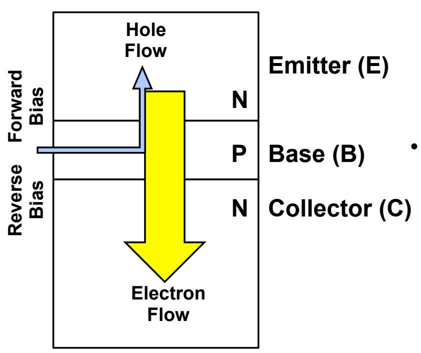
EE105 – Fall 2014
Microelectronic Devices and Circuits

Prof. Ming C. Wu

wu@eecs.berkeley.edu

511 Sutardja Dai Hall (SDH)

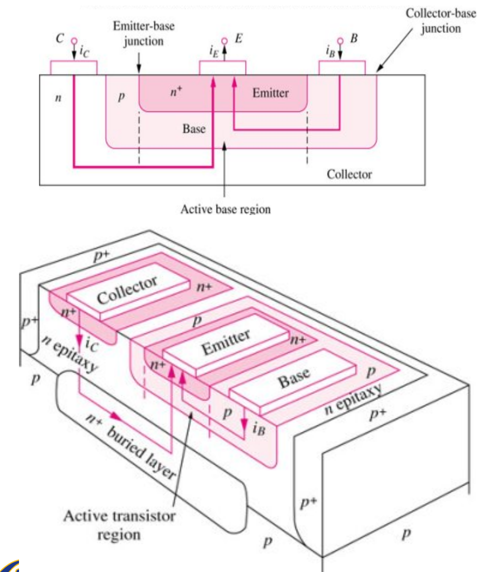
NPN Bipolar Junction Transistor (BJT)



Note: BJT is NOT 2 back-to-back junction diodes.

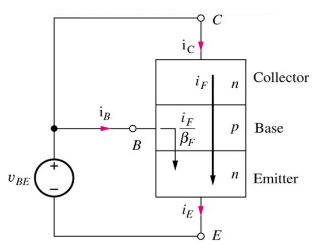
- **3 layers of semiconductors**
  - **Emitter (N-type), Base (P-type), Collector (N-type)**
  - **B-E junction forward-biased**
  - **B-C junction reverse-biased**
- **Two important criteria**
  - **Emitter more heavily doped than base**
    - **Much more electrons injected into base than holes into emitter**
  - **Base very thin**
    - **Most electrons travel through base and reach collector**
- **Current gain**
  - **Small base current controls large collector current**

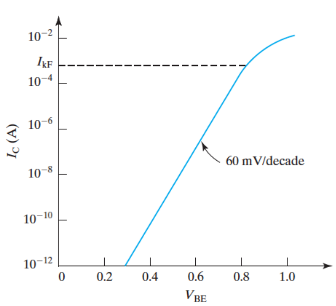
Physical Construction of BJT



- The transistor is usually planar
  - All contacts are on the front side
- Emitter and base are created by "ion implantation"
- To facilitate electrons travel to collector contact, an n+ buried layer is usually employed to reduce collector resistance.
- Typical doping
  - $N_E > 10^{18}$ cm^{-3}
  - $N_B \sim 10^{16}$ cm^{-3}
  - $N_C \sim 10^{15}$ cm^{-3}

npn Transistor Forward Characteristics





Collector current:

$$i_C = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

$$V_T = \frac{kT}{q} \quad \text{(26mV at room temp)}$$

I_S : BJT saturation current

(note: different from pn junction's I_S)

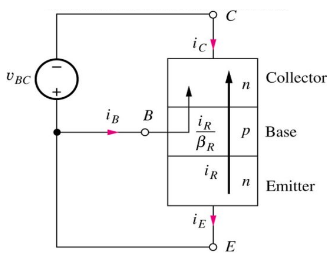
Base current: $$i_B = \frac{i_C}{\beta_F}$$

Emitter current: $$i_E = i_B + i_C = \left(\frac{1}{\beta_F} + 1\right) i_C = \frac{i_C}{\alpha_F}$$

β_F : current gain (typical value: ~ 100)

$\alpha_F = \dfrac{\beta_F}{\beta_F + 1}$: typical value 0.95 to 0.99

npn Transistor Reverse Characteristics
(Low Gain, Used Rarely in This Mode)



β_R is the reverse common-emitter current gain. β_R is typically small, even smaller than 1, because the doping profile is optimized for forward active gain.

Collector current i_C is given by

$$i_C = i_B - i_E = \frac{I_S}{\alpha_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$

Emitter current i_E is

$$i_E = -i_R = I_S\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$

Base current i_B is given by

$$i_B = \frac{i_R}{\beta_R} = \frac{I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$

α_R is the reverse common-base current gain

$$\alpha_R = \frac{\beta_R}{\beta_R + 1}$$

npn Transistor
Complete Transport Model - Valid for Any Bias

$$i_C = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right] - \frac{I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$

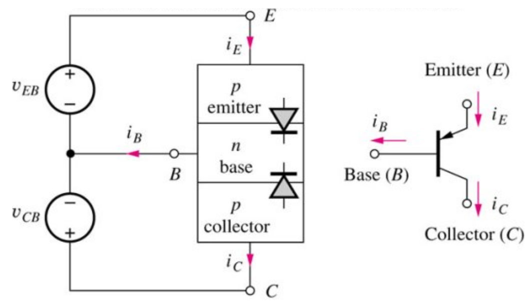
$$i_E = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right] + \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

$$i_B = \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right] - \frac{I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$

First term in both emitter and collector current expressions gives current transported completely across base region.

