BJT - Principles of Operation

- Different concentrations of donors and acceptors in BJT regions

\[ P_E >> N_B >> P_C \]

- Very narrow base thickness compared with diffusion length \( L_D \)

\[ W_B << L_D \]

Typical Doping [1/cm\(^3\)]: \( P_E \sim 10^{20} \), \( N_B \sim 10^{18} \), \( P_C \sim 10^{17} \)

- Current gain \( \beta = \frac{\Delta i_C}{\Delta i_B} \)

\[ \beta \approx \frac{P_E}{N_B} \cdot \left(1 - \frac{W_B}{L_D}\right) \]
Bipolar Junction Transistor (BJT)

Symbolic representation of BJT in circuits

- BJT is a three-terminal device
- The “arrow” shows the direction of current in an emitter
- Only two voltages and two currents are independent

\[
V_{CE} = V_{BE} + V_{CB}
\]

\[
I_E = I_B + I_C
\]
Identification of BJT terminals

How to recognize the terminals using Ohmmeter

- A stand alone transistor can be represented as two p-n junctions. They can be tested separately

1) Type of BJT (n-p-n or p-n-p)
2) Which terminal is the base

3) Which one is the emitter

- Emitter-Base is the most heavily doped p-n junction

Reverse Bias Resistance of B-E junction is much lower than that of C-E junction: \( R_{BE} \ll R_{CE} \)
There are two basic types of BJT: n-p-n and p-n-p. This notation comes from the type and sequence of the semiconductor layers. The direction of the "arrow" specifies the type of BJT in circuit diagrams.
Regimes of BJT

- *Forward active*

  ![BJT Diagram]

  - $V_{CB} > 0$
  - $V_{BE} > 0$

  - $B-E$ junction is *forward* biased, the typical $V_{BE} \approx 0.7 \, V$
  - $C-B$ junction is *reverse* biased
  - The most remarkable property is that collector current *reflects* the base current

  $$\Delta i_C = \beta \cdot \Delta i_B$$

  - Typical *current gain* $\beta \sim 70-200$
  - Collector and emitter currents close to each other $i_C \approx i_E$
Family of *Input* characteristics of BJT

- Input characteristic is a *weak* function of $V_{CE}$
- $i_B(V_{BE})$ can be approximated as a step function at $V_{BE} \approx 0.7V$
Family of Output characteristics of BJT

- **Saturation region:** \( V_{CE} < 0.5 \text{V} \)
- **Active region:** \( i_C \) is a weak function of \( V_{CE} \)
Small signal parameters of BJT

\[ i_C = \beta i_B \]
\[ i_C = g_m V_{BE} \]

- Current gain (empirical parameter) \( \beta \approx 10 \ldots 500 \)
- Transconductance \( g_m = \frac{i_C}{V_T} \) \( g_m \approx 0.1 \ldots 2 \text{A/V} \)
- Input resistance \( r_\pi = \frac{\beta}{g_m} = \frac{V_T}{i_B} \) \( r_\pi \approx 10\Omega \ldots 1\text{k}\Omega \)
- Output resistance \( r_0 = \frac{V_A}{i_C} \) \( r_0 \approx 1 \ldots 100\text{ k}\Omega \)

Early voltage \( V_A \)

\[ V_A \approx 100 \ldots 200 \text{ V} \]
Configurations of BJT in stages

- One node in common for input and output circuits

**Common emitter**

**Common Collector**

**Common Base**
Biasing of BJT with constant $i_B$

- A FORWARD ACTIVE regime requires a forward biased B-E junction and a reverse biased C-B junction.

\[ V_{BE} \approx 0.7V \]

- $R_B$ defines the base current in steady state conditions.

\[ i_B = \frac{V_{CC} - 0.7}{R_B} \]
$\begin{align*}
\text{Loading of BJT} \\
\quad \text{• } R_C \text{ converts the current } i_C \text{ into output voltage} \\
\quad \text{• } \text{The voltage drop across } R_C \text{ decreases } V_{CE} \\
\quad \text{\hfill } V_{CE} = V_{CC} - i_C \cdot R_C
\end{align*}$
Biasing of BJT with constant $V_{BE}$

