CIRCUITS LABORATORY

EXPERIMENT 6

TRANSISTOR CHARACTERISTICS

6.1 ABSTRACT

In this experiment, the output I-V characteristic curves, the small-signal low frequency equivalent circuit parameters, and the switching times are determined for one of the commonly used transistors: a bipolar junction transistor.

6.2 INTRODUCTION

The advent of the modern electronic and communication age began in late 1947 with the invention of the transistor. Rarely has any component of any apparatus received the public attention and acclaim of this invention. Although everyone knows what a transistor radio is, few know how it works or why the transistor itself is so important in electronic systems. From an economic point-of-view its main advantages are small size, low-cost, and high reliability. Basically, however, the importance of the transistor derives from the fact that it is a three-terminal device that can provide amplification or gain. The three terminals serve to isolate input and output, while gain allows for conversion of dc power into signal power.

Two of the most important applications for the transistor are (1) as an amplifier in analog electronic systems, and (2) as a switch in digital systems. In this experiment we will examine some of the characteristics of transistors in these modes of operation. For this purpose we will investigate one of the common transistors, the bipolar junction transistor (BJT).

6.3 BIPOLAR JUNCTION TRANSISTOR (BJT)

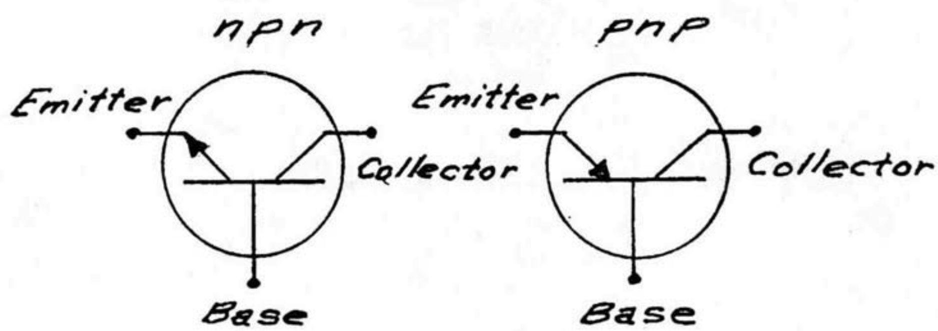


Figure 6.1: Symbols for BJTs.

6.3.1 Basic Concepts

The operation of the BJT is based on the principles of the pn junction. As indicated in Figure 6.1, there are two basic types: (a) the npn and (b) the pnp. In the npn, electrons are injected from the forward-biased emitter into the thin base region where, as minority carriers, they diffuse toward the reverse-biased collector. Some of these electrons recombine with holes in the base region, thus producing a small base current, i_B. The remaining electrons reach the collector where they provide the main source of carriers for the collector current, i_C. Thus, if there are no electrons injected from the emitter, there will be (almost) no collector current and, therefore, the emitter current controls the collector current. Combining currents, the total emitter current is given as

$$i_E = i_B + i_C. \tag{6.1}$$

Note that the total emitter current, $i_E = I_E + i_e$, where I_E is the DC component and i_e is the time varying component. The behavior of the npn transistor is indicated schematically in Figure 6.2 with the voltage polarities required for normal npn operation. For normal pnp operation, the polarity of both voltage sources must be reversed. For the configuration

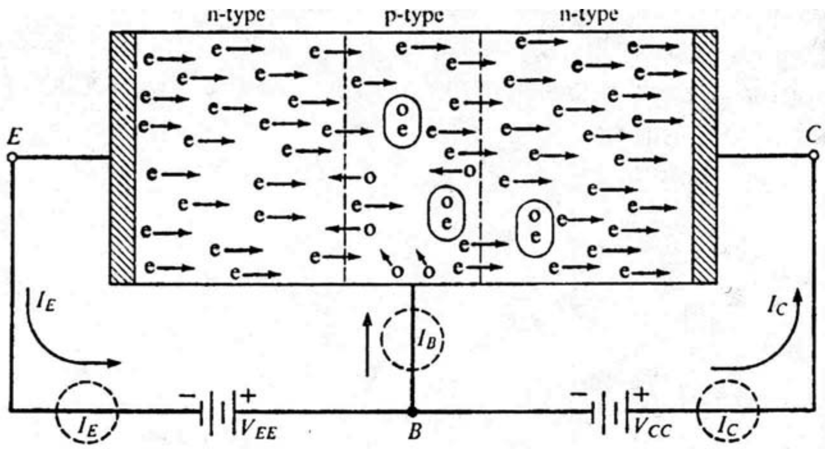


Figure 6.2: Representation of npn transistor in operation with forward biased emitter-base junction and reverse biased collector-base junction (e = electrons, 0 = holes, and oe = recombination of holes and electrons).

shown in Figure 6.2, we can define a (normal operation) DC current gain as

$$\alpha_{DC} = Ii_C / Ii_E \quad (6.2)$$

Since I_C is somewhat less than I_E , α_{DC} is a number less than one. A typical value would be 0.99. It is also useful to define a current transfer ratio as,

$$\beta_{DC} = I_C/I_B \quad (6.3)$$

Using Equations (6.1) and (6.2) in (6.3), we get

$$\beta_{DC} = \alpha_{DC}/(1 - \alpha_{DC}). \quad (6.4)$$

If $\alpha_{DC} = 0.99$, then $\beta_{DC} = 99$.

When the BJT is used in a system with the emitter and base contacts as the input and the collector and base contacts as the output, from Eq. (6.2) the current gain is less than 1. The forward-biased emitter-base junction, however, has a small impedance while the reverse-biased collector-base junction has a large impedance. Thus, the voltage gain is large. This is called the common-base configuration.

