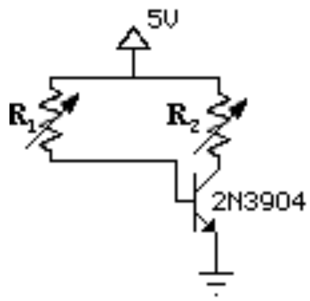
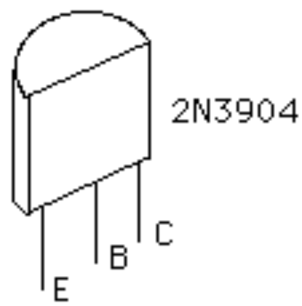
Physics 4700 Experiment 4

Transistors - 1

1) Build the following circuit, with R_1 = 5 MΩ and R_2 = 10 kΩ. Vary I_B between 1 and 30 μA and measure V_{CE} and I_C. Plot I_{C1}, β (= $h_{fe} = I_C / I_B$), V_{CE}, vs. I_B. What is the saturation current and saturation voltage (V_{CE} at saturation)?





2) Design a single stage common emitter amplifier. The amplifier should have the following specs:

a) flat frequency response from 30 Hz to 10 kHz (i.e. -3 dB point at 30 Hz)

b) voltage gain of ≈ 100

c) input impedance > 300 Ω

3) Measure the following properties of your amplifier and compare your results with expectations:

a) DC voltages at operating point (V_E, V_B, V_C).

b) plot voltage gain as a function of frequency (30 Hz - 100 kHz).

c) capture a picture of the amp's output response to a large input sine wave, with time stamp.

Suggested References:

Class notes of course.

Simpson Experiment 13 (P. 862) and 14 (P. 864).

Student Manual for Art of Electronics (most of Chapter 2).

Richard Kass/K.K. Gan
Phys. 4700

Designing the Common Emitter Amp

In this note I will outline a plan for designing a common emitter (CE) amplifier. There are many other ways of designing such an amp however they involve techniques beyond this class. Here are some good references on the subject:

Simpson: Section 5.7 (P. 221) and Experiment 14 (P. 865)
Diefenderfer: P. 152-154
Hayes and Horowitz: P. 115

A general purpose design for the CE amp is given in Fig. 1.

R_1 and R_2 are bias resistors and are used to keep the transistor "turned on" for DC voltages (V_{cc}). R_C and R_E determine the gain of the amp and R_E plays a role in determining the input impedance of the amp. C_E provides a path to ground for AC signals, while C_{in} and C_{out} isolate the input and output of the amp from the DC voltages that are present on the transistor.

Some general rules to keep in mind:

a) Our transistor amp amplifies <u>small</u> signals, typically mV.
b) Typical DC collector current is a few mA.
c) The gain (V_{out}/V_{in}) of a CE amp is $\approx R_C/r_{BE}$ if $R_E = 0$. r_{BE} is intrinsic to the transistor. You can't touch it! It is given by:

$r_{BE} = h_{ie}/h_{fe} \approx 25$ mV$/I_C$. So if $I_C = 1$ mA then $r_{BE} = 25\ \Omega$.

(See Simpson P. 227, 244 or class notes or Hayes and Horowitz P. 113)

d) The AC input impedance of the transistor is $\approx \beta r_{BE}$ (or $h_{fe} r_{be}$).

A typical β is 100. Remember that $\beta = h_{fe} = I_C/I_B$ so for 1 mA of collector current the AC input impedance is $\approx (100)(25) = 2500\ \Omega$.

e) The DC input impedance of the transistor is $\approx \beta R_E$ (or $h_{fe} R_E$). A typical value of R_E is 1 kΩ. So the DC impedance is much larger (e.g. 100 k vs. 2.5 k) than the AC impedance.
f) Since $I_E = I_C + I_B$ and $I_B = I_C/\beta$ we assume that $I_C = I_E$ for design purposes.
g) In order to stabilize the transistor from problems due to heating we should have:

$R_1 \parallel R_2 < 10\ R_E$.

