1. Introduction
The bipolar junction transistor consists of three regions. The emitter has the greatest level of
doping, \(N_n \sim 10^{18}/cm^3\) (recall that the number density of Si is \(6 \times 10^{21}/cm^3\)), while that in the
base is \(N_p \sim 10^{16}/cm^3\) and that in the collector is \(N_n \sim 10^{15}/cm^3\). The current flows from collector
to emitter, which means that the electrons, which are the majority carrier, flow from the emitter
to the collector.

2. Active zone
The base/emitter junction is forward biased, with \(I_C = I_0[\exp(qV_{BE}/kT) - 1]\), while the
base/collector junction is reverse biased. A critical point is that the base is extremely thin so
that electrons from the emitter will diffuse through the base, only to be transported in the
depletion zone formed by the reverse bias and then swept into the collector. The thinness of
the base ensures that the depletion zone entails a significant fraction of the thickness of the
base, so that most electrons from the emitter are swept into the collector rather than leaving
through the base or lost via recombination with holes.
Electrons in the emitter suffer one of three fates:
(1) Recombination with holes in the base
(2) Exiting the base through the external lead
(3) Drift into the collector; this is the major current by a factor, denoted $\beta$, of $\beta \sim 100$

3. Constitutive relations

**Collector current:**

$$I_C = I_B \left[ \frac{I_E}{V_T} \right]$$

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

$I_T$: BJT saturation current

**Collect current increases exponentially with** $V_{BE}$

**Collect current increases linearly with** $I_B$

4. Simplified model of transistor in active zone

We see that $V_{BE} \sim 0.7 \text{ V}$. A brutal model is to replace the transistor, when operating in the Active region, with a model in which the base is connected to a battery and the collector is connected to a dependent current source.
4. Voltage controlled circuit

**Figure:**

- \( V_{BB} = +5V \)
- \( V_{OC} = +10V \)
- \( \beta = 20 \)

**Measure:** \( I_E = 100 \mu A \)

**Question:** Is the transistor in an active zone?

**Check Base-Collector bias**

\[ V_{CB} = V_C - V_B = 10 - 5 = 5V \]

So, B-C junction is reverse biased!

\[ I_C = \frac{\beta I_E}{1 + \beta} = \frac{20 \times 100 \mu A}{21} \approx 9.5 \mu A \]

\[ I_B = \frac{9.5 \mu A}{20} \approx 0.5 \mu A \]

\[ I_C = I_0 (e^{V_{BE}/kT} - 1) \]

**Check Base-Emitter bias**

\[ V_B = \frac{kT}{e} \log \frac{I_C}{I_0} \]

But \( I_0 \approx 1 \times 10^{-16} A \) \( \Rightarrow \) \( V_{BE} = 0.69V \)

So, B-E junction is forward biased!

5. Current controlled circuit

**Figure:**

- \( V_{oc} = 5V \)
- \( \beta = 20 \)
- \( I_B = 100 \mu A \)

**Check voltages**

\[ I_C = \beta I_B = 2mA \]

\[ V_{CB} = V_C - V_B \]

\[ = V_C - V_{BE} \]

\[ = 5V - 0.8V \]

\[ = 4.2V \]

Properly reverse biased

Properly forward biased
6. Analysis of a simple driver circuit

A common emitter driver circuit to pass a fixed current independent of the load.

1. \( V_{CC} = I_B \cdot R_B + V_{BE} \)
2. \( V_{CC} = I_C \cdot R_L + V_{CE} \)
3. \( I_C = \beta I_B \) for \( V_{CE} > V_{CE, SAT} \)

4. \( I_C = \frac{V_{CC} - V_{BE}}{R_B / \beta} \) Use to choose \( R_B \) to set current: \( R_B = \beta \frac{V_{CC} - V_{BE}}{I_C \beta} \)

5. \( V_{CE} = V_{CC} - I_C \cdot R_{LOAD} \)

\[ R_{LOAD} = \frac{R_B}{\beta} (V_{CC} - V_{BE}) \]

\[ R_{LOAD} = \frac{R_B}{\beta} \left( \frac{V_{CC} - V_{CE, SAT}}{V_{CC} - V_{BE}} \right) \]

Close to best \( \beta < 1 \)

\[ 0 < R_{LOAD} < \frac{R_B}{\beta} \left( \frac{V_{CC} - V_{CE, SAT}}{V_{CC} - V_{BE}} \right) \]

Range of \( V_{CE} \) as \( R_L \) varies

\( \frac{V_{CC}}{R_L} \)

\( I_C, Q \)

\( \text{Range of } V_{CE} \text{ as } R_L \text{ varies} \)

\( \text{Slope } = -\frac{1}{R_L} \)
7. Analysis of a the emitter-follower, a unity gain impedance buffer

This circuit can be understood by applying Kirchhoff's voltage law to the left-hand loop. We have:

\[-V_{in} + I_B R_B + V_{BE} + I_E R_E = 0.\]

In the linear regime, \(I_E = (1+\beta)I_B\) so:

\[V_{out} = I_E R_E = (V_{in} - V_{BE}) R_E / [R_E + R_B / (1+\beta)] = (V_{in} - V_{BE}) / [1 + R_B / (1+\beta)R_E]\]

\[\approx V_{in} - V_{BE}\]

since \(\beta >> 1\). To within an offset of \(V_{BE}\), the magnitude of output is the same as that of the input.

The input resistance is found by replacing the transistor with the Active Zone model (panel 4) and performing a Thevenin equivalence analysis, i.e., opening the dependent current source \(I_C\) and shorting the voltage drop \(V_{BE}\). Thus:

\[R_{in} = V_B / I_B = V_{BE} + I_E R_E / I_B = 0 + (1+\beta)R_E = (1+\beta)R_E\]

So we see that the emitter-follower functions with a high(-ish) impedance input.

The output resistance, found similarly by opening the dependent current source \(I_C\) and shorting the voltage sources \(V_{BE}\) and \(V_{in}\), is just

\[R_{out} = V_E / I_E = I_B R_B / I_E - V_{BE} = R_B / (1+\beta) - 0 = R_B / (1+\beta).\]

This is just the resistance of the source divided by the gain.

Both relations generalize to

\[Z_{in} = (1+\beta) Z_E\]

and

\[Z_{out} = Z_{source} / (1+\beta)\]

so that

\[Z_{in} Z_{out} = Z_E Z_{source}.\]