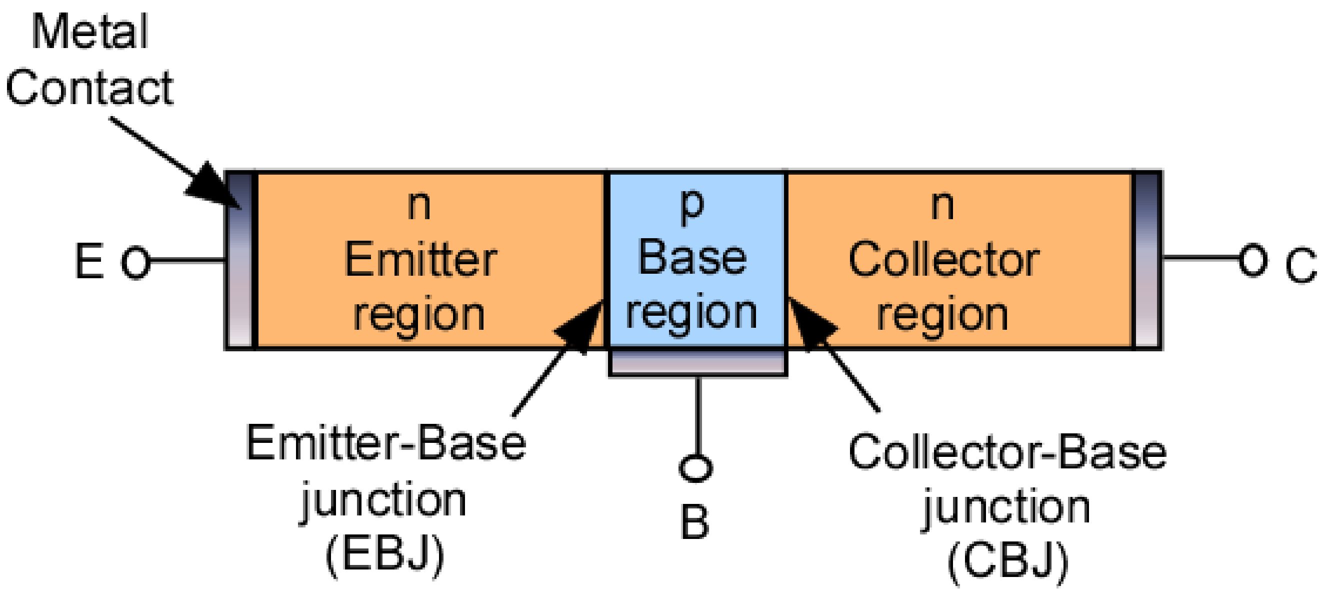
ECE 442
Solid-State Devices & Circuits

14. Bipolar Transistors

Jose E. Schutt-Aine
Electrical & Computer Engineering
University of Illinois
jschutt@emlab.uiuc.edu

