BJT Circuit Configurations

Common base

Common emitter

Common collector
Common emitter current gain

Current Gain Value
\[ \beta \equiv \frac{I_C}{I_B} \]
(typically around 100)

\[ I_E = I_C + I_B \]
BJT Current-Voltage Characteristics

Very small base current (~5-75 μA) causes much higher collector current (up to 7.5 mA). The current gain is ~ 100
Collector current depends on two circuit parameters: the base current and the collector voltage. At high collector voltage the collector current depends on the base current only.

For $I_{\text{base}} = 40 \ \mu\text{A}$, $I_{\text{coll}} = 4 \ \text{mA}$ for any $E_{\text{C-E}}$ greater than 1.5 V
For an arbitrary collector voltage, collector current can be found using the KVL. The KVL for the collector – emitter circuit, \( V_{CC} = I_{RL} \times R_L + V_{CE} \);  

\[
I_{RL} = \frac{V_{CC} - V_{CE}}{R_L}
\]

The \( R_L \) current depends linearly on the collector voltage \( V_{CE} \).  

Resistor \( R_L \) and the C-E circuit of BJT are connected in series, hence \( I_{RL} = I_C \).  

For \( I_b = 40 \ \mu A \) and \( V_{CC} = 13V \), the collector current \( I_C = 4 \ mA \)  

For \( I_b = 75 \ \mu A \) and \( V_{CC} = 14V \), the collector current \( I_C = 4 \ mA \)
1. Input circuit
The input voltage has two components: the DC bias and the AC signal.

DC voltage component biases the base-emitter p-n junction in the forward direction.
AC component is the input signal to be amplified by the BJT.
2. Output circuit

The collector current has two components too.

DC and AC collector currents flow through the BJT in accordance with its I-V characteristics.
The resistance of the B-E junction is very low when $V_{BE} \geq V_{BE0} \approx V_{bi} \approx 0.7 \text{ V}$.

Hence the base current $I_B \approx (V_{in}-V_{BE0})/R_1 = (V_{inDC}-V_{BE0}+V_{inAC})/R_1$

The collector current $I_C$ does not depend on the collector voltage if the latter is high enough.

Hence, $I_C \approx \beta I_B$;

The voltage drop across the load resistance $R_2$: $V_2 = I_C R_2$;

The output voltage $V_{out} = V_{CC} - V_2 = V_{CC} - I_C R_2$;

$V_{out} = V_{CC} - I_C R_2 = V_{CC} - \beta I_B R_2 = V_{CC} - \beta R_2(V_{inDC}-V_{BE0}+V_{inAC})/R_1$;

In signal amplifiers only AC component of the output voltage is important:

$V_{outAC} = - \beta R_2 V_{inAC}/R_1$;

The amplifier voltage gain: $k_V = V_{outAC}/V_{inAC} = - \beta R_2/R_1$;
Common emitter gain summary:
Current gain: $k_1 = \beta$
Voltage gain: $k_V = \frac{V_{outAC}}{V_{inAC}} = -\beta \frac{R_2}{R_1}$
Power gain: $k_p = k_V \times k_1 = -\beta^2 \times \frac{R_2}{R_1}$
BJT design and factors affecting the performance
Base resistance and emitter current crowding in BJTs

The voltage drop along the base layer
\[ V_{bb} = r_{bb} I_b, \]
where \( r_{bb} \) is called the base spreading resistance.

The p-n junction current decreases rapidly when the voltage drops by
\[ \Delta V_{bb} \sim V_{th} = kT/q \]

\[ I = I_s \left( \frac{qV}{e^{kT} - 1} \right) = I_s \left( \frac{V}{e^{V_{th}} - 1} \right) \]

The length of the edge region, \( \Delta d_e \), where most of the emitter current flows may be estimated from:

\[ V_{th} = I_b R_{b\text{max}} \approx I_b \rho_b \frac{\Delta d_e}{t_e W} \]
Emitter current crowding in BJTs (cont.)

\[ V_{th} = I_b R_{b_{max}} \approx I_b \rho_b \frac{\Delta d_e}{t_e W} \]

\[ \rho_b = \frac{1}{qN_b \mu_b} \]

