Transistor

According to Professor Max Shulaker, the invention of fire is what allowed apes to evolve into humans, and transistors are the next invention that is allowing humans to evolve into its next form..? Anyway, the point is, transistors are very important, and all of modern electronics are built with them.

At a high level, the function of a transistor is to either amplify or switch signals.

The most common types of transistors are bipolar junction transistors (BJT) and metal oxide semiconductor field-effect transistors (MOSFET).

Advantages of BJTs

- Faster
- Higher gain

Advantages of MOSFETs

- Ideally no input (gate) current
- Can be packed more densely

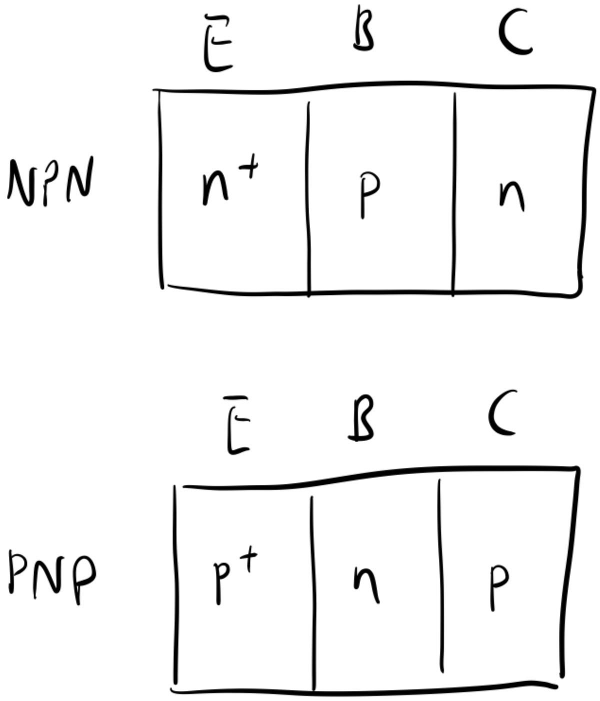
Bipolar Junction Transistors (BJT)

BJTs consist of three regions: emitter, base, and collector.

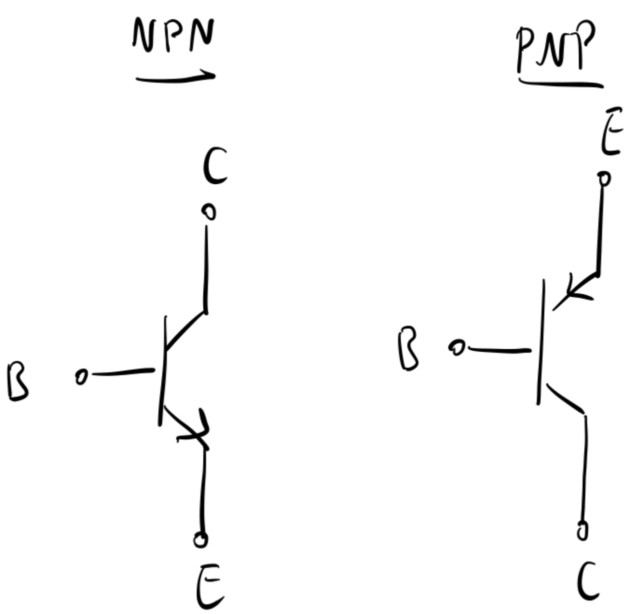
- The emitter is highly doped: it is n++ doped for NPN transistors and p++ doped for PNP transistors.
- The base is moderately doped: p+ for NPN, n+ for PNP.
- The collector is lightly doped: n for NPN, p for PNP.

Device Physics

In typical operation, the base-emitter junction is forward biased (p has higher voltage than n), and the collector-emitter junction is reversed biased (n has higher voltage than p). Forward biasing the B-E junction causes minority carriers (electrons in NPN, holes in PNP) to inject from the emitter into the base. (Effectively, this means that current, which moves in the opposite direction as electrons, will flow from the base to the emitter in an NPN.) This allows the base to inject its majority carriers (electrons in NPN, holes in PNP) into the base, where they diffuse into the collector. This flow of carriers creates the collector current.



