ELEC 2210 EXPERIMENT 7
The Bipolar Junction Transistor (BJT)

Objectives:

The experiments in this laboratory exercise will provide an introduction to the BJT. You will use the Bit Bucket breadboarding system to build and test several DC transistor circuits. The objectives of this experiment include the following:

- Reinforce basic principles of BJTs from ELEC 2210
- Gain an understanding of BJT switching circuits
- Gain more experience with the Bit Bucket breadboarding system
- Continue to develop professional lab skills and written communication skills.

Introduction

A thorough treatment of BJTs can be found in Chapter 5 of the ELEC 2210 textbook, Microelectronics Circuit Design by R.C. Jaeger.

The acronym BJT stands for Bipolar Junction Transistor. BJTs are circuit elements that allow control of a working current by applying a control voltage. They are used primarily in switching circuits and amplifiers. This experiment will focus on the switching applications.

BJTs can be npn or pnp type. The BJT studied in this experiment is the 2N3904, which is an npn BJT with a maximum working current of 200 mA and a maximum power dissipation of 625 mW . The standard circuit symbol and notation for this type of transistor is shown in Fig. 1(a). The PSPICE circuit symbol is shown in Fig. 1(b).

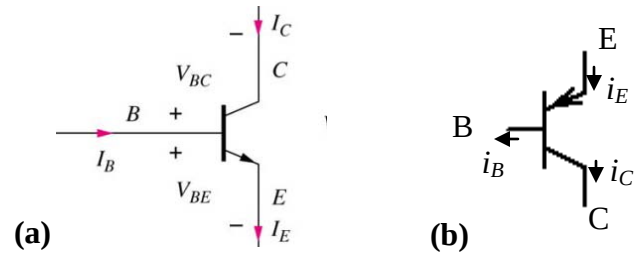


Figure 1. Circuit symbols and nomenclature for BJTs. (a) npn (b) pnp. Current conventions shown are those used in the textbook. However, PSPICE uses a different convention in which all currents are defined to be entering the device terminals.

There are three terminals indicated on the circuit symbols: C = collector, E = emitter, and B = base.

The commonly-used models of the npn BJT (not including breakdown or leakage currents) for the three most common operating regions are given in Table 1:

Table 1. Models of the npn BJT.

Region	Condition(s)	Equation(s)
Cutoff	Both junctions reverse-biased	$i_C = i_E = i_B = 0$
Forward Active	EBJ forward biased* CBJ reverse biased*	$i_C = I_S e^{\frac{v_{BE}}{V_T}}\left(1+\frac{v_{CE}}{V_A}\right)$ $i_B = \frac{i_C}{\beta_F}$ where $\beta_F = \beta_{Fo}\left(1+\frac{v_{CE}}{V_A}\right)$ $i_E = i_C + i_B = i_B(1+\beta_F)$
Saturation	Both junctions forward-biased	$v_{BE} \approx 0.75$ V, $v_{BC} \approx 0.70$ V, $v_{CE} \approx 0.05$ V $\beta_{forced} \triangleq \frac{i_C}{i_B} < \beta_F$

*EBJ = emitter-base junction, CBJ = collector-base junction

In these equations, there are three device parameters:

- I_S is the saturation current, which is proportional to the cross-sectional area of the base region.
- β_{Fo} is the forward current gain parameter. This is commonly denoted h_{FE} on data sheets.
- V_A is the Early voltage. It determines the slope of the BJT output curves in the forward active region. For an ideal device, V_A is infinity.

The output characteristics of a BJT with $\beta_{Fo} = 25$ and $V_A = \infty$ are shown in Fig. 2.

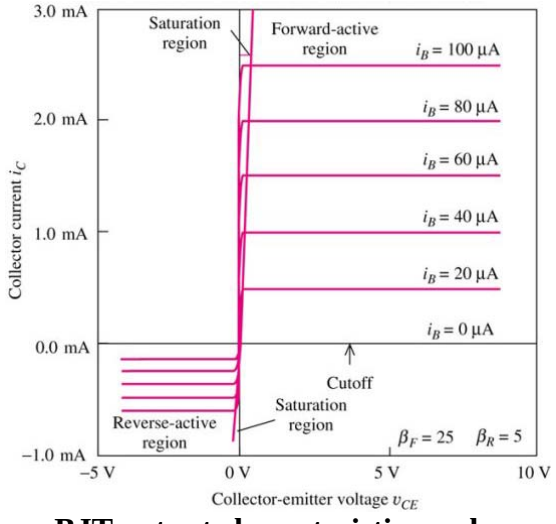


Figure 2. Example npn BJT output characteristics and operating regions.