Bipolar Junction Transistor

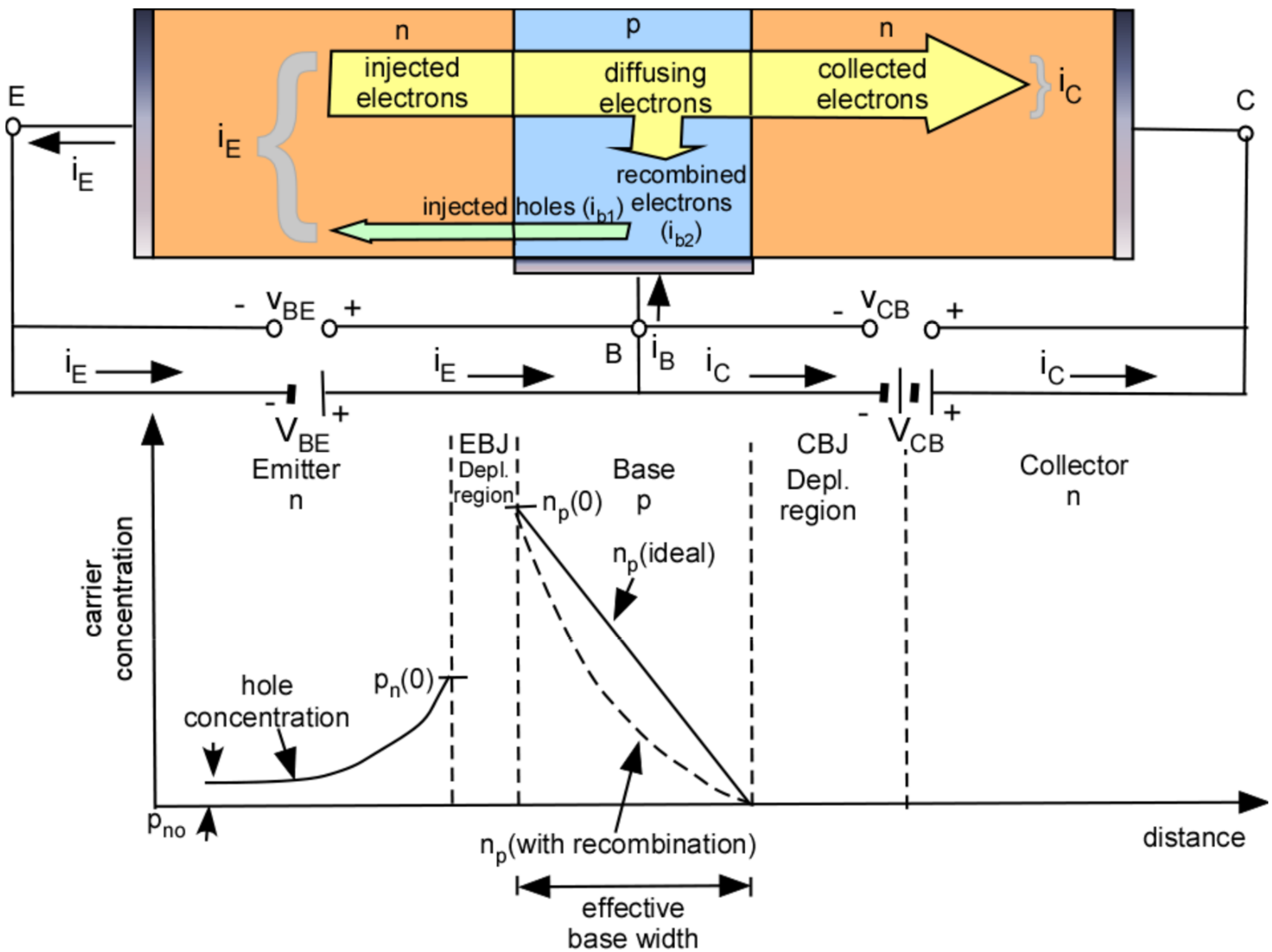
- **Bipolar Junction Transistor (BJT)**
  - First Introduced in 1948 (Bell labs)
  - Consists of 2 pn junctions
  - Has three terminals: emitter, base, collector



BJT – Modes of Operation

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Forw. Active	Forward	Reverse
Rev. Active	Reverse	Forward
Saturation	Forward	Forward

BJT in Forward Active Mode (NPN)



Longitudinal Current Flow

Electrons are minority carriers in the base (p-type)

$$n_p(0) = n_{po} e^{V_{BE}/V_T}$$

Minority electrons will diffuse in the p-type base

$$I_n = A_E q D_n \frac{dn_p(x)}{dx} = A_E q D_n \left(-\frac{n_p(0)}{W} \right)$$

A_E: cross section area of BEJ
W: Effective width of base
N_A: doping concentration base
D_n: electron diffusivity
q: electron charge

