Lecture 4

OUTLINE

• Bipolar Junction Transistor (BJT)
  – General considerations
  – Structure
  – Operation in active mode
  – Large-signal model and $I$-$V$ characteristics

Reading: Chapter 4.1-4.4.2
Voltage-Dependent Current Source

- A voltage-dependent current source can act as an amplifier.
- If $KR_L$ is greater than 1, then the signal is amplified.

\[ V_{in} \leftrightarrow V_{out}, \quad I_1 \leftrightarrow KV_1 \]

\[ A_V \equiv \frac{V_{out}}{V_{in}} = -KR_L \]

\[ V_{out} = -KV_1 R_L \]
Voltage-Dependent Current Source with Input Resistance

- The magnitude of amplification is independent of the input resistance $r_{in}$. 
Exponential Voltage-Dependent Current Source

- Ideally, a bipolar junction transistor (BJT) can be modeled as a three-terminal exponential voltage-dependent current source:

\[ I_s \exp \left( \frac{V_1}{V_T} \right) \]
Reverse-Biased PN Junction as a Current Source

- PN junction diode current is ~independent of the reverse-bias voltage. It depends only on the rate at which minority carriers are introduced into the depletion region.

⇒ We can increase the reverse current by injecting minority carriers near to the depletion region.
A bipolar junction transistor consists of 2 PN junctions that form a sandwich of three doped semiconductor regions. The outer two regions are doped the same type; the middle region is doped the opposite type.
NPN BJT Operation (Qualitative)

In the *forward active mode* of operation:
- The collector junction is reverse biased.
- The emitter junction is forward biased.

\[ V_{CE} > V_{BE} \]
\[ \Rightarrow V_{CB} > 0 \]

\[ V_{BE} = +0.8 \text{ V} \]
\[ V_{B} - V_{E} \]

\[ \beta \equiv \frac{I_C}{I_B} \]
Base Current

- The base current consists of two components:
  1) Injection of holes into the emitter, and
  2) Recombination of holes with electrons injected from the emitter.

\[ I_C = \beta I_B \]
Important features of a well-designed BJT (large $\beta$):

- Injected minority carriers do not recombine in the quasi-neutral base region.
  \[ W_B \approx 0.1 \text{um} \]

- Emitter current is comprised almost entirely of carriers injected into the base (rather than carriers injected into the emitter).

Make quasi-neutral base width small compared to minority-carrier diffusion length $L_B$

Dope emitter more heavily than the base
Carrier Transport in the Base Region

• Since the width of the quasi-neutral base region \((W_B = x_2 - x_1)\) is much smaller than the minority-carrier diffusion length, very few of the carriers injected (from the emitter) into the base recombine before they reach the collector-junction depletion region.
  
  → Minority-carrier diffusion current is ~constant in the quasi-neutral base

• The minority-carrier concentration at the edges of the collector-junction depletion region are ~0.
Diffusion Example Redux

• Linear concentration profile
  \[ p = N \left( 1 - \frac{x}{L} \right) \]
  \[ J_{p,diff} = -qD_p \frac{dp}{dx} = qD_p \frac{N}{L} \]

• Non-linear concentration profile
  \[ p = N \exp \left( -\frac{x}{L_d} \right) \]
  \[ J_{p,diff} = -qD_p \frac{dp}{dx} = \frac{qD_p N}{L_d} \exp \left( -\frac{x}{L_d} \right) \]
Collector Current

\[ I_C = \frac{A_E q D_n n_i^2}{N_B W_B} \left( \exp \frac{V_{BE}}{V_T} - 1 \right) \]

\[ I_C \approx I_S \exp \frac{V_{BE}}{V_T} \quad \text{where} \quad I_S = \frac{A_E q D_n n_i^2}{N_B W_B} \]

• The equation above shows that the BJT is indeed a voltage-dependent current source; thus it can be used as an amplifier.
Emitter Current

- Applying Kirchhoff’s Current Law to the BJT, we can easily find the emitter current.

\[
I_E = I_C + I_B = I_C \left(1 + \frac{1}{\beta}\right)
\]

\[
I_C = \beta I_B \text{ in forward active mode}
\]
Summary of BJT Currents

\[
I_C = I_S \exp \left( \frac{V_{BE}}{V_T} \right)
\]

\[
I_B = \frac{1}{\beta} I_S \exp \left( \frac{V_{BE}}{V_T} \right)
\]

\[
I_E = \frac{\beta + 1}{\beta} I_S \exp \left( \frac{V_{BE}}{V_T} \right)
\]

\[
\alpha \equiv \frac{\beta}{\beta + 1} \quad \text{"common base current gain"}
\]
Parallel Combination of Transistors

- When two transistors are connected in parallel and have the same terminal voltages, they can be considered as a single transistor with twice the emitter area.
Simple BJT Amplifier Configuration

- Although the BJT converts an input voltage signal to an output current signal, an (amplified) output voltage signal can be obtained by connecting a “load” resistor (with resistance $R_L$) at the output and allowing the controlled current to pass through it.
BJT as a Constant Current Source

- Ideally, the collector current does not depend on the collector-to-emitter voltage. This property allows the BJT to behave as a constant current source when its base-to-emitter voltage is fixed.
Constraint on Load Resistance

- If $R_L$ is too large, then $V_X$ can drop to below $\sim 0.8V$ so that the collector junction is forward biased. In this case, the BJT is no longer operating in the active mode, and so $I_C < \beta I_B$

→ There exists a maximum tolerable load resistance.
BJT $I$-$V$ Characteristics

(a) $I_C$ vs $V_{BE}$

(b) $I_C$ vs $V_{CE}$

$I_S \exp \left( \frac{V_{BE2}}{V_T} \right)$

$I_S \exp \left( \frac{V_{BE1}}{V_T} \right)$

$V_{BE} = V_{B2}$

$V_{BE} = V_{B1}$
Active Mode Example \[ I_s = 5 \times 10^{-17} \text{A}, \beta = 100 \]

\[ I_c = I_s e^{\frac{qV_{BE}}{kT}} \]

\[ I_B = \frac{I_c}{\beta} \]

(a) \[ V_{BE} = 700 \text{ mV}, I_c = 1.153 \text{ mA}, V_{CE} = 750 \text{ mV} \]

(b) \[ V_{BE} = 750 \text{ mV}, I_c = 1.69 \mu \text{A}, V_{CE} = 800 \text{ mV} \]

(c) \[ V_{BE} = 800 \text{ mV}, I_c = 0.246 \mu \text{A} \]

(d) \[ V_{BE} = 700 \text{ mV}, I_c = 24.6 \mu \text{A} \]
BJT Large Signal Model

- A diode is placed between the base and emitter terminals, and a voltage-controlled current source is placed between the collector and emitter terminals.
BJT vs. Back-to-Back Diodes

- Figure (b) presents a wrong way of modeling the BJT.