For each curve, the *forward active region* is the region to the right of the knee, i.e., the nearly flat part. The region to the left of the knee is the *saturation region*. For switching applications, the BJT is most like a closed switch when it is in the saturation region, where v_{CE} is small. It is most like an open switch when it is in cutoff, with $i_C = 0$.

A BJT is often used as a current-controlled switch, as illustrated in Fig. 3

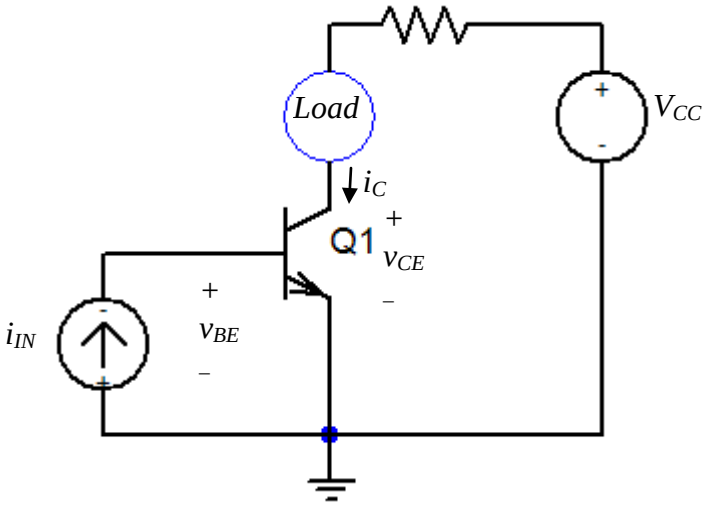


Figure 3. BJT switching circuit. When the input current is sufficiently large, the BJT saturates, and current flows through the load. When the input current is zero, the BJT is in cutoff, and no current flows.

For most switching applications, the BJT is operated in the saturation region when it is conducting current. In this region, the voltage drop across the BJT collector-emitter terminals is small, as desired. The amount of load current in this case is determined by the value of V_{CC} and the load characteristics, and is essentially independent of i_{IN} or the BJT characteristics.

Pre-Lab:

(1) Obtain the data sheet for the 2N3904 MOSFET from the class web site, or from

http://www.fairchildsemi.com/ds/2N/2N3904.pdf

Use this to determine the maximum allowed values of the collector current, the collector-emitter voltage, and the power dissipation. Also determine the range of values of forward current gain (β_{Fo} , also known as h_{FE}).

(2) From the data you found in (1), what is the maximum allowed collector current if V_{CE} = 15 V ? If V_{CE} = 5 V ? Express your results in mA. What are the smallest and largest values of expected base current if the BJT is operating in the forward active region with I_C = 10 mA. Express your answers in μA. **(Prelab continues on next page)**

(3) In which region should the BJT be operating when it is a "closed switch?" Why? In which region should it be operating when it is an "open switch?" Why?

Lab Exercise:

There are 3 parts. Have your GTA sign off on each part before proceeding to the next one.

(1) Curve tracer measurement of transistor β.

- Obtain a 2N3904 BJT, a 330 Ω, ¼-Watt resistor, and a 200 kΩ, ¼-Watt resistor.
- Measure the resistor values using a DMM.
- Using the data sheet as a guide, identify the collector, base, and emitter terminals of the transistor.
- Measure the β of your transistor using the curve tracer.
- Take a digital photograph of the curve tracer display to include in your report.

(2) I_C vs. V_{CE} *for constant base current*

Connect the circuit shown in Fig. 4 to measure I_C vs. V_{CE} with I_B held constant. Proceed as follows:

- Set the Variable DC source to the Minimum position.
- Set the DMM to the mA position, and be sure to use the correct input jacks.
- Turn on the Bit Bucket power.
- Use the DVM on the Bit Bucket to measure the voltage drop across R_B, and thereby determine I_B. This value will not change during Part 1.
- Reconnect the DVM to measure V_{CE} (+ input to collector, – input to emitter).
- Increase the Variable DC source (V_{CC}) slowly up to its maximum, while observing I_C on the DMM. The value of I_C should reach a maximum in the range of 3 mA to 6 mA and V_{CE} should reach about 13 to 14 V when the Variable DC source is turned all the way up. If your readings are not in this range, stop, check your connections, and if necessary ask for help.
- With V_{CC} still at its maximum value, temporarily reconnect the the DVM to measure both transistor junction voltages, V_{BE} and V_{BC} . Record these values. Do they agree with your expectations? (See Table 1. Hints – the BJT is in the forward active region. This is an npn transistor. A forward-biased p-n junction will have about 0.40 to 0.80 volts across it, measured from the p-side to the n-side. A reverse-biased p-n junction will have a lower voltage, including zero or negative values, measured from the p-side to the n-side[1].)

