Resistors and Bipolar Transistors

3.1 Objectives

In this lab, you will examine the current–voltage characteristics of an *npn* bipolar transistor, which closely follows an exponential current–voltage relationship over many decades of current. You will also examine the current–voltage characteristics of an *npn* bipolar transistor with a resistor connected in series with the emitter. You will also examine the voltage transfer characteristics of two simple voltage amplifiers made from a single bipolar transistor and resistors.

3.2 Prelab

The following prelab questions have been constructed to help you prepare to do the lab efficiently. Please complete these questions *before* you come to lab. While you may discuss the prelab questions with your lab partner or with other students in the class, each student in a lab group should complete the prelab assignment individually, so that you each understand the circuit(s) that you will be testing and what you will be doing in the lab.

1. **Forward-Active Bipolar Transistor Characteristics**. The *npn* bipolar transistor comprises two *p*-*n* junctions, the *base-emitter junction* and the *base-collector junction*, that share a common *p*-type region, the base, as shown in Fig. 3.1a. Fig. 3.1b shows a corresponding circuit schematic symbol for such a device. In many circuits involving *npn* transistors, we arrange things so that the base-emitter junction is *forward biased* (i.e., $V_\mathrm{b} > V_\mathrm{e}$) and that the base-collector junction is *reversed biased* (i.e., $V_\mathrm{b} \leq V_\mathrm{c}$). When an *npn* bipolar transistor is operating under these conditions, we say that it is in the *forward-active* mode of operation. In this regime, the collector current, I_c, is nearly independent of the collector voltage, V_c, and it is exponential in the base-emitter voltage over many decades of current, given by

$$I_\mathrm{c} = I_\mathrm{s} e^{V_\mathrm{be}/U_\mathrm{T}} = I_\mathrm{s} e^{(V_\mathrm{b}-V_\mathrm{e})/U_\mathrm{T}},$$

where I_s is the collector saturation current and U_T is the thermal voltage, which are the same as the ones that you encountered in Lab 2. The base current, I_b, is proportional to the collector current, given by

$$I_\mathrm{b} = \frac{I_\mathrm{c}}{\beta} = \frac{I_\mathrm{s}}{\beta} \cdot e^{V_\mathrm{be}/U_\mathrm{T}} = \frac{I_\mathrm{s}}{\beta} \cdot e^{(V_\mathrm{b}-V_\mathrm{e})/U_\mathrm{T}},$$

where β is the *common-emitter current gain* of the transistor, which is typically on the order of 100. Likewise, the emitter current, I_e, is proportional to the collector current,

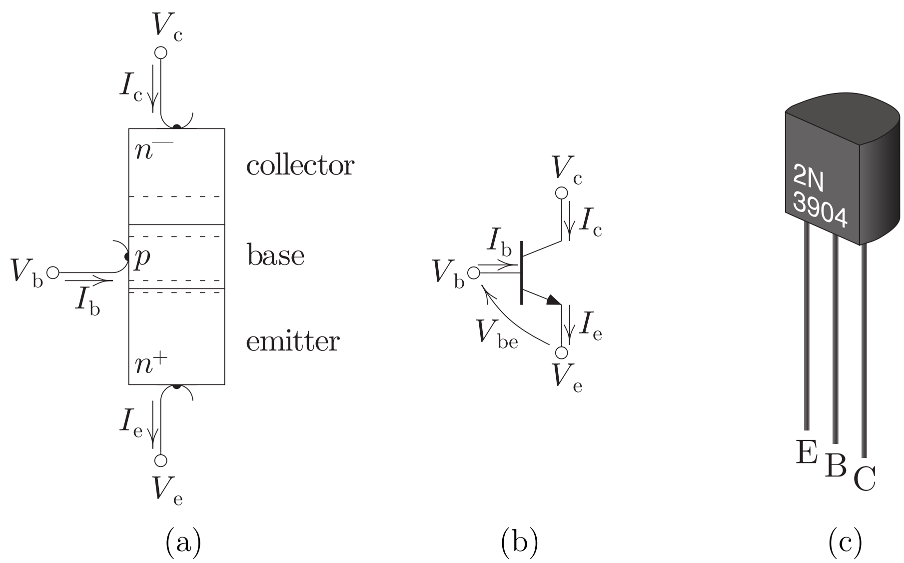

Figure 3.1: Emitter, base, and collector terminal voltages and currents of an *npn* bipolar transistor in (a) a schematic representation of the physical device structure and (b) a circuit schematic symbol. Part (c) shows these terminal locations on a 2N3904 signal transistor in a TO-92 package.