When the BJT is used with the base and emitter terminals as the input and the collector and emitter terminals as the output, from Eq. (6.4) the current gain as well as the voltage gain is large. It is for this reason that this common-emitter (CE) configuration is the most useful connection for the BJT in electronic systems.

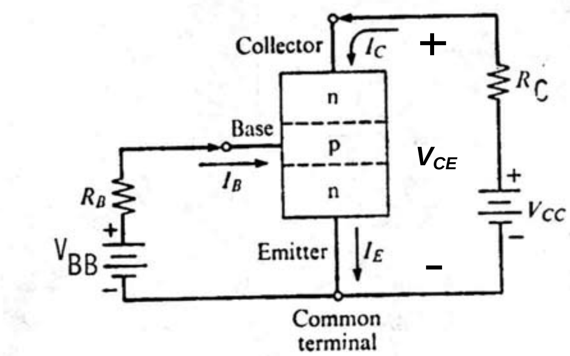


Figure 6. 3a: Cornmon-emitter connections for npn transistor.

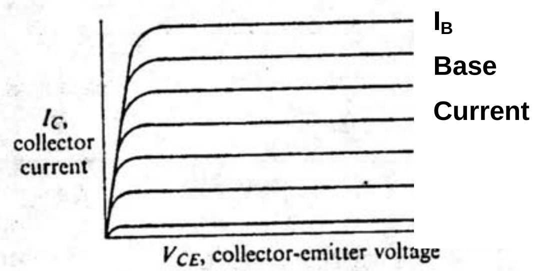


Figure 6.3b: Collector characteristic curves for the common- emitter connection of npn transistor.

This configuration is shown in Figure 6.3a with the output I-V characteristics indicated in Figure 6.3b. Notice from the I-V characteristics that the output collector current is controlled by the input base current as modeled in Equation. (6.3).

6.3.2 Graphical Analysis

A graphical analysis of the BJT as both a switch and an amplifier can be obtained from the output I-V characteristics by means of a load-line construction. If we take V_{cc} = 10 volts and R_c = 1 kΩ in Figure 6.3a, then the load-line intercepts on the output characteristic are V_{CE} = 10 volts and

$$I_C = \frac{V_{CC}}{R_C} = 10\ mA\ . \tag{6.5}$$

These points are indicated in Fig. 6.4. The transistor output V_{CE} and I_C are now constrained by V_{CC} and R_C to have values only along the load-line indicated.

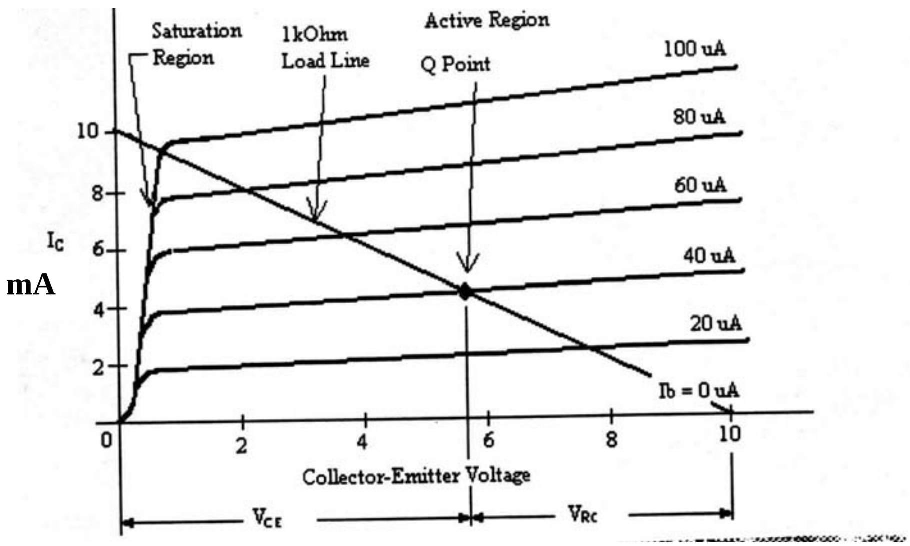


Figure 6.4: Load-line construction and analysis.

The operating point on the load-line, also called the Quiescent or Q point, is the BJT output set point. It is determined by the input circuit. If the input current is not zero (I_B = 40 μA, say), then the operating point is set at a point in the active region between cutoff and saturation. If the input is an open circuit (I_B = 0 μA), then the BJT output is set at the value V_{CC}. The BJT is "cutoff" because I_C is essentially zero and all of V_{CC} appears across the transistor collector-emitter terminals. The BJT is "saturated" if I_C reaches its maximum value along the load line (I_B > 100 μA). Therefore, the transistor can be operated as an OFF switch with I_B = 0 μA and as an ON switch with I_B = 100 μA.

To operate the BJT as an amplifier, it is necessary to set the operating point in the active region. In this case, small signal input voltages (or base currents) will not cause the output voltages (or collector currents) to be distorted due to excursions into the cutoff or saturation regions. The Q point, which specifies the BJT output (i.e., the voltage V_{CE} and current I_C), is determined by the intersection of the load-line and corresponding value of the base current I_B. The value of I_B is controlled by the input circuit (which is R_B and V_{BB} in the CE configuration shown in Fig. 6.3(a)).

6.3.3 DC Equivalent Circuit

The base current can be determined by using the DC model shown in Figure 6.5. This equivalent circuit is used to approximate the operation of the BJT in its normal active region. It should be noted that the use of this equivalent circuit requires that the BJT be in its normal active region. This means that the base to emitter junction must be forward biased and the base to collector junction must be reversed biased.