- The voltage divider ($R_1, R_2$) stabilises $V_{BE}$

\[
\begin{align*}
R_1 & \quad i_l \quad R_C \\
R_2 & \quad V_{BE} \\
\end{align*}
\]

- The values of $R_1$ and $R_2$ are chosen:

1) to satisfy $i_1 \gg i_B$

\[
\frac{V_{CC}}{R_1 + R_2} \gg i_B
\]

2) to provide proper biasing

\[
V_{BE} = V_{CC} \frac{R_2}{R_1 + R_2} = 0.7V
\]
Thermal stabilization with $R_E$

- Introducing $R_E$ is an effective way of thermal stabilization of $i_C$

- Increase of $i_C$ with temperature increases the voltage drop across $R_E$ and leads to the reduction of $V_{BE}$, $i_B$ and $i_C$ respectively

$$V_B = V_{BE} + i_E R_E = const$$
High gain with good temperature stability

- Capacitor $C_E$ shunts $R_E$ for AC (signal) current

\[ C_E \gg \frac{1}{2\pi f_L R_E} \]

- The capacitor value should be large enough to short out $R_E$ at the lowest frequency $f_L$ of AC signal
BJT gain stage
Amplitude and phase relationships

\[ V_C = V_{CC} - i_C R_C \]
\[ V_E = i_E R_E \approx +i_C R_E \]

\[ \frac{\Delta V_C}{\Delta V_B} \approx -\frac{R_C}{R_E} ; \quad \Delta \varphi_{CB}=180^0 \]

\[ \frac{\Delta V_E}{\Delta V_B} = 1; \quad \Delta \varphi_{EB}=0 \]
I. COMMON EMITTER

- High Voltage gain $A_V$
- High Current gain $A_I$
- Low $R_{in}$, high $R_{out}$
- Inverting: $\Delta \phi = 180^\circ$

II. COMMON BASE

- Voltage gain $A_V$ in high frequency bandwidth
- No Current gain: $A_I = 1$
- Low $R_{in}$, high $R_{out}$
- Inverting: $\Delta \phi = 180^\circ$

III. COMMON COLLECTOR

- High $R_{in}$, low $R_{out}$
- No Voltage gain: $A_V = 1$
- High Current gain $A_I$
- Non-inverting: $\Delta \phi = 0^\circ$
Small signal parameters of BJT stage

\[ +V_{CC} \text{ (const)} \]

\[ \Delta V_{in}, \Delta i_{R1}, \Delta i_{R2}, \Delta i_{B}, \Delta V_{out}, \Delta i_{Rc}, \Delta i_{ro} \]

\[ R_{in} = R_1 \parallel R_2 \parallel r_\pi \]

\[ R_{out} = R_C \parallel r_o \]

- For AC current the resistances are connected in parallel
Temperature dependence of BJT characteristics

- The input characteristic is a strong function of temperature

\[ i_B (\mu A) \]

\[ V_{BE} (V) \]

\[ T_2 > T_1 \]

- Current gain \( \beta \) increases with temperature

Steady state collector current \( i_C \) requires temperature stabilization
BJT equivalent circuit for small signals

**BJT Input Resistance** \( r_{\pi} \)

\[ V_{BE} = 0.7 + V_{in}\cos(\omega t) \]

\[ I_{B} = 10 + I_{in}\cos(\omega t) \]

\[ r_{\pi} = \frac{V_{in}}{I_{in}} \]

\( r_{\pi} \) is a differential input resistance
BJT equivalent circuit for small signals

