Transistors

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Transistors
- invented in 1947
- amplify current
- lower power consumption
- cheap for mass production
- robust to vibration
- long working time (decades) when properly used
- replaced vacuum tube
- building block of modern electronics

Some areas where vacuum tube are still good
- ultra high voltage applications (more than 1000 V)
- radiation prone locations

Bipolar junction Transistor (BJT)

NPN-transistor

PNP-transistor

Notation

- Base-emitter current ($I_{be}$)
- Collector-emitter current ($I_{ce}$)
- Base-emitter voltage difference ($V_{be} = V_b - V_e$)
- Collector-emitter voltage difference ($V_{ce} = V_c - V_e$)
Simple NPN-transistor rules

To support shown currents direction

- $V_{ce} > 0$
- $V_{be} > 0$
  - since, it is forward biased diode $V_{be} \approx 0.6$ V
- $V_{cb} > 0$
  - since, it is reversed biased diode, no current goes from collector to base, all collector current is directed to emitter 
  - if $V_{cb} < 0$ transistor goes to saturation and cannot be described by the following simple rule.

If above holds true then $I_{ce} = \beta I_{be}$ thus a BJT is a current amplifier

the static forward current transfer ratio $\beta$ (or sometimes $h_{fe}$) $\approx 100$ ...

$200$

$I_e = I_{be} + I_{ce} = (\beta + 1)I_{be} \approx \beta I_{be}$
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- $I_{ce} = \beta I_{be}$ thus a BJT is a current amplifier
  - the static forward current transfer ratio $\beta$ (or sometimes $h_{fe}$) $\approx 100 \ldots 200$
  - $I_{e} = I_{be} + I_{ce} = (\beta + 1)I_{be} \approx \beta I_{be}$
Simple PNP-transistor rules

Apply the same rules as before for NPN BJT but multiply currents and voltages by -1.

Hints
- the arrow indicates the direction in which current is supposed to flow.
- the arrow always connects the base and emitter.

Design considerations for $\beta$

Remember $\beta$ is not a constant!
It depends on many parameters
- temperature
- collector current
- varies from device to device even in the same batch

Good design should not depend on $\beta$ value.

Constant current source

Current through the load resistor does not depend on the load resistance.

$I_L = I_C = \beta I_{be} = \beta \frac{V_{ctrl} - 0.6V}{R_{set}}$

This is actually a sample of bad design since the current through the load depends on $\beta$. 

Notes
Constant current source

Current through the load resistor does not depend on the load resistance.

\[ I_L = I_C = \beta I_{BE} = \beta \frac{V_{CTRL} - 6V}{R_{SET}} \]

This is actually a sample of bad design since the current through the load depends on \( \beta \).

\[ V_C = V_{CC} - R_L I_L \]

Remember that \( V_C \) must be > \( V_B \) thus current cannot be bigger than the saturation current

\[ I_{SAT} = \max(I_L) \leq \frac{V_{CC} - V_B}{R_L} \approx \frac{V_{CC}}{R_L} \]

From \( V_{CC} \) point of view, left schematic is equivalent to the right one.

\[ R_{TRANS} = \frac{V_C}{I_L} = \frac{V_{CC} - R_L I_L}{I_L} \]

Transistor

\( Transistor-(\text{form})-(\text{re})sistor \)

Constant current source. Power dissipation.

Transistor power dissipation

\[ P_{TRANS} = P_{BE} + P_{CE} = V_{BE} I_{BE} + V_{CE} I_{CE} \]

Since \( V_{CE} \leq V_{CC} \), \( I_{BE} = I_{BE} = I_{CE} \), and \( I_{CE} = I_L \)

\[ P_{TRANS} \approx V_{CE} I_{CE} = R_{TRANS} I_L^2 \]
Constant current source. Power dissipation.

Transistor power dissipation

\[ P_{\text{trans}} = P_{\text{be}} + P_{\text{ce}} = V_{\text{be}}I_{\text{be}} + V_{\text{ce}}I_{\text{ce}} \]

Since \( V_{\text{be}} \leq V_{\text{ce}} \), \( I_{\text{be}} \ll I_{\text{ce}} \), and \( I_{\text{be}} = I_L \)

\[ P_{\text{trans}} = V_{\text{ce}}I_{\text{ce}} = R_{\text{trans}}I_L^2 \]

Maximum power dissipation in transistor is when \( R_{\text{trans}} = R_L \)

Voltage controlled switch

When properly designed, outcome does not depend on reasonable variations of \( \beta \)

Recall that typically \( \beta = 100 \ldots 200 \)

We will assume the worst case scenario \( \beta = 10 \)

Notice that \( R_L \) limits collector current

\[ I_L = \frac{V_{\text{cc}}}{R_L} \]

\[ I_{\text{be}} = \frac{V_{\text{ctrl}} - 6V}{R_B} = I_L \frac{\beta}{\beta} \]

\[ R_B \leq \frac{V_{\text{ctrl}} - 6V}{V_{\text{cc}}} \frac{1}{\beta R_L} \]
Gain. What gain?

We achieved the input impedance increase.

$$R_{\text{input}} = \frac{V_{\text{in}}}{I_{\text{be}}} \approx R_L (\beta + 1)$$

As a result our $V_{\text{in}}$ source is not overloaded and our load receive all required current (as long as the collector power supply can support it).