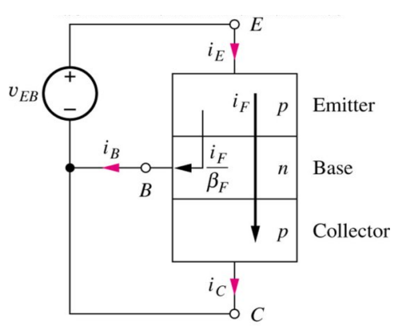
Symmetry exists between base-emitter and base-collector voltages in establishing dominant current in bipolar transistor.

pnp Transistor Structure



- Voltages v_{EB} and v_{CB} are positive when they forward bias their respective pn junctions.
- Collector current and base current exit transistor terminals and emitter current enters the device.

pnp Transistor Forward Characteristics



Collector current i_C equals the forward transport current is

$$i_C = i_F = I_S\left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1\right]$$

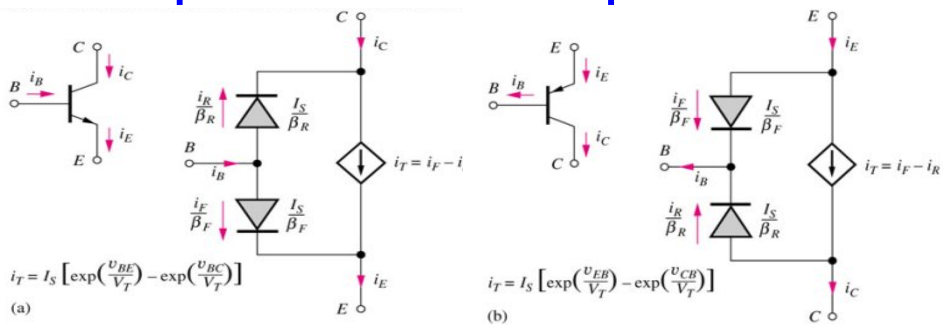
Base current i_B is given by

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

Emitter current i_E is given by

$$i_E = i_C + i_B = \frac{i_C}{\alpha_F}$$

Transport Model Circuit Representations



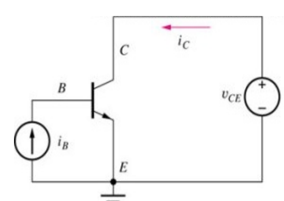
In ***npn*** **transistor (expressions are analogous for** ***pnp*** **transistors), the total current traversing base is modeled by a current source given by:**

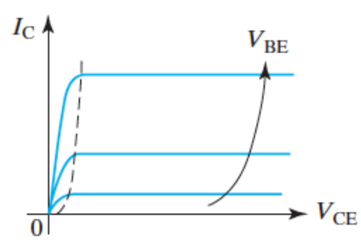
$$i_T = i_F - i_R = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right]$$

Diode currents correspond directly to the two components of base current.

$$i_B = \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right] - \frac{I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$

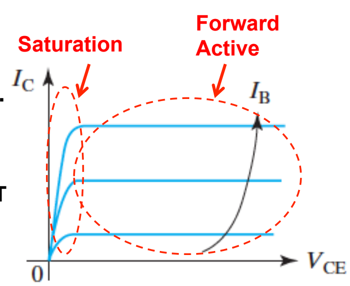
i-v Characteristics





Collect current increases exponentially with V_{BE}

- **Flat part of the i-v curves is called "forward active" region.**
- **The non-flat part is called "saturation" region**
  - **Please note Saturation in BJT and MOSFET refers to opposite regions**



Collect current increases linearly with I_B

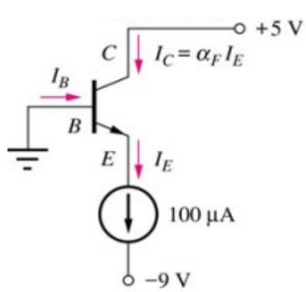
Operation Regions of Bipolar Transistors

Base-Emitter Junction	Base-Collector Junction	
	Reverse Bias	Forward Bias
Forward Bias	Forward-Active Region (Good Amplifier)	Saturation Region (Closed Switch)
Reverse Bias	Cutoff Region (Open Switch)	Reverse-Active Region (Poor Amplifier)

