BC} \geq V_{BC,ON}$. Up to $V_{BC,ON}$ the current carried by the BC forward biased diode is still extremely small, so assume the behavior of the device still acceptable:
  - As a rule of thumb we permit "soft" saturation:
    $V_{BC} < 400$ mV $\leftrightarrow$ $V_{CB} > -400$ mV
    ($V_{CB}= V_{CE} - V_{BE} > -400$ mV $\leftrightarrow$
    $\leftrightarrow$ $V_{CE} > V_{BE} - 400$ mV $\leftrightarrow$ $V_{CE} > 400$ mV)


source: Sedra & Smith

__Typically assume:__

$V_{CE}(edge) = 800mV$

$V_{CE,SAT}(soft) = V_{CB,ON} + V_{BE,ON} \cong 400$ mV

$V_{CE,SAT}(deep) \equiv V_{CE,SAT} \cong 200$ mV

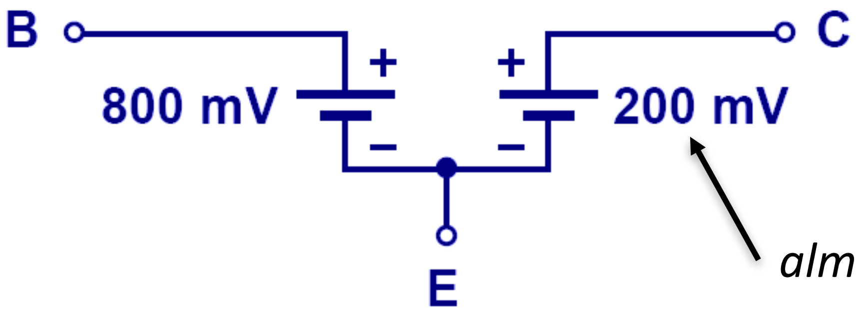
edge between active region saturation region:
$V_{CB} = 0 \leftrightarrow V_{CE} = V_{BE}$

“Deep” Saturation

source: Razavi

- In deep saturation the BC diode carries a significant amount of current, so the transistor bear no longer any resemblance to a controlled current source.

- The collector-emitter voltage approaches a constant value called $V_{CE,\ SAT}$ and the transistor can be modeled as follows:



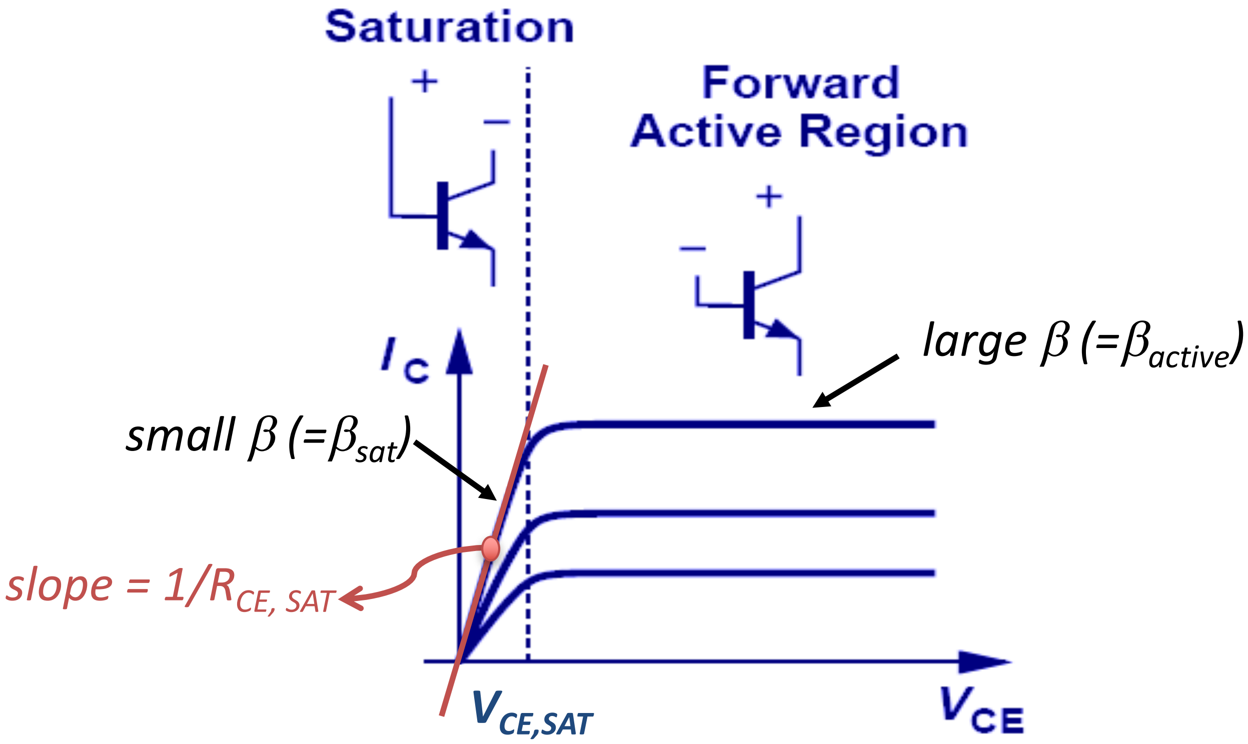
almost a short

NPN BJT in Saturation mode

source: Sedra & Smith

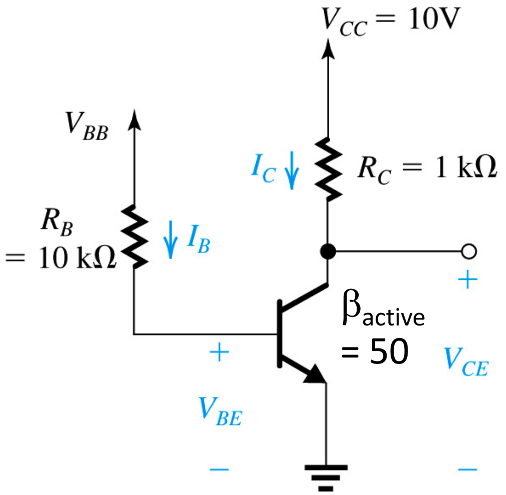
- In saturation the I_C vs. V_{CE} curves are rather steep indicating that the saturated BJT exhibits a low resistance ($R_{CE,SAT}$ ranges from a few ohms to a few tens of ohms). This result was to be expected from the fact that between C and E we have two forward biased diodes

source: Razavi



Example

source: Sedra & Smith



Find V_{BB} to set the transistor in:

(a) Active mode with $V_{CE} = 5V$

(b) Edge of saturation

(c) Deep in saturation with $\beta_{forced} = 10$

a)

$$V_{CE}=V_{CC}-R_CI_C \rightarrow I_C = \frac{V_{CC}-V_{CE}}{R_C} = 5mA \rightarrow I_B = \frac{I_C}{\beta_{active}} = 100\mu A \rightarrow V_{BB}= V_{BE}+R_BI_B = 0.8+10k\times100\mu = 1.8V$$

b)

$$I_C = \frac{V_{CC}-V_{CE}\,(edge)}{R_C} = \frac{10-0.8}{1000} = 9.2mA \rightarrow I_B = \frac{I_C}{\beta_{active}} = 184\mu A \rightarrow V_{BB}= V_{BE}+R_BI_B = 0.8+10K\times184\mu \approx 2.64V$$

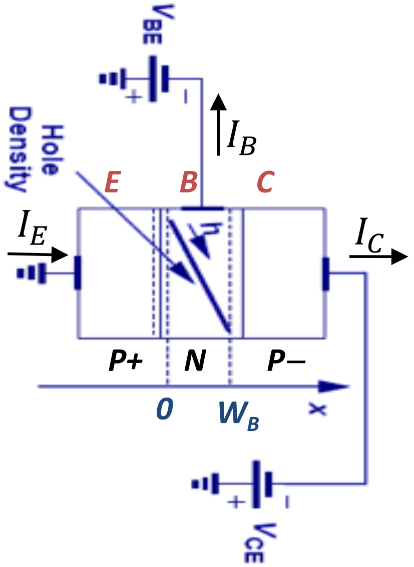
c)

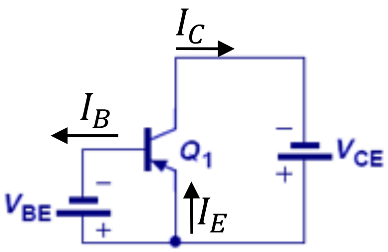
$$I_C = \frac{V_{CC}-V_{CE}\,(deep)}{R_C} = \frac{10-0.2}{1000} = 9.8mA \rightarrow I_B = \frac{I_C}{\beta_{forced}} = 980\mu A \rightarrow V_{BB}= V_{BE}+R_BI_B = 0.8+10K\times980\mu \approx 10.6V$$

PNP transistor

- All the principles that applied to NPN also apply to PNP, with the exception that emitter is at a higher potential than base and base at a higher potential than collector.