Collector current: $i_C = I_n = I_S e^{v_{BE}/V_T}$

$$I_S = \frac{A_E q D_n n_i^2}{N_A W}$$

i_C is independent of v_{CB}

Base Current

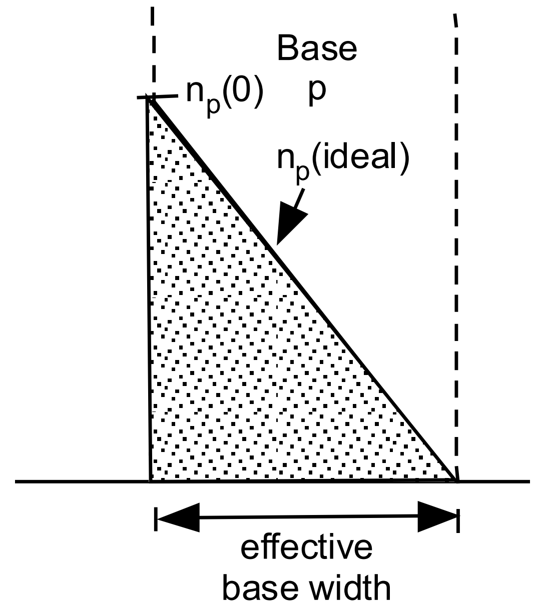
- **Base current: Two components**
  - Hole injection into emitter ➔ i_{B1}
  - Electron recombination in base ➔ i_{B2}

$$i_{B1} = \frac{A_E q D_p n_i^2 e^{v_{BE}/V_T}}{N_D L_p}$$

D_p: hole diffusivity in emitter
L_p: hole diffusion length in emitter
N_D: doping concentration of emitter

$$i_{B2} = \frac{Q_n}{\tau_b}$$

Q_n: minority carrier charge in base
τ_b: minority carrier lifetime



From area under triangle

$$Q_n = A_E q \times \frac{1}{2} n_p(0) W = \frac{A_E q W n_i^2}{2N_A} e^{v_{BE}/V_T}$$

BJT Operation: Longitudinal and Base Currents

- Base current has two functions
  - Feed recombination that occur in the base
  - Support reverse injection
- Base current is small because
  - Base is thin
  - Has large lifetime
  - Emitter is much more heavily doped than base
- Longitudinal current
  - Depends (exponentially) on emitter junction voltage
  - Is independent of collector junction voltage
  - Field due to collector-base voltage attracts carriers but has no effect on rate of attraction

BJT Operation: Current Gain

- **Total Base current:** $i_B = i_{B1} + i_{B2}$

$$i_B = I_S\left(\frac{D_p}{D_n}\frac{N_A}{N_D}\frac{W}{L_p} + \frac{1}{2}\frac{W^2}{D_n\tau_b}\right)e^{v_{BE}/V_T}$$

Define a current gain β such that

$$\beta = \frac{i_C}{i_B}$$

Using previous relation for i_C

$$\beta = \frac{1}{\left(\frac{D_p}{D_n}\frac{N_A}{N_D}\frac{W}{L_p} + \frac{1}{2}\frac{W^2}{D_n\tau_b}\right)}$$