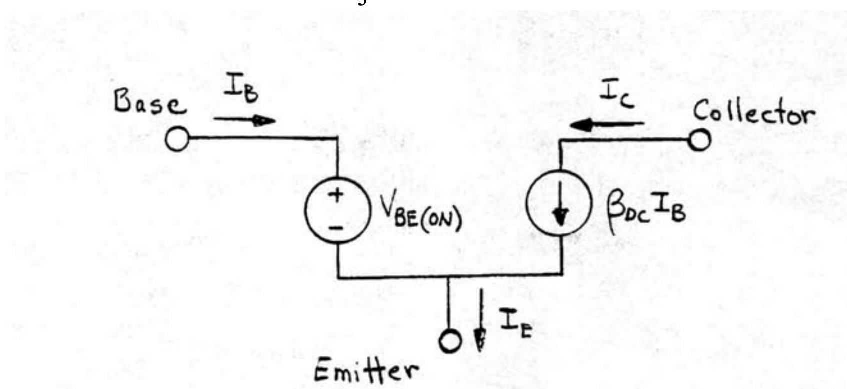


Figure 6.5: DC model for BJT in normal active region.

Since the base-to-emitter of the BJT is forward biased, it can be represented by a forward biased junction diode with voltage drop $V_{BE(ON)}$. The reversed-biased collector-to-emitter junction is assumed to be an ideal dependent current source with current equal to the DC current gain, β_{DC}, multiplied by the value of the base current, I_B. Substituting this equivalent circuit for the BJT in the CE configuration shown in Figure 6.3a results in the circuit shown in Figure 6.6. This circuit can now be analyzed to determine the value of the base current. Using KVL for the base circuit yields

$$-V_{BB} + I_B R_B + V_{BE(ON)} = 0 \quad . \tag{6.6}$$

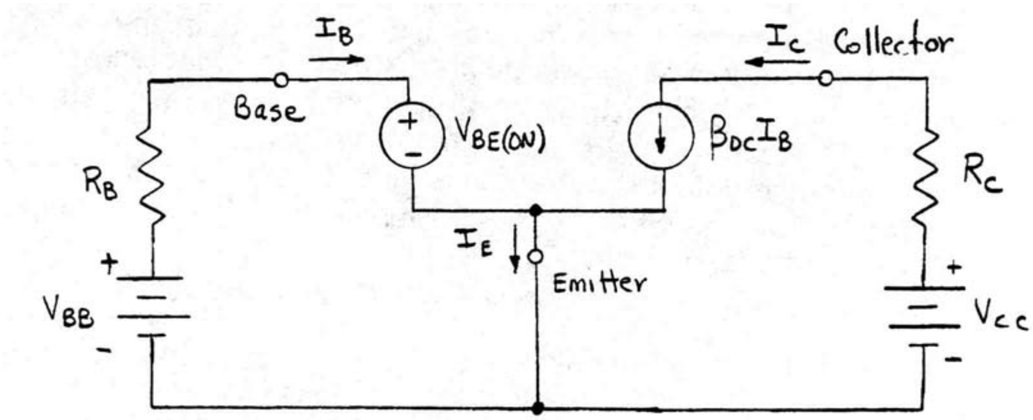


Figure 6.6: CE equivalent circuit for BJT in normal active region

Solving for I_B yields

$$I_B = \frac{V_{BB} - V_{BE(ON)}}{R_B} \,. \tag{6.7}$$

Normally, $V_{BE(\,ON)}$ is assumed to be 0.7 volts for a silicon BJT. If we assume V_{BB} = 4 volts and R_B = 82 KΩ, then,

$$I_{BQ} = \frac{4 - 0.7}{82\ k\Omega} \approx 40\mu A \tag{6.8}$$

Examining Figure 6.4 shows that the Q point for the BJT is where the I-V curve for I_B = 40 μA intersects the 1KΩ load-line. The value of I_{CQ} and V_{CEQ} are now easily determined from the IV coordinate values of the Q point. In this case, the value of I_{CQ} is approximately 4.4 mA and V_{CEQ} is approximately 5.6 volts. Notice that the value of β_{DC} can also be determined graphically once the Q point is established. From the definition of β_{DC} provided in Eq. (6.3), it follows that β_{DC} = (4.4 mA)/(40μA) = 110 for this example.

The value of the collector current (I_C) and collector to emitter voltage (V_{CE}) can also be determined using the DC model substituted for the BJT as shown in Figure 6.6. Applying KVL to the output circuit yields

$$-V_{CC} + I_C R_C + V_{CE} = 0 \quad . \tag{6.9}$$

Solving for I_C gives

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} \tag{6.10}$$

Solving for V_{CE} gives

$$V_{CE} = V_{CC} - I_C R_C \; . \tag{6.11}$$

From Eq. (6.3) we know that

$$I_C = \beta_{DC} I_B \; . \tag{6.12}$$

Substituting into Eq. (6.11) above gives

$$V_{CE} = V_{CC} - (\beta_{DC} I_B) R_C \quad . \tag{6.13}$$

Continuing with our example, it follows that I_{CQ} = (110) (40 μA) = 4.4 mA and V_{CEQ} = 10 - (4.4) (1) = 5.6 V using the DC Model.

6.3.4 AC or Small Signal Equivalent Circuit

In order to analyze the operation of the BJT as an amplifier, an AC (or small signal) equivalent circuit is utilized. A widely used small signal circuit model is called the Hybrid-π model and is shown in Figure 6.7. Use of this small signal model assumes the BJT is operating in its normal active region; that is, it is biased at a Q point in the active region and provides an equivalent circuit for small changes in voltage and current around the Q point.