source: Razavi



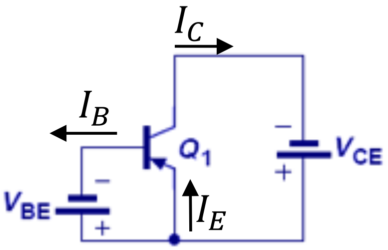


NOTE:
Use the currents directions shown in figure and VEB and VEC to get all positive values

PNP transistor

source: Razavi

- Equations for PNP in active mode



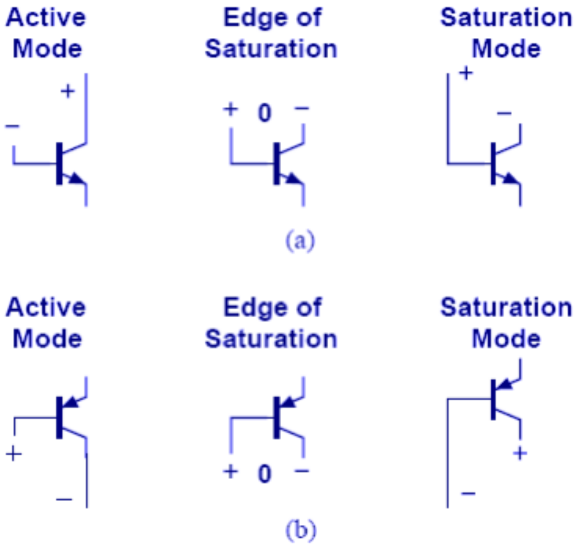
$$I_C = I_S \exp\frac{V_{EB}}{V_T}$$

$$I_B = \frac{I_S}{\beta}\exp\frac{V_{EB}}{V_T}$$

$$I_E = \frac{\beta+1}{\beta} I_S \exp\frac{V_{EB}}{V_T}$$

$$I_C = \left(I_S \exp\frac{V_{EB}}{V_T}\right)\left(1+\frac{V_{EC}}{V_A}\right)$$

- A comparison between NPN (a) and PNP (b)

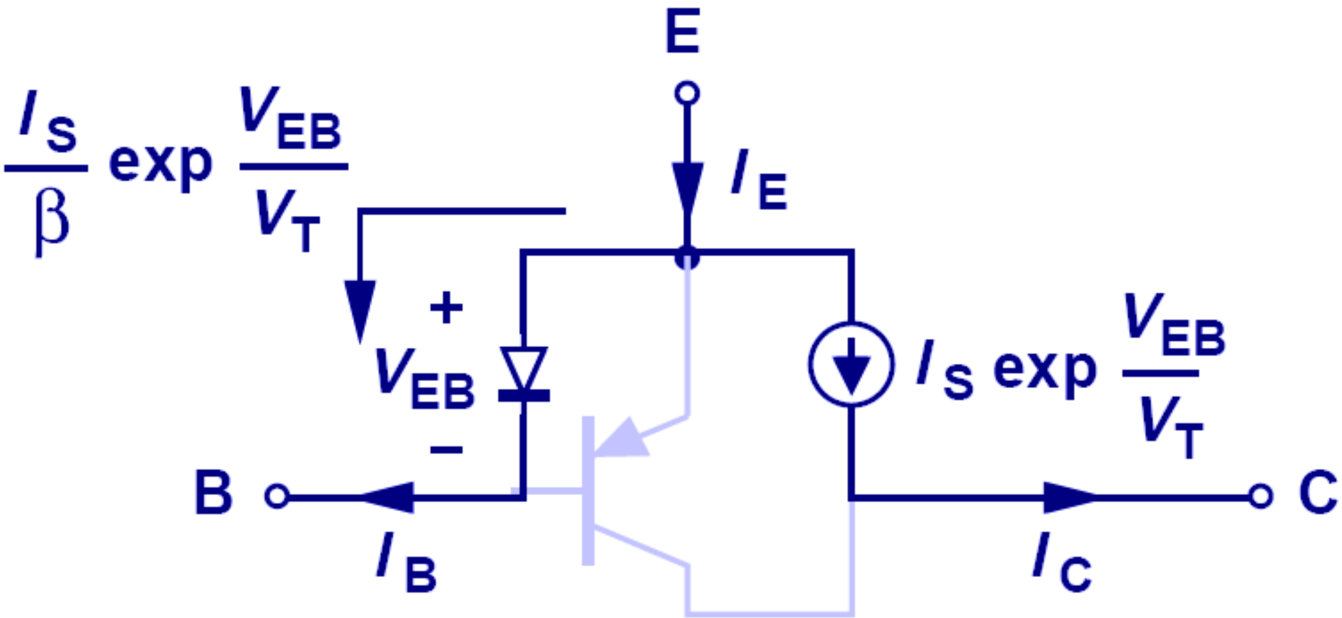


(a)