Binary Logic States

Example 1

- **Problem: Estimate transistor terminal currents and base-emitter voltage**
- **Given data: I_S =10^{-16} A, α_F = 0.95, V_{BC} = V_B - V_C = -5 V, I_E = 100 μA**
- **Assumption: BJT in forward-active**
- **Analysis:**



$$I_C = \alpha_F I_E = 0.95(100\mu A) = 95\ \mu A$$

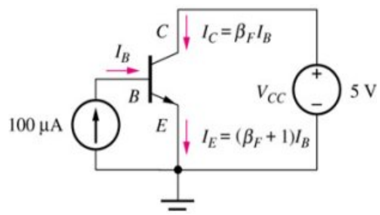
$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.95}{1-0.95} = 19$$

$$I_B = \frac{I_C}{\beta_F} = \frac{95\mu A}{19} = 5\ \mu A$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) = 0.689\ V$$

Example 2

- **Problem: Estimate terminal currents and voltages**
- **Given data: $I_S = 10^{-16}$ A, $\alpha_F = 0.95$, $V_C = +5$ V, $I_B = 100$ μA**
- **Assumptions: BJT in forward active**
- **Analysis:**



$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.95}{1-0.95} = 19$$

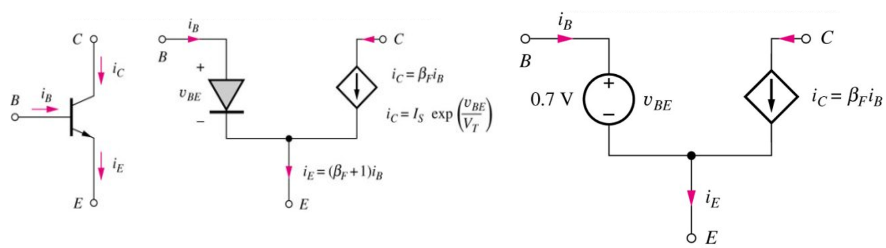
$$I_C = \beta_F I_B = 19(100\mu A) = 1.90\ mA$$

$$I_E = (\beta_F + 1)I_B = 20(100\mu A) = 2.00\ mA$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) = 0.025V \ln\left(\frac{1.9mA}{0.1fA}\right) = 0.764\ V$$

$$V_{BC} = V_B - V_C = V_{BE} - V_C = 0.764 - 5 = -4.24\ V$$

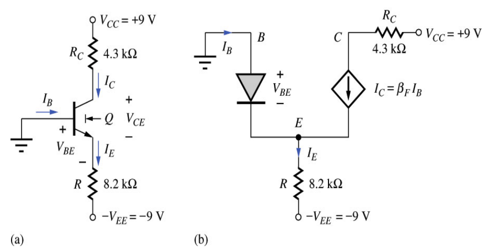
Simplified Circuit Model Forward-Active Region



- **Current in base-emitter diode is amplified by common-emitter current gain β_F and appears at collector; base and collector currents are exponentially related to base-emitter voltage.**
- **Base-emitter diode is replaced by constant voltage drop model (V_{BE} = 0.7 V) since it is forward-biased in forward-active region.**
- **dc base and emitter voltages differ by 0.7-V diode voltage drop in forward-active region.**

Simplified Forward-Active Region Model Example 3

- **Problem: Find transistor Q-point**
- **Given data: $\beta_F = 50$, $\beta_R = 1$**
- **Assumptions: Forward-active region of operation, $V_{BE} = 0.7$ V**
- **Analysis:**



$$V_{BE} + 8200 I_E - V_{EE} = 0$$

$$\therefore I_E = \frac{9 - 0.7}{8200} \frac{V}{\Omega} = 1.01\ mA$$

$$I_B = \frac{I_E}{\beta_F + 1} = \frac{1.01mA}{51} = 19.8\ \mu A$$

$$I_C = \beta_F I_B = 50(19.8\mu A) = 0.990\ \text{mA}$$

$$V_{CE} = V_{CC} - I_C R_C - (-V_{BE})$$

$$V_{CE} = 9 - 0.99mA(4.3K) + 0.7 = 5.44\ V$$

Forward-active region is correct.

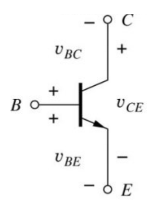
Simplified Circuit Model Saturation Region

- **In the saturation region, both junctions are forward-biased, and the transistor operates with a small voltage between collector and emitter. v_{CESAT} is the saturation voltage for the npn BJT.**

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) - \frac{I_S}{\alpha_R} \exp\left(\frac{V_{BC}}{V_T}\right) \qquad I_B = \frac{I_S}{\beta_F} \exp\left(\frac{V_{BE}}{V_T}\right) + \frac{I_S}{\beta_R} \exp\left(\frac{V_{BC}}{V_T}\right)$$

$$V_{CESAT} = V_{BE} - V_{BC} = V_T \ln\left[\left(\frac{1}{\alpha_R}\right) \frac{1 + \frac{I_C}{(\beta_R + 1) I_B}}{1 - \frac{I_C}{\beta_F I_B}}\right] \quad \text{for} \quad I_B \geq \frac{I_C}{\beta_F}$$

No simplified expressions exist for terminal currents other than $i_C + i_B = i_E$.



Simplified Model