See Simpson (P. 215-221) or Diefenderfer (P. 148) for a discussion of thermal stability.

With rules a-g *in mind we are ready to design the CE amplifier.*

1) Pick V_{cc}. Let's use $V_{cc} = 15$ Volts since all our lab supplies go up to this value.

2) We want the voltage gain $G = V_{out}/V_{in} > 100$. From rule c

$$G \approx R_C/r_E = R_C/(25\ \Omega/I_C).$$

From the 2N3904 spec sheet (Fig. 2) $I_C = 2.5$ mA looks like good place to operate the transistor (any choice in the linear region of the transistor would be OK):

$$G \approx R_C/10 > 100$$

$$R_C > 1000\ \Omega$$

Pick $R_C = 2000\ \Omega$.

3) We now need to decide what the maximum collect current (I_C) we will allow. From the spec sheet 4 mA looks reasonable. Applying Kirchhoff's law to the circuit in Fig. 1 yields the following load line (I_C vs. V_{CE}) equation:

$$I_C = V_{cc}/(R_E + R_C) - V_{CE}/(R_E + R_C)$$

(when $I_C = 4$ mA, $V_{CE} = 0$ Volts and when $I_C = 0$ mA, $V_{CE} = 15$ Volts)

$V_{CE} \approx$ 5-6 Volts is in the linear region. From the spec sheet we see that I_B must be ≈ 10 μA.

4) Using #3 from above we can find R_E.

$$I_C(\max) = V_{cc}/(R_E + R_C) = 4 \text{ mA} = 15 \text{ V}/(2000\ \Omega + R_E)$$

$$R_E = 1.75\ \text{k}\Omega$$

5) We can now find V_E and thus V_B.

$$V_E = I_E R_E \approx I_C R_E = (2.5 \text{ mA})(1.75\ \text{k}\Omega)$$

$$V_E \approx 4.4 \text{ Volts}$$

Remember $V_B = V_E + 0.6$ Volts for an NPN transistor.

$$V_B \approx 5 \text{ Volts}$$

6) We can now find R_1 and R_2 since:

$$V_B = [15 \text{ V}][R_2/(R_1 + R_2)] \text{ with } V_B = 5 \text{ V}.$$

From rule g on P. 1 we need $R_1 \parallel R_2 < 10\ R_E = 17.5$ kΩ.

Also R_1 and R_2 must provide enough base current ($I_B \approx 10$ μA)

$$V_{cc}/(R_1 + R_2) >> I_B \approx 10\ \mu\text{A}.$$

A choice of R_1 and R_2 that satisfies all of the above is:

$R_1 = 10$ kΩ and $R_2 = 5$ kΩ. There are <u>many</u> other choices.

7) The AC input impedance of the amp can now be calculated:

$$1/Z_{input} \approx 1/R_1 + 1/R_2 + 1/R_{transistor} = 1/(10\ \text{k}\Omega) + 1/(5\ \text{k}\Omega) + 1/R_{transistor}$$

$R_{transistor} = \beta r_{BE} \approx 1$ kΩ for $I_C = 2.5$ mA, $\beta = 100$ (see rule d).

$$Z_{input} = 800\ \Omega.$$

8) We now need to find values for the three capacitors, C_E, C_{in}, and C_{out}.

C_E must provide an AC ground for the emitter so we must have:

$$X_{CE} = 1/(2\pi f C_E) << R_E = 1.75\ \text{k}\Omega.$$

Let $X_{CE} = R_E/10$. The lowest frequency we are concerned with is 30 Hz so:

$$C_E = 1/(2\pi f X_{CE}) = 1/(2\pi \times 30 \times (R_E/10)) = 30\ \mu\text{F}.$$

9) Finally we need to choose C_{in} and C_{out}. Pick these capacitors so we have the –3 dB points at 30 Hz. Remember $\omega_{3dB} = 1/RC$. For the input $R \approx 800\ \Omega$ and for the output $R \approx 1$ MΩ (scope resistance). Thus we have:

$$C_{in} \approx 1/(800\ \Omega\ 2\pi\ 30) = 6\ \mu\text{F}$$

$$C_{out} \approx 1/(1\ \text{M}\Omega\ 2\pi\ 30) = 0.005\ \mu\text{F}$$

We have now determined all R's and C's. When you build the circuit don't be too disappointed (or surprised) if your measurements are different than the above calculations. We used a very simple model of the transistor.

