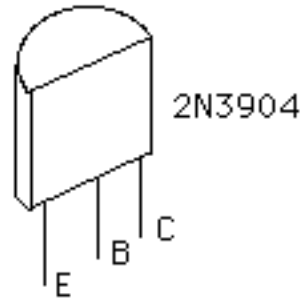
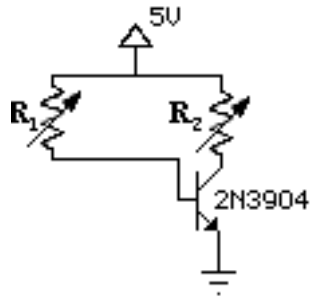


## Physics 4700 Experiment 4

### Transistors - 1

1) Build the following circuit, with  $R_1 = 5\text{ M}\Omega$  and  $R_2 = 10\text{ k}\Omega$ . Vary  $I_B$  between 1 and 30  $\mu\text{A}$  and measure  $V_{CE}$  and  $I_C$ . Plot  $I_C$ ,  $\beta (= h_{fe} = I_C / I_B)$ ,  $V_{CE}$ , vs.  $I_B$ . What is the saturation current and saturation voltage ( $V_{CE}$  at saturation)? Measure  $I_C$  with a handheld multimeter and  $I_B$  with a bench precision multimeter.



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  $\approx 100$
- c) input impedance  $> 300\ \Omega$

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 pictures of the amp's response to sine waves of different amplitudes, one small to show the proper operation of the amp and one large to show output saturation, 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).

### 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 small 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:

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

(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  $\beta$  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 k $\Omega$ . 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  $\approx 10$   $\mu$ A.

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

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

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

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  $R_1 \parallel R_2 < 10 R_E = 17.5 \text{ k}\Omega$ .

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

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

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

$$R_1 = 10 \text{ k}\Omega \text{ and } R_2 = 5 \text{ k}\Omega. \text{ There are many other choices.}$$

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

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

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

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

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

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

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

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

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

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

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.

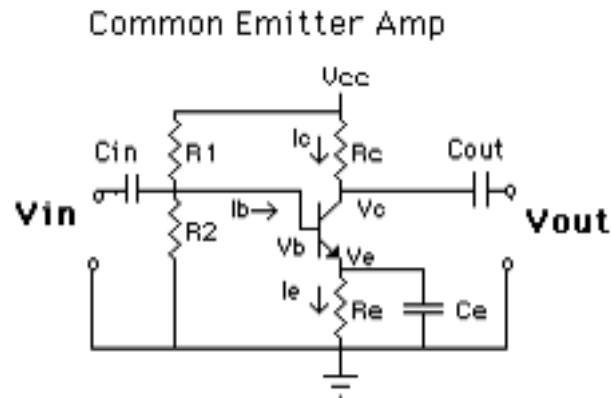


Fig. 1

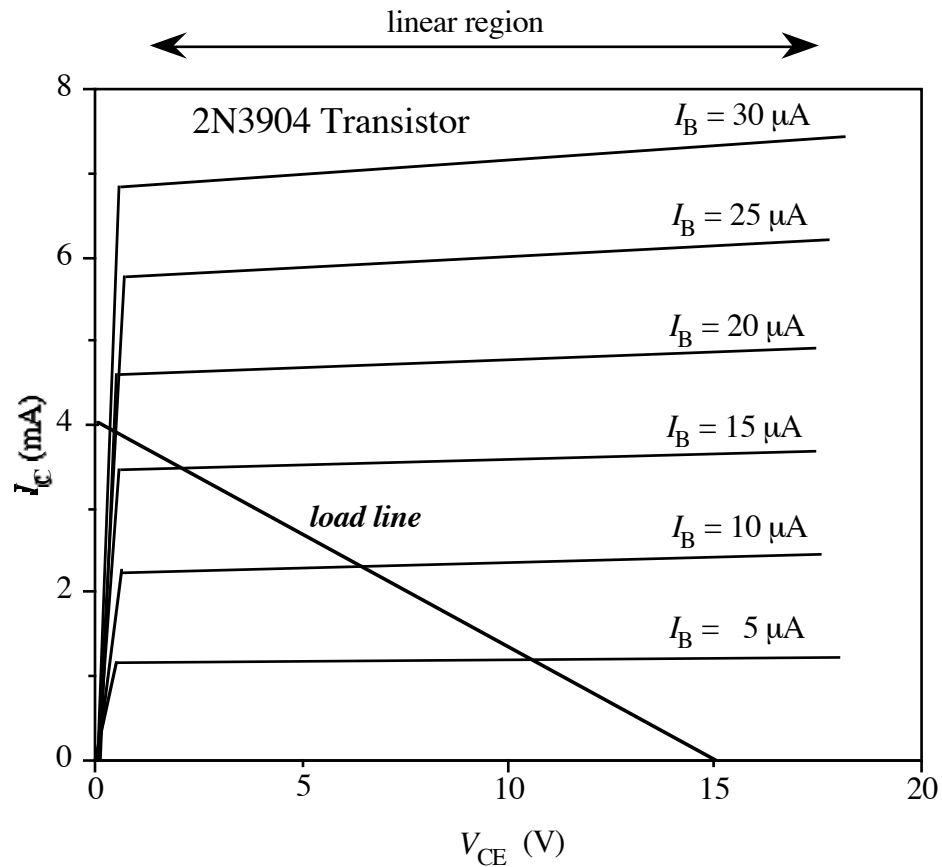


Fig. 2: 2N3904 Spec Sheet.