From these,

\[ \Delta d_e \approx \frac{V_{th} t_e W}{I_b \rho_b} = \frac{V_{th}}{I_b} q N_b \mu_b t_e W_b \]
Example

Estimate the effective emitter length, $\Delta d_e$ for the BJT having the following parameters:
$I_b = 50 \, \mu A$;
$N_b = 10^{17} \, \text{cm}^{-3}$
$\mu_b = 400 \, \text{cm}^2/\text{V-s}$
$W_b = 0.1 \, \mu \text{m}$
$t_e = 100 \, \mu \text{m}$

$$\Delta d_e \approx \frac{V_{th}}{I_b} q N_b \mu_b t_e W_b$$

$\Delta d_e = 3.33 \times 10^{-4} \, \text{cm} = 3.33 \, \mu \text{m}$
Large periphery B JT Design
Base narrowing (Early effect)
The depletion width of the p-n junction depends on the applied voltage:

(Here W is the depletion region width not the width of the base as in BJT!)
In the BJT, this effect means that the effective width of the base is less than $W_b$:

$$W_{\text{eff}} = W_b - X_{\text{deb}} - X_{\text{dcb}}$$

where $W_b$ is the physical thickness of the base, $x_{\text{deb}}$ and $x_{\text{dcb}}$ are the depletion region widths from the emitter and collector sides. The depletion widths are given by $(N_c \gg N_b)$:

$$x_{\text{deb}} = \left[ \frac{2\varepsilon_0 (V_{bi} - V_{be})}{q N_b} \right]^{1/2}$$

$$x_{\text{dcb}} = \left[ \frac{2\varepsilon_0 (V_{bi} + V_{cb}) N_c}{q N_b^2} \right]^{1/2}$$

$x_{\text{dcb}}$ is usually the most important factor since the voltage applied to collector is high.

The doping level in collector, $N_{DC}$ has to be lower than that of the base, $N_{AB}$, to reduce the Early effect:

$$N_C \ll N_B$$
Due to Early effect the effective base thickness depends on the collector voltage. In the gain expression, $W$ should be replaced with $W_{\text{eff}}$:

$$\beta_{rec} = \frac{2 L^2_p}{W^2_{\text{eff}}}$$

The Early effect decreases the output resistance, and hence the voltage gain of BJTs.
Punch-through breakdown in BJTs -
- the result of the Early effect

The punch-through breakdown voltage $V_{pt}$:

$$W = x_{dcb}$$

$$V_{pt} = \frac{qW^2}{2 \varepsilon \varepsilon_0} \frac{N_b (N_c + N_b)}{N_c}$$
BJT Model

- Gummel-Poon model used in SPICE and other simulators

Applying KCL to the BJT terminals:

\[ I_e = I_c + I_b \]

Collector – emitter current relationship:

\[ I_c = \alpha I_e \]

where \( \alpha \) is called a common base current gain

Hence, \n
\[ I_c = \alpha (I_c + I_b) \]

Common emitter current gain is defined as:

\[ I_c = \beta I_b \]

The last two expressions link common emitter and common base current gains
Simplified Gummel-Poon BJT equivalent circuit

- Emitter junction:
  \[ I_{be} = \frac{I_{se}}{\beta_F} \left[ \exp \left( \frac{V_{be}}{n_F V_{th}} \right) - 1 \right] \]

- Collector junction:
  \[ I_{bc} = \frac{I_{sc}}{\beta_R} \left[ \exp \left( \frac{V_{bc}}{n_R V_{th}} \right) - 1 \right] \]

\[ V_{th} = kT/q = 0.026 \text{ V at 300 K} \]
Gummel-Poon BJT equivalent circuit accounting for the leakage currents

- Emitter-base leakage diode:

\[ I_{\text{Leak}_{\text{be}}} = I_{se} \left[ \exp\left( \frac{V_{be}}{n_E V_{th}} \right) - 1 \right] \]

- Collector-base leakage diode:

\[ I_{\text{Leak}_{\text{bc}}} = I_{sc} \left[ \exp\left( \frac{V_{bc}}{n_C V_{th}} \right) - 1 \right] \]