Transistors

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Transistor Families

- There are two major families of transistors: Bipolar junction transistors (BJT) and field-effect transistors (FET).
- BJTs have 3 terminals and come in two varieties, as NPN and PNP transistors.
- N stands for n-type material and P stands for p-type material.
- A PN junction forms a diode => BJTs initially look like two back-to-back connected diodes.
NPN BJT Symbol/Structure

PNP BJT Symbol/Structure
NPN BJT Operation

• NPN transistor measured with Ohm-meter: Current flows from base to emitter and from base to collector. No current flows from emitter to base and no current flows from collector to base.

• For normal power/signal amplification the base-emitter pn-junction (diode) is forward biased and the base-collector junction is reverse biased.

Cross Section of NPN BJT

Electrons from emitter are initially attracted to holes in base if $v_{BE} \approx 0.7$ V. But the excess electrons (from N+) are attracted to $+V_{CC}$ => small $i_B$ current controls large $i_C$ current.
NPN BJT Operation

- Emitter region is n-type material with high concentration of excess electrons (N+).
- Base region is p-type material with small concentration of excess holes (P).
- Electrons from emitter are attracted to base if $v_{BE} \sim 0.7\, \text{V}$ (forward biased pn-junction).
- Only few electrons recombine with holes in base. All others are attracted to collector through positive $V_{CC}$ voltage.

PNP BJT Operation

- Same principle as for NPN BJT operation with roles of holes and electrons interchanged.
- Emitter is p-type material with high concentration of holes (P+). Emits holes instead of electrons.
- Base-emitter voltage $v_{BE} \sim -0.7\, \text{V}$ for forward bias of base-emitter np-junction.
- Collector voltage is more negative than emitter voltage to attract excess holes.
BJT Operating Modes

- Bipolar junction transistors can operate in three different modes:
  - Cutoff mode: Base emitter junction not forward biased, \( i_B = 0 \). BJT acts like open switch.
  - Active mode: Base-emitter junction forward biased, \( v_{CE} > 0.5 \text{ V} \) \((-0.5\text{ V} \text{ for PNP})\). BJT acts like current amplifier from \( i_B \) to \( i_C \) \( (i_C = \beta \cdot i_B, \beta = 10...200) \).
  - Saturation mode: Base-emitter junction forward biased and \( v_{CE} \approx 0 \text{ V} \). BJT acts like closed switch.

Current-Controlled Current Source

- To model active devices like transistors which can amplify signals and waveforms, dependent sources are used.

\[ \text{Current-controlled current source (CCCS). Input current } i_1 \text{ is sensed (somewhere in a circuit) and the output is the scaled (amplified) replica } \beta \cdot i_1. \text{ For BJTs } \beta \text{ is typically in the range } 10...200. \]
NPN BJT Operating Modes

- **Active Mode**: $i_B > 0 A$, $V_{CE} > 0.5 V$
- **Cutoff Mode**: $i_B = 0 A$, $i_C = 0 A$
- **Saturation Mode**: $i_B > 0 A$, $V_{CE} < 0.5 V$

PNP BJT Operating Modes

- **Active Mode**: $i_B > 0 A$, $V_{EC} > 0.5 V$
- **Cutoff Mode**: $i_B = 0 A$, $i_C = 0 A$
- **Saturation Mode**: $i_B > 0 A$, $V_{EC} < 0.5 V$
Common Emitter Circuit

\[ V_Y \]: \[ -V_C + V_i + V_{BE} = 0 \]
\[ \Rightarrow i_E = \frac{V_i}{R_E} = \frac{V_{BE} - V_C}{R_E} \]
\[ \Rightarrow V_C = V_{CE} - \beta R_C i_E \]
\[ V_{CE} = R_C (V_i - V_{BE}) \]

Gain:
\[ \frac{dV_C}{dV_i} = -\frac{\beta R_C}{R_E} \]

Common Collector Circuit

\[ V_Y \]: \[ -V_C + V_i + V_{BE} + V_C = 0 \]
\[ \Rightarrow R_C i_E + (\beta + 1) R_E i_E = V_C - V_{BE} \]
\[ \Rightarrow i_E = \frac{V_C - V_{BE}}{R_C + (\beta + 1) R_E} \]
\[ \Rightarrow V_C = \frac{(\beta + 1) R_C}{R_C + (\beta + 1) R_E} (V_i - V_{BE}) \]

Voltage Gain:
\[ \frac{dV_C}{dV_i} = \frac{(\beta + 1) R_C}{R_C + (\beta + 1) R_E} \quad \Rightarrow \quad 1 \text{ as } \beta \to \infty \]
Common Emitter Example
LM 386 Audio Amplifier