**BJT Output Resistance** $r_0$

$r_0$ is a differential output resistance

$$V_{CE} = 5 + V_{out}\cos(\omega t)$$

$$I_C = 1 + I_{out}\cos(\omega t)$$

$$r_0 = \frac{V_{out}}{I_{out}}$$
Small signal parameters of BJT

- **Current gain** (empirical parameter) \( \beta \approx 10 \ldots 500 \)
- **Transconductance** \( g_m = i_C / V_T \) \( g_m \approx 0.1 \ldots 2 \text{A/V} \)
- **Input resistance** \( r_\pi = \beta / g_m = V_T / i_B \) \( r_\pi \approx 10 \Omega \ldots 1 \text{k\Omega} \)
- **Output resistance** \( r_0 = V_A / i_C \) \( r_0 \approx 1 \ldots 100 \text{k\Omega} \)

![Diagram of BJT with labels: base, collector, emitter, \( i_C = \beta i_B \), \( i_C = g_m V_{BE} \), \( r_\pi \), \( r_0 \), \( V_A \approx 100 \ldots 200 \text{V} \), \( 0 \), \( V_{CE} \)]
Stage with *Common Emitter*

- High Voltage gain $A_V$
- High Current gain $A_I$
- Inverting: $\Delta \phi = 180^\circ$
- Low $R_{in} \approx r_\pi$
- High $R_{out} \approx (r_o \parallel R_C)$
Stage with *Common Collector*

- Suitable as a *current buffer*

![Diagram of a common collector stage]

- High input resistance $R_{in} = \frac{V_{in}}{i_B} \approx \beta R_E$

  $$V_{in} = V_{BE} + V_E = i_B r_\pi + (i_B + i_C) R_E = i_B [r_\pi + (1+\beta)R_E] \approx i_B \beta R_E$$

- Low output resistance $R_{out}$

- No Voltage gain $A_V \approx 1$
Stage with *Common Base*

- *High bandwidth* of voltage gain
- Low input resistance $R_{in} \approx r_{\pi}$
- High output resistance $R_{out} \approx (r_o \parallel R_C)$
- Inverting: $\Delta \phi = 180^\circ$
- No Current Gain: $\alpha = \Delta i_C / \Delta i_E \leq 1$

\[ \alpha = \frac{\beta}{\beta + 1} \approx 1 \]
Load line and $Q$-point of the gain stage

\[ V_{CE} = V_{CC} - i_C R_C \]

- The load line can be determined using two points:
  1) \( V_{CE} = V_{CC} \) at \( i_C = 0 \)
  2) \( i_C = V_{CC}/R_C \) at \( V_{CE} = 0 \)

- Quiescent (or $Q$) point is the intersection of the load line with the corresponding output characteristic
- The slope of the load line equals \( 1/R_C \)
- Setting the $Q$-point in the middle of the load line allows to obtain the maximum swing of output signal
The load line defines the relationship between the variation of $i_B$ and the variation of $V_{BE}$. 
The maximum undistorted swing of the output voltage depends on the position of Q-point.

1) Optimum Q

2) Q₁ or Q₂
Operating point of a BJT stage

\[ V_B = V_{CC} \frac{R_2}{R_1 + R_2} = V_{BE} + i_E R_E \approx 0.7 + i_C R_E \]

\[ i_C \approx \frac{V_B - 0.7}{R_E} \]

\[ V_{CE} = V_{CC} - i_C [R_E + R_C] \]

• The desirable operating point is \( V_{CE} \approx V_{CC}/2 \)
Load line and Q-point for AC signal

- If capacitor $C_E$ is in parallel to $R_E$, the AC load line is

$$V_{CE} = V^* - i_c R_C$$

- Q-point is the same for DC and AC load lines

- $V^* = V_{CC} - i_{CQ} R_E$, $i_{CQ}$ - the current corresponding to Q-point
Properties of BJT at High Frequencies

- At high frequencies the gain is mainly limited by the diffusion time $\tau_D$ of minor carriers through the base.

\[
\beta \quad dB
\]

- \textit{Cut-off frequency} $f_T$ corresponds to unity gain $\beta = 1$.

\[
f_T = \frac{1}{2\pi \tau_D}
\]

- \textit{Gain-bandwidth product} $\beta \Delta f = f_T$ allows to estimate the number of stages to obtain the required gain in the specified bandwidth.