(b)

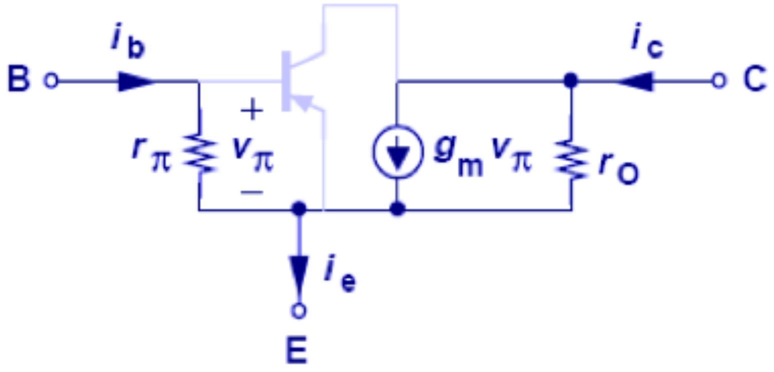
PNP BJT in active mode: large signal (DC) model

source: Razavi



PNP BJT in active mode: small signal (AC) model

source: Razavi



- The small signal model for the PNP transistor is exactly IDENTICAL to that of the NPN. This is not a mistake !

PNP BJT is deep saturation

source: Gray & Meyer

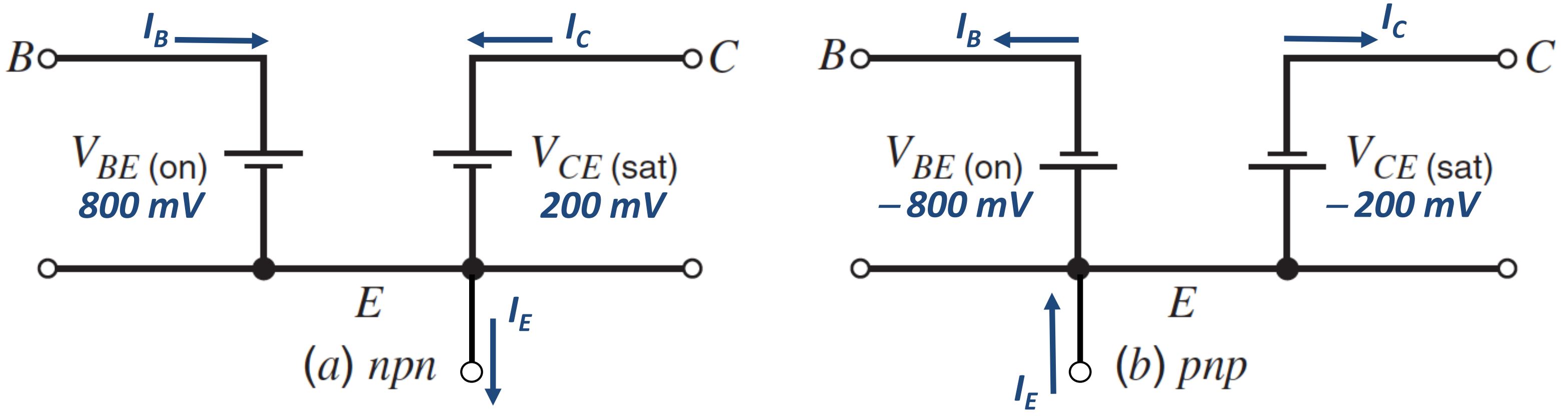


Figure 1.13 Large-signal models for bipolar transistors in the saturation region.

Summary of operating regions

NPN Bipolar Transistor		
Region	V_{BE}	V_{BC}
Cutoff	$< V_{BE(on)}$	$< V_{BC(on)}$
Forward Active	$\geq V_{BE(on)}$	$< V_{BC(on)}$
Reverse Active	$< V_{BE\ (on)}$	$\geq V_{BC(on)}$
Saturation	$\geq V_{BE(on)}$	$\geq V_{BC(on)}$

PNP Bipolar Transistor		
Region	V_{EB}	V_{CB}
Cutoff	$< V_{EB(on)}$	$< V_{CB(on)}$
Forward Active	$\geq V_{EB(on)}$	$< V_{CB(on)}$
Reverse Active	$< V_{EB\ (on)}$	$\geq V_{CB(on)}$
Saturation	$\geq V_{EB(on)}$	$\geq V_{CB(on)}$