β is the common-emitter current gain

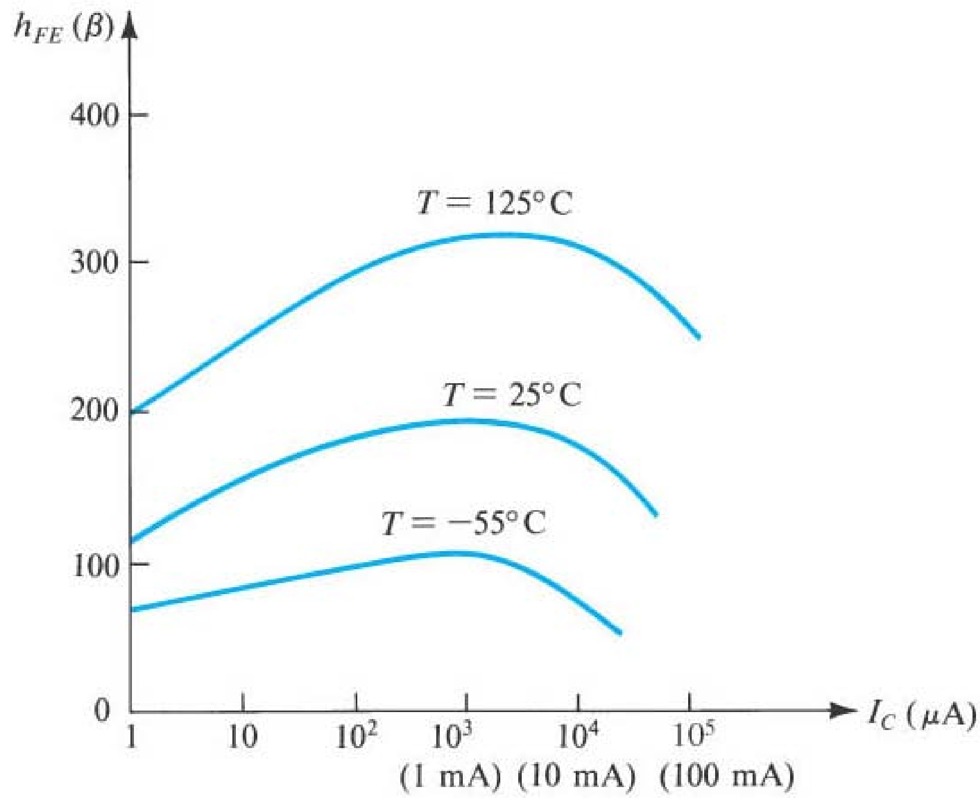
In order to achieve a high gain β we need

