Announcements

• HW#3, Prob. 2: Re-draw I-V plots for $W_B$ reduced by a factor of 2.
• In case of a major earthquake:
  – Try to duck/crouch on the floor in front of the seats for cover.
  – Once the earthquake stops, evacuate the building in an orderly manner.

Outline

• BJT (cont’d)
  – PNP transistor (structure, operation, models)
• BJT Amplifiers
  – General considerations

Reading: Chapter 4.6-5.1
Current Flow in a “Long-Base” PN Junction

- The quasi-neutral N-type and P-type regions have low resistivity, whereas the depletion region has high resistivity.
  - When an external voltage $V_D$ is applied across the diode, almost all of this voltage is dropped across the depletion region.

- A relatively small $E$-field exists in the quasi-neutral regions $\rightarrow$ drift current

\[
\frac{J_n}{J_p}_{x=0} = \frac{D_n}{N_A L_n} \quad \frac{D_p}{N_A L_n} \quad \frac{D_n}{N_D L_p}
\]
Review of BJT Operation (Active Mode)

• The emitter junction is forward biased.
  → Carriers diffuse across the emitter junction; thus, minority-carrier concentrations are enhanced (by $e^{V_{D}/V_T}$) at the edges of the emitter-junction depletion region. More minority carriers are “injected” into the base vs. emitter, because the emitter is more heavily doped than the base.

• The collector junction is reverse biased (or not strongly forward biased).
  → Minority-carrier concentrations are ~0 (since $e^{V_{D}/V_T} \approx 0$) at the edges of the emitter-junction depletion region.

• The minority-carrier concentration gradient in the quasi-neutral base region (of width $W_B$) results in minority-carrier diffusion toward the collector junction.
  • If $W_B$ is much shorter than the minority-carrier diffusion length, then most of the minority carriers injected from the emitter will reach the collector-junction depletion region, and then drift into the quasi-neutral collector.
  • The collector current is primarily due to carriers “collected” from the base.
Common-Emitter Current Gain, $\beta$

• Assuming that no minority-carrier recombination occurs within the quasi-neutral base region:
  
  – The collector current is equal to the current due to minority-carrier injection from the emitter into the base:

$$I_C = \frac{A_E q D_B n_i^2}{N_B W_B} \left(e^{V_{BE}/V_T} - 1\right)$$

  – The base current is equal to the current due to minority-carrier injection from the base into the emitter:

$$I_B = \frac{A_E q D_E n_i^2}{N_E W_E} \left(e^{V_{BE}/V_T} - 1\right) \equiv \frac{I_C}{\beta}$$

• The current gain $\beta$ can thus be expressed as a function of the BJT physical parameters:

$$\beta = \frac{D_B N_E W_E}{D_E N_B W_B}$$
Impact of Early Effect on BJT Currents

- For a fixed value of $V_{BE}$, $W_B$ decreases with increasing $V_{CE}$ (because the width of the collector-junction depletion region increases with increasing reverse bias), so that the minority-carrier concentration gradient in the quasi-neutral base region increases. Thus, $I_C$ increases (slightly) with increasing $V_{CE}$.

\[ I_C \cong \frac{A_E q D_B n_i^2}{N_B W_B} e^{\frac{|V_{BE}|}{V_T}} \left( 1 + \frac{|V_{CE}|}{V_A} \right) \]

- The base current is not impacted:

\[ I_B = \frac{A_E q D_E n_i^2}{N_E W_E} e^{\frac{|V_{BE}|}{V_T}} \equiv \frac{I_C}{\beta} \]

- Thus, the current gain $\beta$ increases with increasing $V_{CE}$.

\[ \beta = \frac{D_B N_E W_E}{D_E N_B W_B} + \frac{|V_{CE}|}{V_A} \equiv \beta_0 + \frac{|V_{CE}|}{V_A} \quad \quad I_E = \left( \frac{\beta_0 + 1}{\beta_0} + \frac{|V_{CE}|}{V_A} \right) I_S e^{\frac{|V_{BE}|}{V_T}} \]
Small-Signal Models for Independent Sources

• The voltage across an independent voltage source does not vary with time.
  → Its small-signal voltage is always zero.
Thus, it is regarded as a short circuit for the purpose of small-signal analysis.