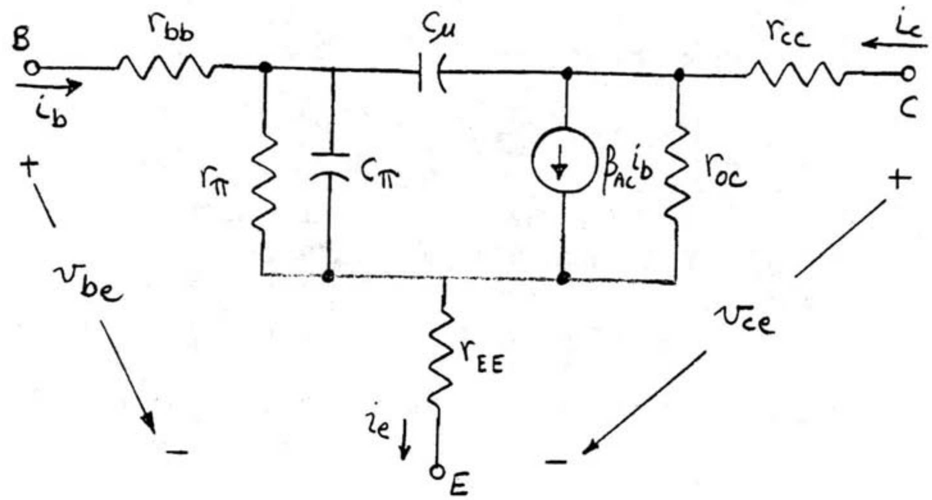


Figure 6.7: Hybrid-π model for BJT.

In this equivalent circuit, r_{bb}, r_{ee}, and r_{cc} represent the ohmic resistance of each region. Thus, r_{bb} is the resistance of the thin base region, r_{ee} is the resistance of the emitter region, etc. Typical values of these ohmic resistances are:

r_{bb} = 20 to 200 Ω

r_{ee} = 0.5 to 5Ω

r_{cc} = 10 to 100Ω .

The resistance r_π represents the small signal or AC resistance of the forward- biased base-ernitter junction. C_π is the space-charge capacitance of the base- emitter junction plus the diffusion capacitance of the injected carriers while C_μ is the space-charge capacitance of the reversed-biased collector-base junction. Finally, the resistance r_{oc} is the effective small signal output resistance from the collector to emitter and β_{AC} represents the small signal or AC current transfer ratio between the collector and the base. At low frequencies, the capacitive reactances of C_π and C_μ are large and can be neglected. In addition, the values of the ohmic resistances, i.e., r_{bb}, r_{ee} and r_{cc}, can often be ignored. This results in a simplified small signal model, which can be used for low frequency analysis, and is shown in Figure 6.8. Notice that the polarity of the AC currents (i_b, i_c, and i_e) and the AC voltages (V_{be}, V_{ce}) are assumed as shown in Figure 6.8.

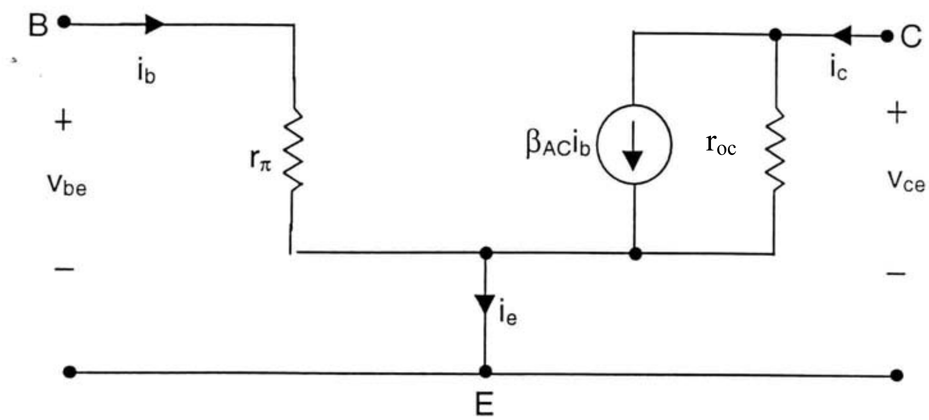


Figure 6.8: Low frequency hybrid-π model for a BJT

Each of the parameters of Fig. 6.8 can be determined for a given BJT. To do this, we need to take into account the effects of small variations around the dc operating point (or Q point). First, we determine the small-signal resistance of the base-emitter junction. Viewed from the base side, it follows that

$$r_\pi = \left.\frac{\Delta v_{BE}}{\Delta i_B}\right|_{v_{CE} = \text{const.}(V_{CEQ})} \quad (6.14)$$

and it can be shown that

$$r_\pi = \frac{\beta_{AC} V_T}{I_{CQ}} \quad (6.15)$$

where V_T is the thermal voltage and depends only on the base-emitter junction temperature. V_T is defined by

$$V_T = \frac{kT}{q} \tag{6.16}$$

where k = Boltzmann's constant = 1.38×10^{-23} J/K

T = absolute temperature, K = 273 + temperature in deg. C.

q = electron charge = 1.602×10^{-19} Coulomb

At normal room temperature, V_T = 26 mV. Thus, at 27° C.,

$$r_\pi = \frac{\beta_{AC}(26mV)}{I_{CQ}}. \tag{6.17}$$

Thus, r_π can be determined from the Q point, the junction temperature of the transistor, and the value of β_{AC} for the transistor.