D_n: large
L_p: large
N_D: large
N_A: small
W: small

Typically $50 < \beta < 200$

In special transistors, β can be as high as 1000

Current Gain Temperature Dependence



BJT Operation: Emitter Current

- **Emitter current:** $i_E = i_C + i_B$

$$i_E = \frac{\beta+1}{\beta} i_C = \frac{\beta+1}{\beta} I_S e^{v_{BE}/V_T}$$

Define α such that $i_C = \alpha i_E$

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

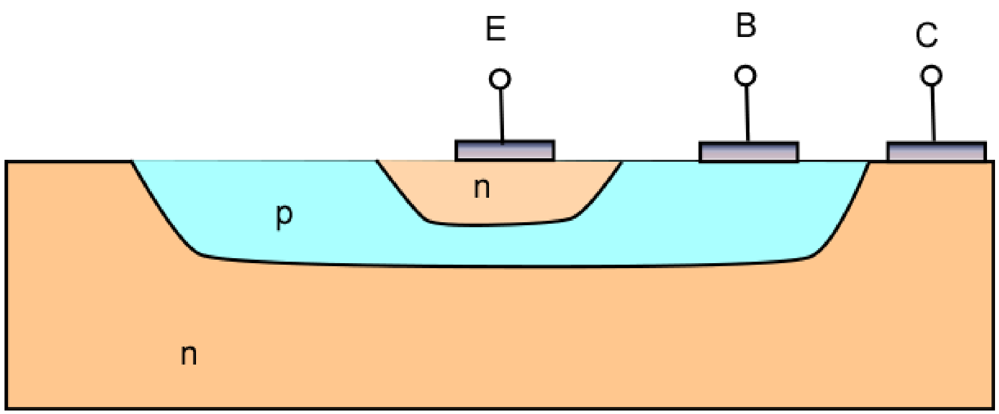
Using previous relation for i_C

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

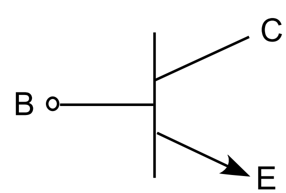
α is the common-base current gain

$$\alpha \approx 0.99$$

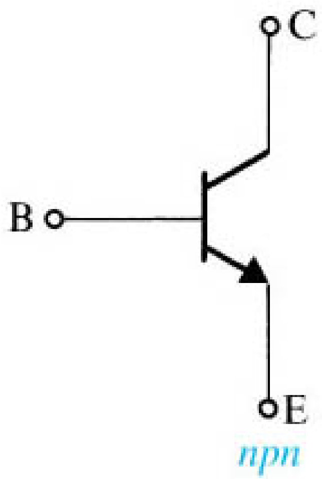
Structure of BJT's



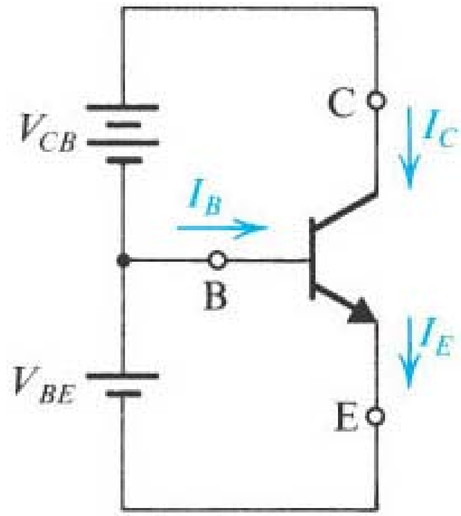
Collector surrounds emitter region → electrons will be collected