• The current through an independent current source does not vary with time
  → Its small-signal current is always zero.
Thus, it is regarded as an open circuit for the purpose of small-signal analysis.
The operating principle of a PNP BJT is the same as that of an NPN BJT. Note that the bias-voltage polarities are reversed for the PNP device, compared to an NPN device.

- The emitter is biased at a higher potential than the base.
- The collector is biased at a lower potential than the base.
NPN vs. PNP BJTs

- The directions of current flow and operation modes for NPN and PNP BJTs are shown below:
PNP BJT Terminal Currents

\[ I_C = I_S \left( \exp \frac{V_{EB}}{V_T} \right) \left( 1 + \frac{V_{EC}}{V_A} \right) \]

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

\[ I_E = \left( \frac{\beta_0 + 1}{\beta_0} + \frac{V_{EC}}{V_A} \right) I_S \left( \exp \frac{V_{EB}}{V_T} \right) \]

\[ \beta_0 = \frac{D_B N_E W_E}{D_E N_B W_B} \]
Large-Signal Model for PNP BJT

\[ I_S \frac{\exp \left( \frac{V_{EB}}{V_T} \right)}{\beta} \]

Where:
- \( I_S \) is the saturation current
- \( \beta \) is the current gain
- \( V_{EB} \) is the base-emitter voltage
- \( V_T \) is the thermal voltage

Diagram showing the PNP BJT with current relationships and voltage levels.
PNP BJT Biasing

- Note that the emitter is biased at a higher potential than the base and the collector.
Small-Signal Analysis

![Circuit Diagram]

- $V_{in} = 1.7 \text{ V}$
- $R_C = 300 \Omega$
- $I_C$
- $V_{out}$
- $V_{CC} = 2.5 \text{ V}$
The small-signal model for a PNP transistor is identical to that of an NPN transistor. Note that the polarity of the small-signal currents and voltages are defined to be in the opposite direction with respect to the large-signal model. This is OK, because the small-signal model is used only to determine changes in currents and voltages.
Small-Signal Model Example 1
Small-Signal Model Example 2

- Note that the small-signal model is identical to that in the previous example.
Small-Signal Model Example 3

- Note that the small-signal model is identical to that in the previous examples.
Small-Signal Model Example 4

(a)

(b)
# BJT Amplifiers: Overview

## General Concepts
- Input and Output Impedances
- Biasing
- DC and Small-Signal Analysis

## Operating Point Analysis
- Simple Biasing
- Emitter Degeneration
- Self-Biasing
- Biasing of PNP Devices

## Amplifier Topologies
- Common-Emitter Stage
- Common-Base Stage
- Emitter Follower
Voltage Amplifier

• In an ideal voltage amplifier, the input impedance is infinite and the output impedance is zero.

• In reality, the input and output impedances depart from their ideal values.

(a) Microphone, Amplifier, Speaker

200 Ω

R_m

10 mV

v_m

(b) 200 Ω

R_m

R_in

v_m

(c)

R_\text{amp}

R_L

8 Ω

v_\text{amp}

v_{out}
Input/Output Impedances

• The figures below show how input and output impedances are determined.
  – All independent sources are set to zero.
Input Impedance Example

• Note that input/output impedances are usually regarded as small-signal quantities.
  – The input impedance is obtained by applying a small change in the input voltage and finding the resultant change in the input current:

\[
\frac{V_x}{I_x} = r_\pi
\]
Impedance at a Node

- When calculating I/O impedances at a port, we usually ground one terminal. We often refer to the “impedance seen at a node” rather than the impedance between two nodes (i.e. at a port).
Impedance seen at the Collector

- The impedance seen at the collector is equal to the intrinsic output impedance of the transistor, if the emitter is grounded.

\[ R_{out} = r_o \]
Impedance seen at the Emitter

- The impedance seen at the emitter is approximately equal to the inverse of its transconductance, if the base is grounded.

\[
\frac{v_x}{i_x} = \frac{1}{g_m + \frac{1}{r_\pi}}
\]

\[
R_{out} \approx \frac{1}{g_m}
\]

\((V_A = \infty)\)
Summary of BJT Impedances

1. Looking into the base, the impedance is $r_\pi$ if the emitter is (ac) grounded.
2. Looking into the collector, the impedance is $r_o$ if emitter is (ac) grounded.
3. Looking into the emitter, the impedance is $1/g_m$ if base is (ac) grounded and Early effect is neglected.