From the small signal circuit model in Figure 6.8 we see that a small change in current at the input to the transistor (i.e., the base current, i_b) will result in a change of the current at the output of the transistor (i.e., the collector current, i_c). These two current changes are related by the small signal current gain of the transistor, β_{AC}. So,

$$i_c = \beta_{AC}\, i_b + v_{ce}/r_{OC}\,. \tag{6.18}$$

The AC current gain can be determined by

$$\beta_{AC} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_{V_{CE}=V_{CEQ}=\text{const}} \tag{6.19}$$

Finally, the effective output resistance inherent in the transistor from the collector to the emitter is determined as

$$r_{OC} = \left.\frac{\Delta v_{CE}}{\Delta i_C}\right| I_B = I_{BQ} = \text{const.} \tag{6.20}$$

Using the above and analyzing the characteristic curve and Q point from Figure 6.4

$$\beta_{AC} = \left.\frac{(6.7-2.3)mA}{(60-20)\mu A}\right|_{v_{CE}=V_{CEQ}\approx 5.6V} = \frac{4.4mA}{40\mu A} = 110 \qquad (6.21)$$

and

$$r_{OC} = \left.\frac{(9-1)V}{(4.8-4.0)mA}\right|_{i_B=I_{BQ}=40\mu A} = \frac{8V}{0.8mA} = 10k\Omega \quad . \qquad (6.22)$$

The operation of the CE amplifier shown in Figure 6.3a, as a result of applying a small AC signal to the input, can now be analyzed using our small signal model. Assume a 3.3 volt peak-to-peak sinusoidal signal is placed in series with V_{BB} as shown in Figure 6.9. In this case, a sinusoidal voltage v_{in} = 1.65 V sin(ωt) is applied in addition to the DC voltage V_{BB}.

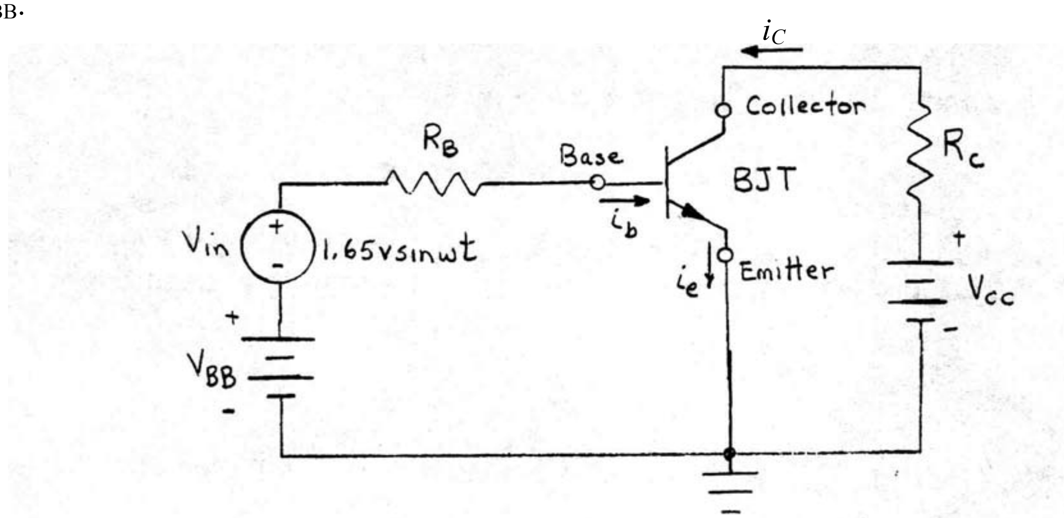


Figure 6. 9: Sinusoidal signal input voltage.

In order to analyze the circuit, the small signal model is substituted into the circuit in place of the BJT and the DC voltages are eliminated as shown in Figure 6.10.

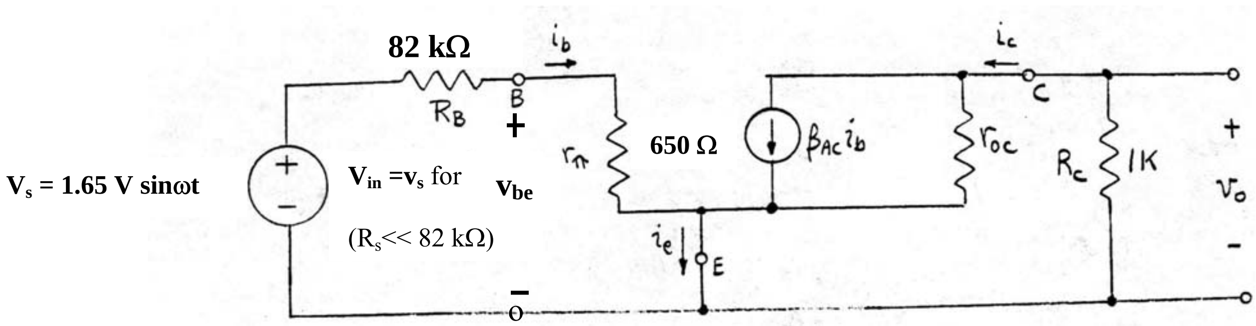


Figure 6.10: Small signal equivalent circuit

It follows using KVL that

$$v_0 = -i_C R_C = -\beta_{AC}\, i_b\, (R_C \,||\, r_{OC}) \tag{6.23}$$

and

$$v_{in} = i_b\, (R_B + r_\pi) \tag{6.24}$$

Therefore,

$$\frac{v_0}{v_{in}} = \frac{-\beta_{AC} i_b (R_C \,||\, r_{OC})}{i_b (R_B + r_\pi)} = \frac{-\beta_{AC}(R_C \,||\, r_{OC})}{R_B + r_\pi} \;. \tag{6.25}$$

Substituting values into Eq. (6.25) yields

$$\frac{v_0}{v_{in}} = \frac{-110(1k \,||\, 10k)}{(82\ k + 0.650k)} = \frac{-100}{82.65} \approx -1.21 \;. \tag{6.26}$$

It follows that the output voltage is given by

$$v_0 = -1.21\ v_{in} = (-1.21)\ (1.65\text{ V } \sin \omega t\,) \approx 2.0\text{ V } \sin \omega t \;. \tag{6.27}$$