Circuit-Level Behavior



There are three modes of operation for a BJT:

- Forward Active Region (the important, useful one): B-E junction is forward biased, C-B junction is reversed biased
- Saturation Region: B-E junction is forward biased, C-B junction is forward biased. The BJT will act like a short, and collector current cannot be controlled by modulating base voltage/current.
- Cutoff Region: B-E junction is reverse biased, C-B junction is reverse biased. No current will flow.

Early Effect (Base Width Modulation)

As the collector-base voltage increases, the depletion region at the collector-base junction increases, decreasing the effective base width, which increases current. This relation (increase in voltage causing an increase in current) can be modeled as a resistance. The Early effect is why BJTs have a noninfinite output resistance. The equivalent effect in MOSFETs is channel length modulation.

Forward Active Region

Equations:

$$I_C = I_S(1+\frac{V_{CE}}{V_A})exp(\frac{V_{BE}}{V_{th}})$$

$$I_B = \frac{I_C}{\beta_F}$$

$$\beta_F = \beta_{F0}(1+\frac{V_{CB}}{V_A})$$

$$r_o = \frac{V_A}{I_C}$$

I_S is saturation current, which is a function of the device physical properties.

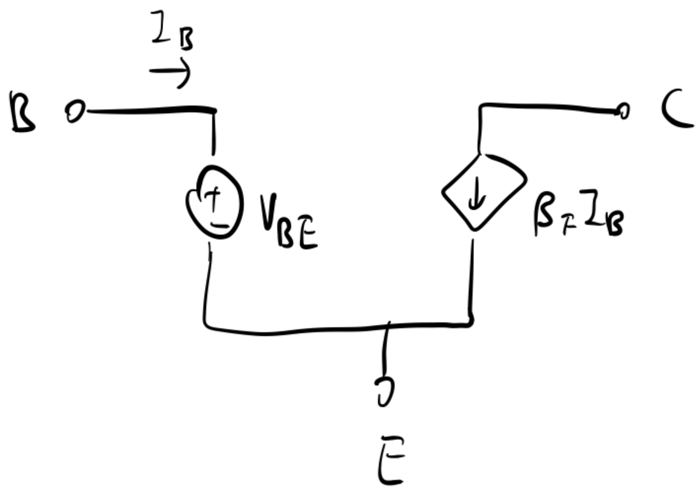
V_{th} is the thermal voltage $\frac{KT}{q}$, which is about 25mV at room temperature.

V_A is the Early voltage. It quantifies the Early effect/base width modulation of the device.

β_{F0} is the large-signal current gain of the device when V_{CB} = 0V. It can vary greatly betweeen devices.

Large-Signal Model

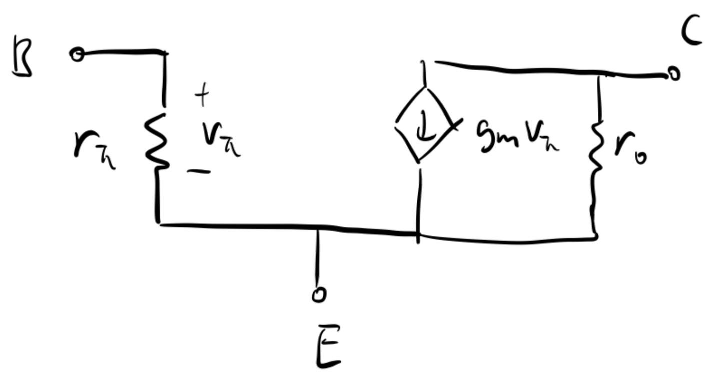
The large-signal model of BJTs is shown below.



Generally, V_{BE} can be assumed to be 0.6V.

Small-Signal Model

The small-signal model of BJTs is shown below.



The small-signal model parameters are as follows:

$$g_m = \frac{dI_C}{dV_{BE}} = \frac{I_C}{V_{th}}$$ $$r_{pi} = \frac{\beta_0}{g_m}$$ $$r_o = \frac{V_A}{I_C}$$