Announcements

- Homework 11 due today
- Homework 12 (the last one!) due next Tuesday
- Lab 9 (the last one!) this week
- Reading: Chapter 7 (7.1-5.)
Lecture Material

- Last lecture
  - Finished cascode amplifier
  - Bipolar junction transistor
- This lecture
  - Bipolar junction transistor
  - Large and small-signal models

Ideal BJT Structure

- NPN or PNP sandwich (Two back-to-back diodes)
- How does current flow? Base is very thin.
- A good BJT satisfies the following
  \[ I_C \approx -I_E \]
  \[ I_C \gg I_B \quad I_C \approx I_s e^{\frac{qV_{BE}}{kT}} \]
Actual BJT Cross Section

- Vertical npn sandwich (pnp is usually a lateral structure)
- n+ buried layout is a low resistance contact to collector
- Base width determined by vertical distance between emitter diffusion and base diffusion

BJT Layout

- Emitter area most important layout parameter
BJT Schematic Symbol

- Collector current is control by base current linearly
- Collector current is an exponential function of the base-emitter voltage

![BJT Schematic Symbol]

BJT Collector Characteristic

- Ground emitter
- Fix \( V_{CE} \)
- Drive base with fixed current \( I_B \)
- Measure the collector current

![BJT Collector Characteristic]
Collector Characteristics ($I_B$)

- Saturation Region (Low Output Resistance)
- Reverse Active (Bad Transistor)
- Forward Active Region (Very High Output Resistance)

Breakdown
Linear Increase
Exponential Increase

Base-Emitter Voltage Control

- Saturation Region (Low Output Resistance)
- Reverse Active (Bad Transistor)
- Forward Active Region (High Output Resistance)
Transistor Action

- Base-emitter junction is forward biased and collector-base junction is reverse biased.
- Electrons “emitted” into base much more than holes since the doping of emitter is much higher.
- Magic: Most electrons cross the base junction and are swept into collector.

Base (p)  Emitter (n+)  Collector (n)

$V_{CB} > 0$

$V_{BE} > 0$

Base width much smaller than diffusion length. Base-collector junction pulls electrons into collector.
Diffusion Currents

Minority carriers in base form a uniform diffusion current. Since emitter doping is higher, this current swamps out the current portion due to the minority carriers injected from base.

BJT Currents

Collector current is nearly identical to the (magnitude) of the emitter current ... define

\[ I_C = -\alpha_F I_E \quad \alpha_F = .999 \]

\[ -I_E = I_C + I_B \]

DC Current Gain:

\[ I_C = -\alpha_F I_E = \alpha_F (I_B + I_C) \]

\[ I_C = \frac{\alpha_F}{1 - \alpha_F} I_B = \beta_F I_B \quad \beta_F = \frac{\alpha_F}{1 - \alpha_F} = .999 = 999 \]
Origin of $\alpha_F$

Base-emitter junction: some reverse injection of holes into the emitter $\rightarrow$ base current isn’t zero

![Diagram of transistor with base-emitter junction](image)

Some electrons lost due to recombination

Typical: $\alpha_F \approx 0.99$ \hspace{1cm} $\beta_F \approx 100$

Collector Current

Diffusion of electrons across base results in

$$J_n^{\text{diff}} = qD_n \frac{dn_p}{dx} = \left( \frac{qD_n n_{PB0}}{W_B} \right) e^{\frac{qV_{BE}}{kT}}$$

$$I_S = \left( \frac{qD_n n_{PB0} A_E}{W_B} \right)$$

$$I_C = I_S e^{\frac{qV_{BE}}{kT}}$$
Base Current

Diffusion of holes across emitter results in

\[
J_{\text{diff}}^p = -qD_p \frac{dp_{nE}}{dx} = qD_p p_{nE0} \frac{qV_{BE}}{e^{qV_{BE}/kT} - 1} = -2D_p p_{nE0} (\ )
\]

\[
I_B = \left( qD_p p_{nE0} A_E \frac{qV_{BE}}{e^{qV_{BE}/kT} - 1} \right)
\]

Current Gain

\[
\beta_p = \frac{I_C}{I_B} = \frac{qD_n n_{pB0} A_E}{W_B} \frac{D_n}{D_p} \left( \frac{n_{pB0}}{p_{nE0}} \right) \left( \frac{W_E}{W_B} \right)
\]

\[
\left( \frac{n_{pB0}}{p_{nE0}} \right) = \frac{n_i^2}{N_{A,B}} = \frac{N_{D,E}}{N_{A,B}}
\]

Minimize base width

Maximize doping in emitter