The output voltage swing can also be determined from the IV characteristic curve and Q point shown in Figure 6.4. The variation of the total base current, i_B, is given by

$$i_B = I_B(\text{DC}) + i_b(\text{AC}) \;. \tag{6.28}$$

We have already determined that I_B(DC)) = I_{BQ} = 40μA from the Q point. The AC component of the base current is given by

$$i_b(AC) = \frac{v_{in}}{(R_B + r_\pi)} = \frac{1.65V \sin \omega t}{82.65k} \approx 20 \sin \omega t \qquad \mu A \tag{6.29}$$

It follows that the base current changes ± 20μA (or 40μA peak-to-peak). Thus, during the positive half cycle, the base current changes from 40μA to 60μA and during the negative halt cycle, it changes from 40μA to 20μA. Plotting this change on Figure 6.4 and moving along the 1 KΩ load-line results in a value of $i_C \approx$ 6.4mA for i_B = 60μA and $i_c \approx$ 2.4mA for i_B = 20μA. Thus, $V_0 = V_{ce}$ changes from approximately 3.7V to 7.5V which represents a 3.8 V peak-to-peak voltage output or Vo = -1.9V sin ωt where the minus sign represents the 180° phase shift between the input and output voltages.

6.3.5 Switching Times

The transistor switch cannot respond instantaneously to a turn-on or a turn-off signal. In many applications, it is important to be aware of the magnitude of possible errors caused by a time delay in the switching circuit and how to minimize the time lags. In Figure 6.11, the response of a transistor switching circuit is shown when a turn-on and turn-off signal V_B is applied to the input circuit.

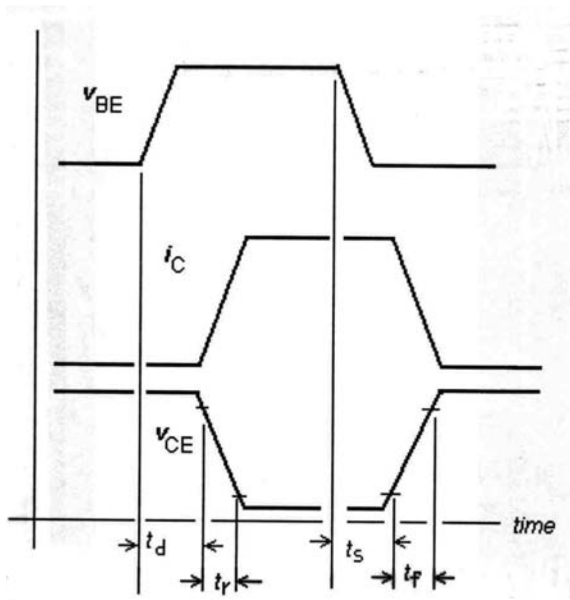


Figure 6.11(a) Transistor Switching Times

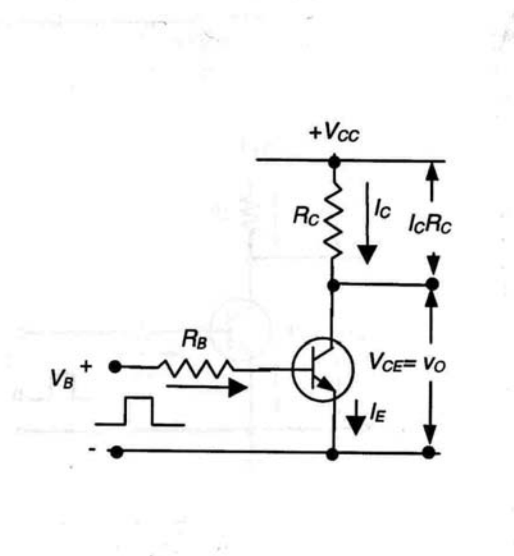


Figure 6.11(b) Transistor Switching Circuit

Each segment of the turn-on and turn-off times will be considered briefly. First, there is a delay time, t_d. The base-emitter input capacitance must charge through R_B before the base-emitter junction is actually forward biased; there is a finite transit time for the first minority carriers to cross the base region; and some time is required for the collector current to reach 10% of its final value.

Next, there is the rise time, t_r. This is the time needed to establish the concentration of minority carriers in the base region (i.e., the electron density in the p-type base of the npn transistor), which is required to carry 90% of the final value of I_C. The combination of t_d and t_r is the turn-on time, t_{ON} . The rise time can be substantially reduced if the base current is larger than the minimum needed for saturation.

Assuming now that the signal was of sufficient duration and magnitude to saturate the transistor, it is important to consider the turn-off behavior. First, there is the storage time, t_s. This is the time necessary to clear the collector-base junction of excess minority carriers and to decrease I_C to 90% of its maximum value.

The fall time, t_f, is the time required for the output current to fall from 90% to 10% of its maximum value, and depends on the time required to discharge the collector-emitter capacitance and the time required for the minority carriers in the base to be collected. The combination of t_s and t_f is the turn-off time t_{OFF}. These switching times are usually measured by comparing V_{CE} to V_B on a dual-trace oscilloscope. Depending upon the transistor and the measurement apparatus, it may not be possible to determine all four switching times individually.

6.4 EXPERIMENTAL PROCEDURE

6.4.1 BJT Curve Tracer Analysis

You will be provided with a npn BJT and should first produce a copy of the transistor's characteristics using the Tektronix 571 Curve Tracer. Your laboratory instructor will provide an overview regarding the operation and settings to use on the curve tracer.