given by

$$I_e = \frac{I_c}{\alpha} = \frac{I_s}{\alpha} \cdot e^{V_{be}/U_T} = \frac{I_s}{\alpha} \cdot e^{(V_b - V_e)/U_T},$$

where α is the *common-base current gain* of the transistor, which is typically slightly less than unity (e.g., 0.98). The emitter, base, and collector currents also related to one another through

$$I_e = I_c + I_b.$$

(a) Using these relationships among the currents, find a relationship between the two current gains, α and β.

(b) Find an expression for the incremental resistance of the base terminal, r_b, which is given by

$$r_b = \frac{\partial V_b}{\partial I_b},$$

in terms of the base current, I_b.

(c) An incremental *transfer conductance* or *transconductance* gain (sometimes also called a *mutual conductance*, denoted by g_m, of a circuit or a device is a measure of by how much a given current changes in response to a small change in a voltage at some other location in the circuit or device. For an *npn* bipolar transistor, we shall take the incremental transconductance gain to be defined as

$$g_m = \frac{\partial I_c}{\partial V_b}.$$

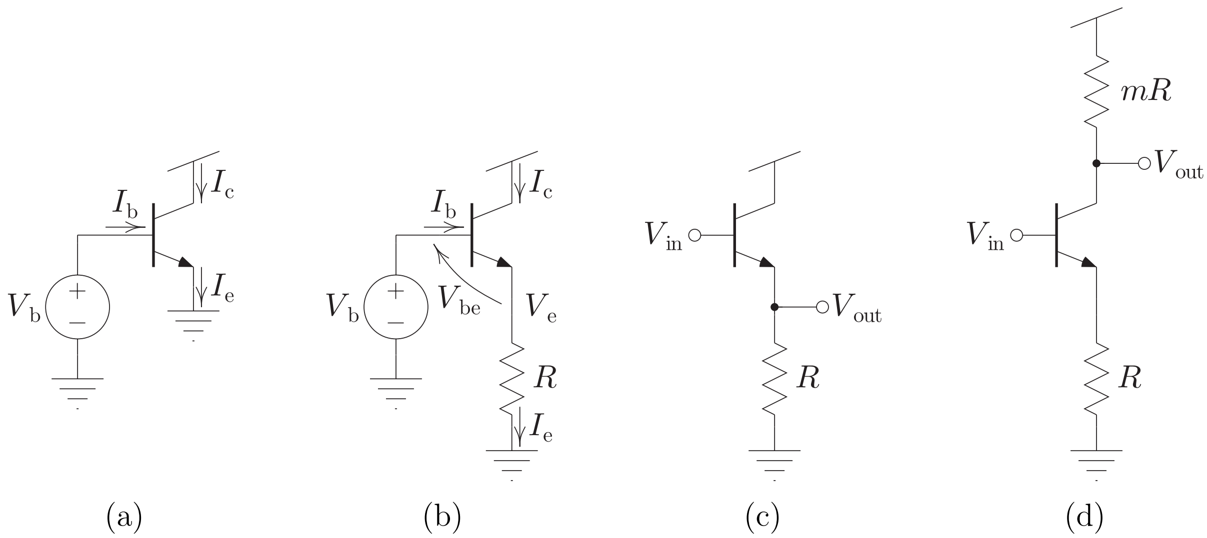

Figure 3.2: Various circuits involving an *npn* bipolar transistor and resistors, including (a) a bipolar transistor, (b) a bipolar transistor with an emitter-degeneration resistor, (c) an emitter-follower, and (d) an inverter.

Find an expression for g_m in terms of the collector current, I_c.

(d) How are r_b and g_m related to each other?

2. **Emitter-Degenerated Bipolar Transistor**. Consider the circuit shown in Fig. 3.2b comprising an *npn* bipolar transistor and a resistor, R, connected between the emitter and ground. Such a resistor is called an *emitter-degeneration* resistor, becasue it limits or *degenerates* the transconductance gain of the transistor forcing the emitter voltage change whenever the base voltage does, which has the effect of reducing the effectiveness of the base terminal at changing the collector current.