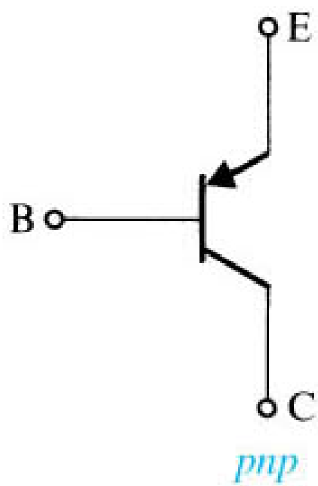


BJT Transistor Polarities

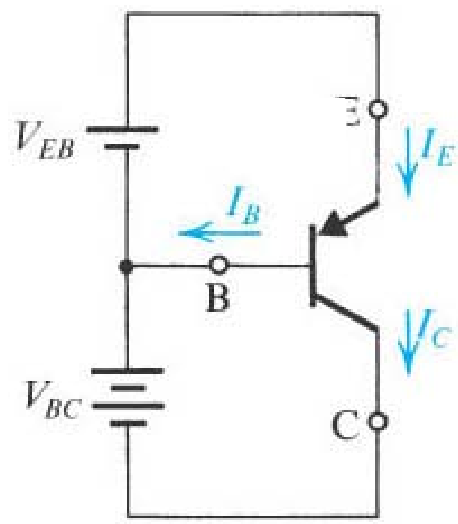


NPN



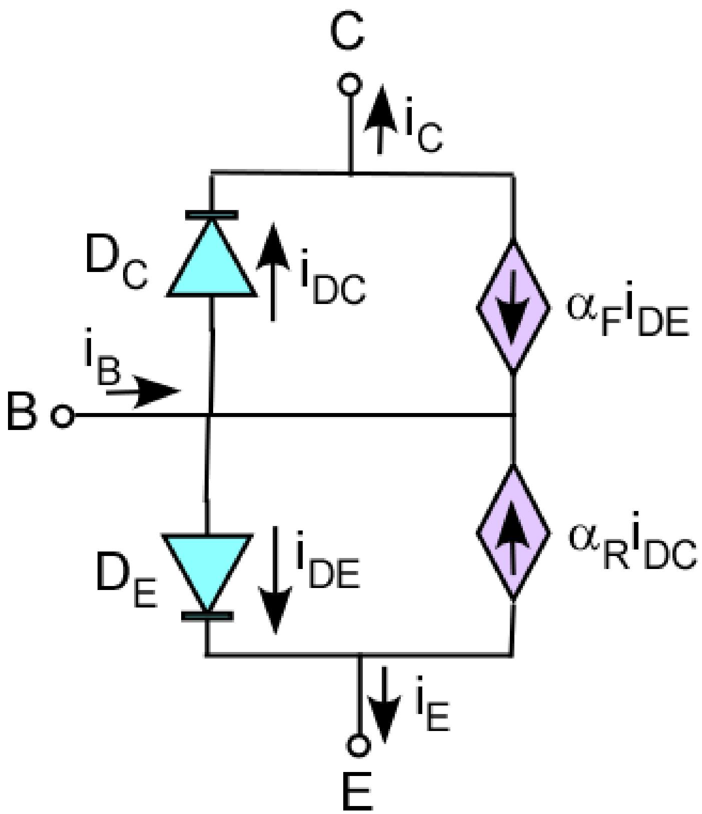


PNP



Ebers-Moll Model

NPN Transistor



$$i_E = \left(\frac{I_S}{\alpha_F}\right)\left(e^{v_{BE}/V_T} - 1\right) - I_S\left(e^{v_{BC}/V_T} - 1\right)$$

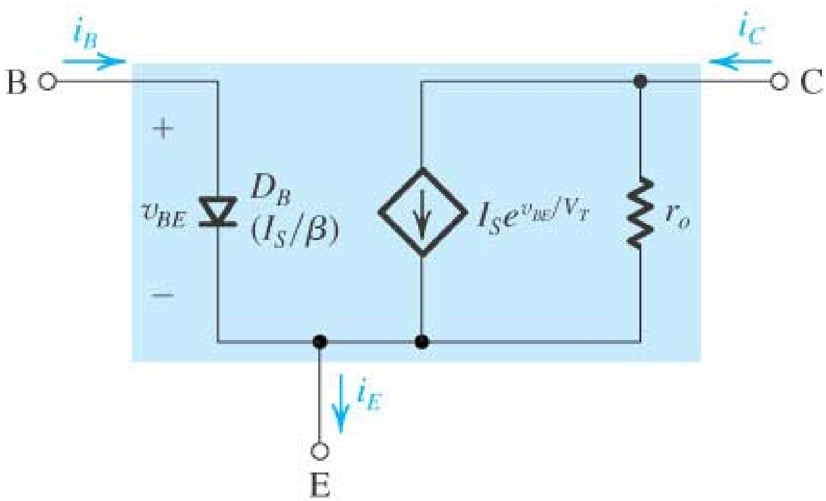
$$i_C = I_S\left(e^{v_{BE}/V_T} - 1\right) - \left(\frac{I_S}{\alpha_R}\right)\left(e^{v_{BC}/V_T} - 1\right)$$

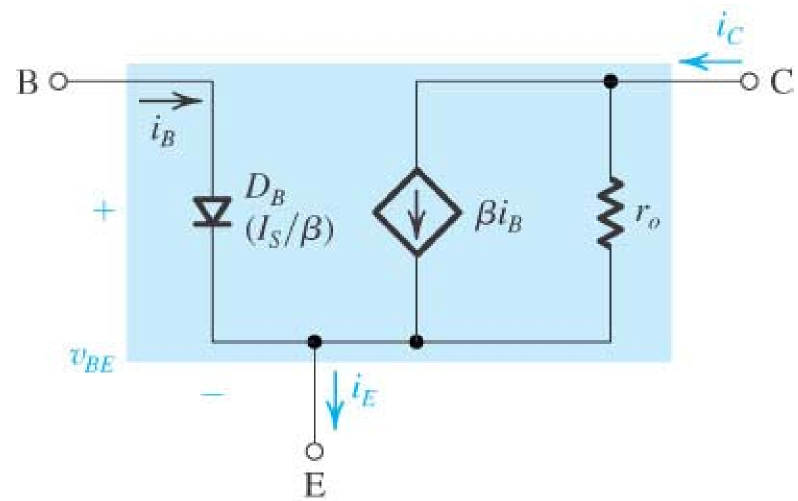
$$i_B = \left(\frac{I_S}{\beta_F}\right)\left(e^{v_{BE}/V_T} - 1\right) + \left(\frac{I_S}{\beta_R}\right)\left(e^{v_{BC}/V_T} - 1\right)$$

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} \qquad \beta_R = \frac{\alpha_R}{1-\alpha_R}$$

Describes BJT operation in <u>all</u> of its possible modes

Common-Emitter Large-Signal Model





- Common → terminal is common to input and output
- Common → terminal is used as reference or ground