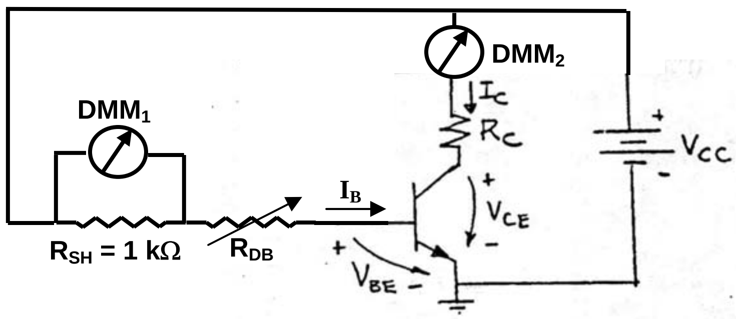
(a) With an R_C and V_{CC} as specified by your laboratory instructor, and a grounded emitter, draw the corresponding load-line on your copy of the transistor's characteristic curve. Determine and record an appropriate "Q" point along the load-line for "midpoint biasing" that is a good approximation for operation as a minimum distortion amplifier. Specify I_{CQ}, V_{CEQ}, and I_{BQ} for your Q point. (Note: I_{BQ} is determined by multiplying the base current per step indication by the number of steps you count from cutoff to the desired Q point ***using interpolation*** *for the distance between two base steps.)*

(b) Determine and record β_{DC}, β_{AC}, and r_{OC} using graphical techniques and Equations (6.3), (6.19) and (6.20), respectively.

(c) Finally, determine and record the value of i_B required to switch the BJT from cutoff to saturation along the load-line determined in (a) above.

6.4.2 BJT DC Bias Model and Measurements

Measurements of the DC bias characteristics can best be made using the circuit shown in Figure 6.12 below:



$R_B = R_{SH} + R_{DB}$

$I_B = V_{DMM1}/R_{SH}$

For R_{SH} = 1 kΩ,

$I_B = 0.001V_{DMM1}$

Figure 6.12 DC Bias Measurement Circuit

(a) Construct this circuit with the values of R_C and V_{CC} used in 6.4.1 above, a shunt resistor R_{SH} = 1 kΩ, and a decade box with **R_{DB} = 999,999 Ω**. Now adjust R_{DB} until the BJT is biased at the V_{CEQ} point previously defined in 6.4.1 (a) above. Note that on any mV scale, DMM_1 reads I_B directly in μA. At this point, take appropriate measurements of I_{BQ} and I_{CQ} and compute the value of β_{DC} using Equation (6.3). Also measure V_{CC}, V_{BEQ}, and V_{CEQ} using a third DMM and record these voltages.

(b) Using the DC model for the transistor, compute the value of R_B required to saturate the transistor. Note that $R_B = R_{SH} + R_{DB}$. Now, change the value of the decade resistor box used for R_{DB} slowly in about 5 increments between the Q point value and the saturation value and record the value of I_B, I_C and V_{CE} at each point. Continue to decrease R_{DB} until you have reached saturation, i.e., constant I_C, but **don't overdrive** the BJT.

(c) Now open the base connection so that $I_B = 0$ and measure the leakage current with the DMM set to the 200μA scale.

6.4.3 BJT Small Signal Equivalent Circuit Parameter Measurements

Measurement needed to calculate the small signal equivalent circuit parameters can best be made by connecting the BJT as shown in Figure 6.13 below.

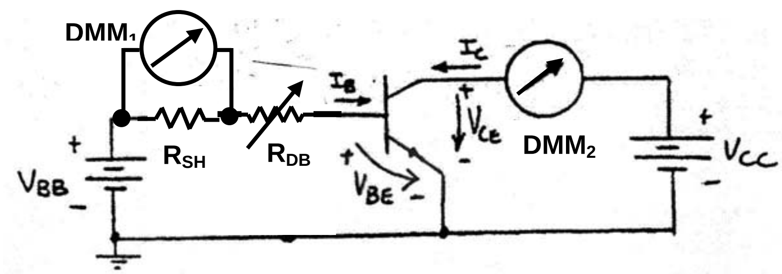


Figure 6.13 Small Signal Parameter measurement Circuit

As indicated, one DC supply is to be used to provide the input voltage V_{BB} to the base through a shunt resistor R_{SH} of 1 kΩ and a decade box **R_{DB} with resistance set to 470 kΩ**. A second DC supply is to be used to supply the collector voltage V_{CC} directly without any collector resistor. Note that DMM_1 is used to measure the base current I_B. Note also that on any mV scale, DMM_1 measures base current I_B directly in μA. The second DMM is to be used to measure the collector current I_C directly in mA. A third DMM (not shown) is used to measure V_{CE} or V_{BE}, as required.

Bias the BJT at the Q point determined in 6.4.1 (a) by setting V_{CE} equal to V_{CEQ} by adjusting V_{CC}. Now adjust V_{BB} to get the desired I_{CQ}. Measure I_{BQ} and calculate the value of β_{DC}. Compare this value the β_{DC} obtained in 6.4.2(a) above. Is it the same?

(a) Determine and record data needed to calculate β_{AC} and r_π using Equations (6.19) and (6.14), respectively, by adjusting V_{BB} to obtain approximately ±20% changes in I_B around the Q point value and measuring the resultant changes in I_C and V_{BE}.

(b) Reset V_{BB} to obtain I_{CQ}. Now determine and record data needed to calculate r_{OC} using Eq. (6.20) by changing V_{CE} ± 20% around the Q point and measuring the resultant changes in I_C. Note and record any change in I_B and V_{BE}.