   (a) Find an expression for the incremental base resistance of the emitter-degenerated bipolar transistor shown in Fig. 3.2b. Express your answer as a function of the base currnet, I_b.

   (b) Find an expression for the incremental transconductance gain of the emitter-degenerated bipolar transistor shown in Fig. 3.2b. Express your answer as a function of the collector current, I_c.

   (c) Suppose that we increase V_b in the circuit of Fig. 3.2b by a small amount, δV_b, resulting in a small change in V_e. Find an expression for the resulting δV_e.

   (d) Let us define the *turn-on current* of the transistor, I_{on}, as the collector current at which the change in the V_e is just half the change in V_b. Find an expression for I_{on} as a function of R.

   (e) Let us define the *turn-on voltage* of the transistor, V_{on}, as the base-emitter voltage of the transistor when the collector current is I_{on}. Find an expression for V_{on} as a function of I_{on}.

(f) Suppose that we would like to find the relationship between the collector current, I_c, and the applied base voltage, V_b for the circuit of Fig. 3.2b. Apply KCL to the emitter node to find a nonlinear relationship that holds between V_b and V_{be}. You would have to invert this relationship to eliminate the emitter voltage from the description. Express your relation in terms of V_{on} and U_T.

(g) What approximation can you make to invert the relationship that you found in part (f) when $V_{be} < V_{on}$ by more than a few U_T? In this regime, find an expression relating I_c to V_b.

(h) What approximation can you make to invert the relationship that you found in part (f) when $V_{be} > V_{on}$ by more than a few U_T? In this regime, find an expression relating I_c to V_b.

3.3 Experiments

You will be doing four experiments in this lab. In the first experiment, you will be examining the current–voltage characteristics of an *npn* bipolar transistor. In the second experiment, you will be looking at how these characteristics change when you connect a resistor in series with the emitter. In the third experiment, you will examine the voltage transfer characteristics of a single-transistor voltage buffer made from a bipolar transistor, which is called an *emitter follower*, because the output voltage (i.e., the emitter voltage) follows the input voltage (i.e., the base voltage). Finally, in the fourth experiment, you will examine the voltage transfer characteristics of a simple inverting voltage amplifier made from a single bipolar transistor, which is called an *inverter* or a *common-emitter amplifier*. As you did in Lab 2, you will be using a 2N3904 *npn* bipolar transistor for this lab, whose pinout is shown in Fig. 3.1c.

In your lab report, you should include graphs of all theoretical and experimental curves. In general, you should plot the measurements in a point style so the individual points are distinguishable. Any theoretical fits to the data should be plotted on the same graph as the experimental data in a line style.

3.3.1 Experiment 1: Bipolar Transistor Characteristics

Obtain the `lab3.zip` file, which contains measured base and collector currents as a function of base voltage with the collector held at +5 V, as shown in Fig. 3.2a. The measured collector current spans a range from about 1 nA to about 10 mA. Make a single semilog plot showing both the collector current and base current as a function of base voltage (i.e., a Gummel plot) along with appropriate theoretical fits and extracted parameter values. Does the collector current follow an exponential relationship with the base voltage?

Plot the current gain, β, which is defined as the ratio of the collector current to the base current, as a function of the base current (you should make the base-current-axis logaritmic for this plot). Is the current gain constant with base current? If not, under what circumstances would it be reasonable to assume it to be constant? Extract the incremental base resistance, r_b, from your base current–voltage characteristic and make a log-log plot of r_b versus I_b along with an appropriate theoretical fit. Does the theoretical fit match the data? Extract the incremental transconductance gain, g_m, of the bipolar transistor from your collector-current/base-voltage transfer characteristic. Make a log-log plot of g_m versus I_c along with an appropriate theoretical fit. Does the theoretical fit match the data?

Repeat this experiment in LTspice. In your report, include a schematic of your LTspice set-up. In your report, you only need to include the Gummel plot and the plot of transconductance gain vs collector current from your simulation results along with appropriate fits. How do your simulations results generally compare to the measured data?

