Bipolar Junction Transistors (BJT)

A Bipolar Transistor essentially consists of a pair of PN Junction Diodes that are joined back-to-back.
Reverse polarity is applied to the right diode. Positive battery polarity attracts electrons. There are no electrons on the p-side of the diode. The diode current is nearly zero.

Forward polarity is applied to the left diode. Positive battery polarity attracts electrons. If the battery voltage exceeds the built-in voltage, there is a high current flowing through.
Forward polarity is applied to the left diode. There is a high current flowing through it. The electrons entering p-region recombine with holes to form a current loop.

Reverse polarity is applied to the right diode. There are still no electrons on the p-side of the diode (they have all recombined at the left junction). The current is nearly zero.
• Forward polarity is applied to the left diode. Electrons from the left n-region get injected into the p-layer driven by a positive terminal of the battery 1.
• The p-layer being very thin, most of the injected electrons have low chances to recombine; they reach the 2nd junction and drift toward positive terminal of the battery 2.
• Therefore high current flows through 2nd p-n junction.

The P-layer is made VERY THIN
n-p-n bipolar transistor

Device structure

Circuit symbol

Emitter  Base  Collector

p-n-p bipolar transistor

Device structure

Circuit symbol

Emitter  Base  Collector
Electron and hole fluxes in n-p-n transistor:

(1) electrons injected from emitter into the base and reaching the collector junction (as large as possible);
(2) holes supplied by the base contact to initiate electron injection (as small as possible);
(3) injected electrons lost to recombination in the base (as small as possible);
(4) holes injected from the base into emitter recombining with electrons (as small as possible).
Electron and hole fluxes in p-n-p transistor:

1. Holes injected from emitter into the base and reaching the collector junction;
2. Electrons supplied by the base contact to initiate hole injection;
3. Injected holes lost to recombination in the base;
4. Electrons injected from the base into emitter recombining with holes.
Carrier concentrations and Terminal Currents (p-n-p transistor case):

Hole concentration at the e-b junction:

$$\Delta p_e = p_{b0} \left( e^{qV_{be}/kT} - 1 \right) \gg p_{b0}$$

Hole concentration at the b-c junction ($V_{cb} < 0$):

$$\Delta p_c = p_{b0} \left( e^{qV_{cb}/kT} - 1 \right) \approx -p_{b0}$$

Within the base, the injected hole concentration decreases **linearly** with $x$

Why linearly?
- The base width $W$ is larger than that of the e-b and c-b depletion regions. Therefore, the electric field in most of the base, $E \approx 0$.
- Therefore, the hole current (1) through the base is mainly the diffusion current:
  \[ I_p = A q D_p \frac{\partial p}{\partial x} \]
- The current (1) is nearly constant throughout the base because the recombination current (3) is very small.

- Therefore: $dp/dx = \text{const}$;
- The line that has a constant slope is a straight line.
Terminal Currents: Collector and Emitter currents (p-n-p transistor case):

Assuming small recombination loss in the base,

\[ I_c \approx I_e \approx A q D \frac{\partial p}{\partial x} \approx A q D_p \frac{\Delta p_e}{W} \]

\( W \) is the BJT base thickness
Terminal Currents : Base recombination current
(p-n-p transistor case):

Total charge of the holes injected into the base (the area under the $\Delta p(x)$ line):

$$Q_p = A q\frac{\Delta p_e W}{2}$$

This charge reproduces due to recombination; the required time is the hole lifetime $\tau_p$.

Therefore, the base recombination current, $I_{brec} = Q/t$:

$$I_{brec} = A q\frac{\Delta p_e W}{2\tau_p}$$
Current gain (recombination limited)

Collector current:

\[ I_c \approx Aq D_p \frac{\Delta p_e}{W} \]

Base recombination current:

\[ I_{brec} = Aq \frac{\Delta p_e W}{2 \tau_p} \]

Collector-base current gain (limited by recombination only) \( \beta_{\text{rec}} = \frac{I_c}{I_{brec}} \):

\[ \beta_{\text{rec}} = \frac{I_c}{I_{brec}} \approx \frac{Aq D_p \frac{\Delta p_e}{W} 2\tau_p}{Aq \Delta p_e W} = \frac{2 D_p \tau_p}{W^2} \]

The diffusion length: \( L_p = \sqrt{D_p \tau_p} \)

Therefore: \[ \beta_{\text{rec}} = \frac{2 L_p^2}{W^2} \]
Emitter injection efficiency

Electrons injected from the base into emitter – the current component (4), increase total base and emitter currents but DO NOT contribute into the collector current as they do not increase the injection.

The ratio of the “useful” emitter current (the hole current in p-n-p device) over the total emitter current is called emitter injection efficiency”; for a p-n-p transistor:

\[
\gamma = \frac{I_{ep}}{I_{ep} + I_{en}}
\]
Emitter injection efficiency (cont.)

For a p-n-p transistor:

$$\gamma = \frac{I_{ep}}{I_{ep} + I_{en}} = \frac{1}{1 + \frac{I_{en}}{I_{ep}}}$$

The electron and hole currents are mainly the diffusion currents:

For the hole current in the base: $$I_{ep} \approx qA \frac{\Delta p_{eb} D_p}{W};$$

The electron current from the base into the emitter: $$I_{en} \approx qA \frac{\Delta n_{be} D_n}{L_n};$$

The current ratio:

$$\frac{I_{en}}{I_{ep}} = \left( \frac{\Delta n_{be}}{\Delta p_{eb}} \right) \frac{D_n}{D_p} \frac{W}{L_n}$$

must be as small as possible for the highest injection efficiency

$$\Delta n_{be} = n_{p0} e^{qV/kT} = \frac{n_i^2}{N_Ae} e^{qV/kT}$$

$$\Delta p_{eb} = p_{n0} e^{qV/kT} = \frac{n_i^2}{N_Db} e^{qV/kT}$$

$$\frac{\Delta n_{be}}{\Delta p_{eb}} = \frac{N_Db}{N_Ae} \ll 1;$$
Emitter injection efficiency (cont.)

For any BJT type (p-n-p or n-p-n) high emitter injection efficiency requires:

\[ \frac{N_b}{N_e} << 1; \]

where \( N_b \) and \( N_e \) are the base and the emitter doping levels.

![Typical doping profile in n-p-n BJT](image)

Typical doping profile in n-p-n BJT
BJT current gain

Current gain limited by recombination in the base:

\[ \beta_{rec} = \frac{2L_p^2}{W^2} \]

\( \beta_{rec} = \frac{2L_n^2}{W^2} \)

Current gain limited by injection efficiency:

\( \beta_0 = \frac{N_{Ae}D_pL_n}{N_{Db}D_nW} \)

\( \beta_0 = \frac{N_{De}D_nL_p}{N_{Ab}D_pW} \)

\( \beta_0 \) is related to emitter injection efficiency \( \gamma \) as

\[ \beta_0 = \frac{\gamma}{1-\gamma} \]

The overall current gain:

\[ \beta = \frac{1}{\left( \frac{1}{\beta_{rec}} + \frac{1}{\beta_0} \right)} \]