6.4.4 BJT Square Wave Testing

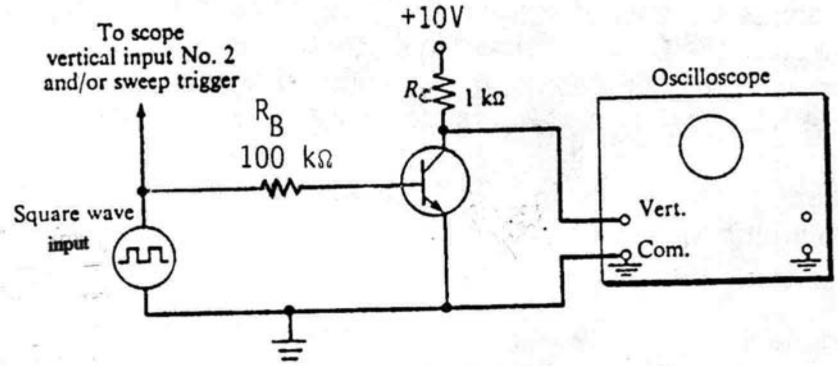


Figure 6.14: Square wave testing circuit

Connect the BJT as indicated in Figure 6.14 with R_B equal to 100 kΩ, V_{CC} equal to +10 volts, and R_L equal to 1 kΩ.

(a) Set the amplitude and DC offset on the square-wave generator to drive the transistor from cutoff to saturation. This is best obtained by setting the peak to-peak (p-p) value of the function generator output to its minimum value and adjusting the DC offset so the BJT is biased at a Q point with V_{CE} = 5 Volts. Now increase the p-p output value to the level required to drive the transistor from cutoff to saturation. Recall that since all BJTs are cutoff at I_B = 0, make sure that the square-wave goes from zero to the proper polarity and value of V_B to drive the transistor into saturation. Measure and record values of delay, rise, storage, and fall times as indicated in Figure 6.11(a) and make a sketch of the waveforms observed on the oscilloscope.

(b) Next, set V_B to about one-half of the value required to drive the BJT into saturation so Q remains in its active region, and measure and record t_{ON} and $t_{OFF.}$ You do not need to individually measure t_d , t_r , t_S , and t_f , just t_{ON} and t_{OFF} .

6.5 REPORT

6.5.1 Attach your transistor characteristics showing construction of the load-line per 6.4.1 (a) and the Q point. Identify the values for I_{BQ}, V_{CEQ}, and I_{CQ}.

6.5.2 Show your work in determining β_{DC}, β_{AC}, and r_{oc} per 6.4.1 (b). Per 6.4.1 (c), indicate the value of $I_{B,}$ obtained from the characteristic curve, that is needed to saturate the BJT . Also, compute the value of r_π using Equation (6.15).

6.5.3 Using your measurements from 6.4.2(a), determine the values of I_{BQ}, I_{CQ}, and β_{DC}. Compare these to those obtained from the characteristic curve in 6.4.1 (b).

6.5.4 Show your computations of the value of R_B required to drive the BJT to the edge of saturation in 6.4.2(b). Make a table illustrating the measurements of V_{CE} and I_C as the value of R_B is decreased from the Q point value to the saturation value.

6.5.5 Describe the measurements you made and the value obtained for the leakage current in 6.4.2(c).

6.5.6 Using the measurements from 6.4.3, determine the values of β_{AC}, r_{π}, and r_{oc}. Compare the value of β_{AC} and r_{oc} with the values obtained from the characteristic curve in 6.4.1 (b). Finally, compare the value of r_π obtained using the measurements to that obtained using Eq. (6.15).

6.5.7 Insert your measured parameters for the BJT into Figure 6.10 and determine the small signal output voltage across the 1 kΩ resistor for a 2 mV peak-to-peak sinusoidal input voltage, i.e., V_{in} = 1 mV sin(ωt).

6.5.8 Sketch the waveform observed on the oscilloscope when the BJT is driven into saturation and cutoff and indicate t_d, t_r, t_s, and t_f, respectively. What is t_{ON} and t_{OFF} for this case? What is t_{ON} and t_{OFF} when Q remains in its active region? Compare these values to the previous values.

6.5.9 Design problem:

There is a need for a test fixture at in the Electrical Laboratory at WU for testing 2N2222A npn transistors for adequate current gain. Specifications are:

$\beta_{DC} \geq 150$ for

$I_{BQ} = 25\mu A$ and

$V_{CEQ} \leq 5$ Volts.

The transistor is to be accepted if it meets the above criteria; rejected if it fails.

Using only one DC power supply and whatever resistors, lamps, relays, and auxiliary transistors you may need, design the electrical circuit needed to provide a "go - no go" test for high gain npn transistors. To simplify matters, assume that relays are available with operating coils that have high resistance and, therefore, draw negligible current and that pull-in of the relay contacts occurs when the voltage across the coil ≥ 5 Volts DC. Also, assume that green and red light emitting diodes (I_F = 10 mA & V_F = 1.5 V) are available for use as "go" (green) and "no go" (red) indicators.

Document your design as follows:

6.5.9.1 Briefly describe your design process,

6.5.9.2 Provide a circuit diagram for the transistor test circuit,

6.5.9.3 Define all component values needed for the test circuit.

6.6 REFERENCES

6.1 Sedra, Adel S. and Smith, Kenneth C., **Microelectronic Circuits,** 5th Edition, Oxford University Press, New York, 2004

6.2 Ben G. Streetman, **Solid State Electronic Devices**, 2nd Ed. (Prentice-Hall, Englewood Cliffs, NJ, 1980).

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6.4 Maimstedt, H. V., Enke, C. G., Crouch, S. R., **Control of Electrical Ouantities In Instrumentation,** (Benjamin, Menlo Park, NJ, 1973).

6.5 Sifferien, T. P., and Vartanian, V., **Digital Electronics**, (Prentice-Hall, Englewood Cliffs, NJ, 1970).