3.3.2 Experiment 2: Emitter-Degenerated Bipolar Characteristics

Next, for at least three resistor values that span at least two orders of magnitude and the least of which is at least $100\,\Omega$, simulate the current–voltage characteristics of an emitter-degenerated 2N3904, as shown in Fig. 3.2b. Sweep the base voltage from ground to $+5\,\mathrm{V}$. In your report, include a schematic of your LTspice set-up. As with the resistor in series with the diode-connected transistor that you examined in Lab 2, you should observe two qualitatively distinct regions of operation. Make a single semilog plot showing collector current versus base voltage for all of the resistor values that you used along with the collector characterisic and theoretical fit that you obtained in Experiment 1. For each resistor value, make a linear plot of collector current as a function of base voltage along with an appropriate theoretical fit. For each of these plots, are the fit parameters consistent with the resistor values and the transistor's collector characteristics?

For each resistor, extract the incremental resistance of the base terminal, R_b, with emitter degeneration from the base current–voltage characteristics. Make a single log-log plot showing R_b as a function of I_b along with appropriate theoretical fits. Do the theoretical fits match the data? Also, for each resistor, extract the incremental transconductance gain of the transistor with emitter degeneration, G_m, from the collector characteristics. Make a single log-log plot showing G_m as a function of I_c, along with appropriate theoretical fits. Do the theoretical fits match the data?

3.3.3 Experiment 3: Follower Voltage Transfer Characteristics

The circuit that you investigated in Experiment 2 is often used as a simple voltage buffer, which is commonly called an *emitter follower*. In this context, the transistor's base voltage is the circuit's input and the transistor's emitter voltage is its output, as shown in Fig. 3.2c. In this configuration, the emitter voltage *follows* the base voltage's lead, whence its name. This circuit is also called a *common-collector amplifier* by those with a penchant for circuit taxonomy, because the collector terminal is at a common potential (i.e., a possible reference level shared by the input and output voltages). For one of the resistor values that you used in Experiment 2, measure the emitter follower's output voltage as you sweep its input voltage from ground to $+5\,\mathrm{V}$. In your report, include a schematic of your LTspice set-up. Make a plot showing the emitter follower's *voltage transfer characteristic* (VTC), which is a plot of V_out as a function of V_in, along with a theoretical fit. What is the incremental voltage gain of the emitter follower? What is the difference between V_in and V_out for this circuit? What determines this voltage difference?

3.3.4 Experiment 4: Inverter Voltage Transfer Characteristics

Now, for at least three resistor values that are small integer multiples of the emitter resistor that you used in Experiment 3, simulate the VTC of the circuit shown in Fig. 3.2d. This circuit is commonly used as a simple inverting voltage amplifier, called an *inverter*. It is sometimes also called a *common-emitter amplifier* (with emitter degeneration). In this context, the base voltage again serves as the circuit's input the collector voltage is its output. In your report, include a schematic of your LTspice set-up. Make a single plot showing all of the VTCs along with appropriate theoretical fits. You should also include the emitter-follower VTC from Experiment 3 on this plot. For each collector resistor, what is the incremental voltage gain of the amplifier? What determines this voltage gain?

3.4 Postlab

In Experiment 4, you probably noticed that, as you increased the inverting amplifier's input voltage, its output voltage decreased at first (whence the name *inverting* amplifier). However, as the input voltage continued to increase, at some point, the output voltage stopped decreasing, turned around, and started increasing with increasing input voltage. In this postlab, you will be considering the reason for this curious behavior.

1. For each of the following bipolar transistor operating modes, provide the set of input voltages that you swept over for one of your inverter VTCs for which the transistor is in that mode. Note that it is possible that the transistor does not enter all of these modes—if the transistor never enters a particular mode, indicate that it does not do so.

   (a) Cut Off

   (b) Forward Active

   (c) Forward Soft Saturation

   (d) Deep Saturation

   (e) Reverse Soft Saturation

   (f) Reverse Active

2. Does the turn-around point correlate with a change of the transistor's operating mode? If so, identify the relevant modes. If not, what does the turn-around point correlate with?

3. For a bipolar transistor, we normally expect that the collector current is very nearly the same as the emitter current and that the base current is very compared to the emitter and collector currents. After the turn-around point, do the terminal currents behave in this expected way? If not, how do they instead behave?