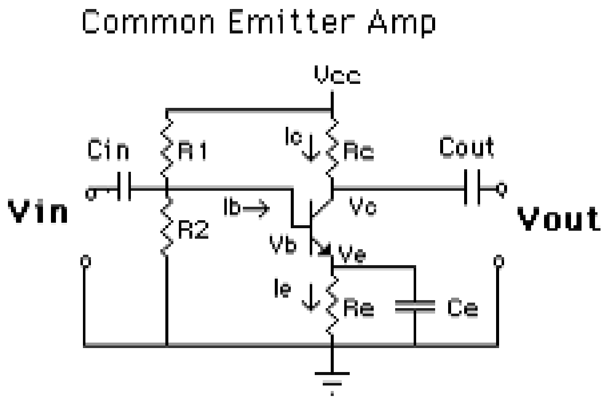


Fig. 1

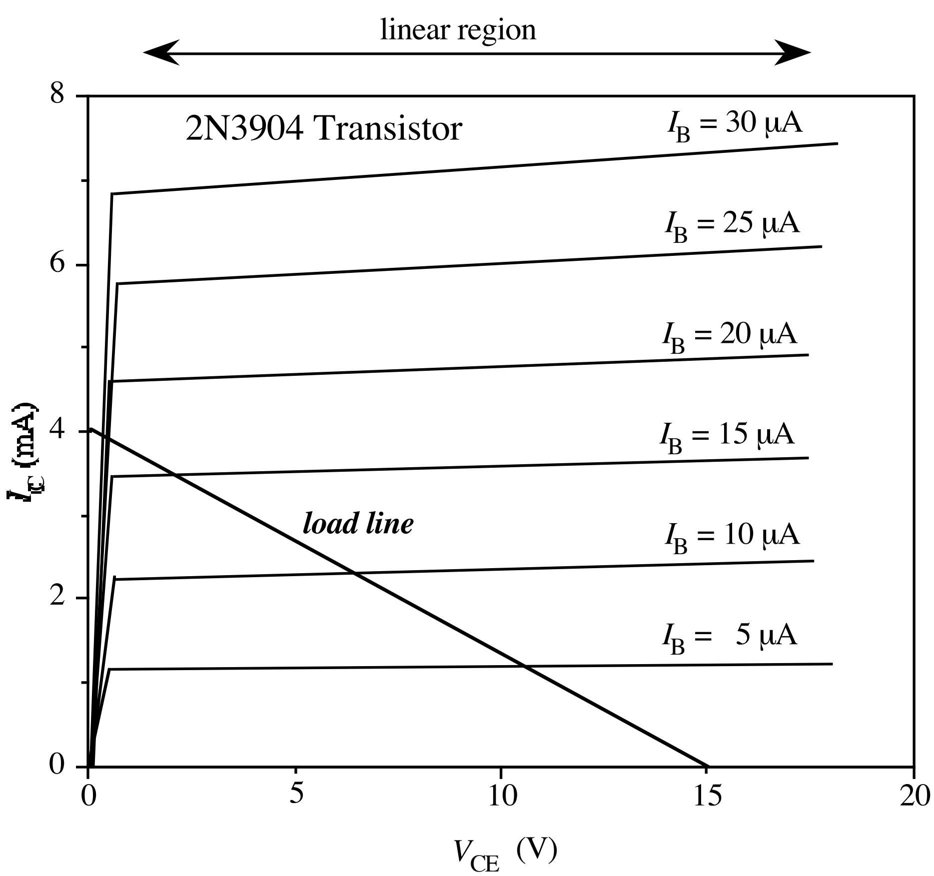


Fig. 2: 2N3904 Spec Sheet.