[1] The term "reverse-biased" is often used somewhat loosely in electronics to refer to a junction that is not forward biased and thus not carrying significant current.

- With V_{CC} still at its maximum value, calculate and record the dc current gain, $h_{FE} = I_C / I_B$. Compare this to the value measured in Part 1 on the curve tracer.
- Reconnect the DVM to measure V_{CE} . Record I_C vs. V_{CE} for a number of data points over the full range of V_{CC}. Start at the maximum value and work your way down, incrementally reducing V_{CC}. At some relatively low value of $V_{CE,}$ there will be a very rapid drop-off of current ("knee"), as shown in Fig. 2. This knee is the transition from the forward active region to the saturation region. Try to capture enough data to get a good smooth plot, including this knee point.
- When you are fairly certain you have rounded the knee and entered saturation ($V_{CE} \approx 0.1$ V), use the DVM to once again measure the junction voltages and compare with your expectations. Are both junctions now forward-biased?

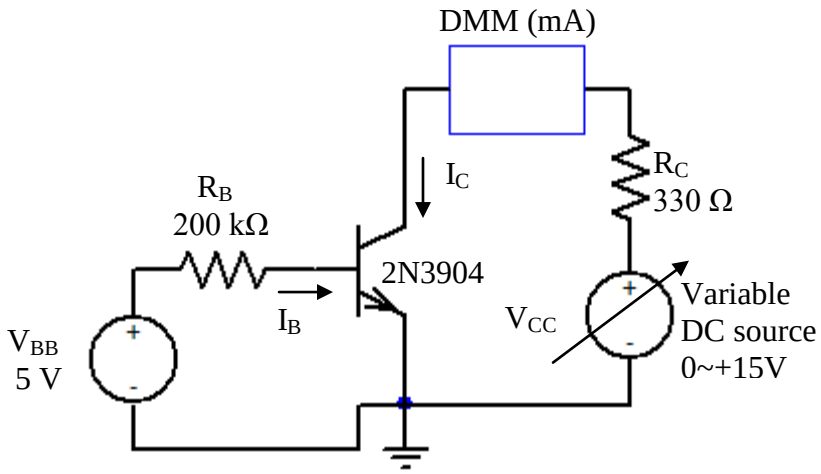


Figure 4. Circuit for measuring I_C vs. V_{CE}.

(3) *BJT Switching Circuits*

Connect a switching circuit in which the load is each of the following:

(a) A red LED. Construct the circuit shown in Fig. 5. Measure and record the values of each resistor before placing them in the circuit. Use a "Pulse Switch" on the Bit Bucket to provide the control voltage, V_{BB}. Press the switch to verify that the LED comes on, and draws about 9 mA of current. Measure and record in a table the values of V_{CE}, V_{BE}, V_{BC}, I_B and I_C when the LED is on and when it is off. In order to determine I_B, measure the voltage drop across R_B using the onboard DVM, and use Ohm's law to calculate the base current.

From the description of the operating regions given in Table 1, can you confirm that the BJT is in saturation when the LED is on, and in cutoff when the LED is off? (Hint: In

saturation, both junctions should be forward biased. In cutoff, both junctions should be reverse biased.)

Calculate the "forced beta" (ratio of I_C to I_B) when the LED is on. Does this confirm that the transistor in saturation? (Hint: see Table 1. If $\beta_{forced} < \beta_F$, the BJT is saturated. You measured β_F , also known as h_{FE}, in Part 1.)

(b) A 5V DC fan. Remove the LED and the 330 Ω resistor in Fig. 5, and in their place connect the provided fan. Observe the fan polarity (black wire should be connected to the collector of the BJT, red to the DMM). Measure and record V_{CE}, V_{BE}, V_{BC}, I_B and I_C when the fan is on and when it is off, and calculate β_{forced} when the fan is on. Does the transistor still saturate when the fan is on?

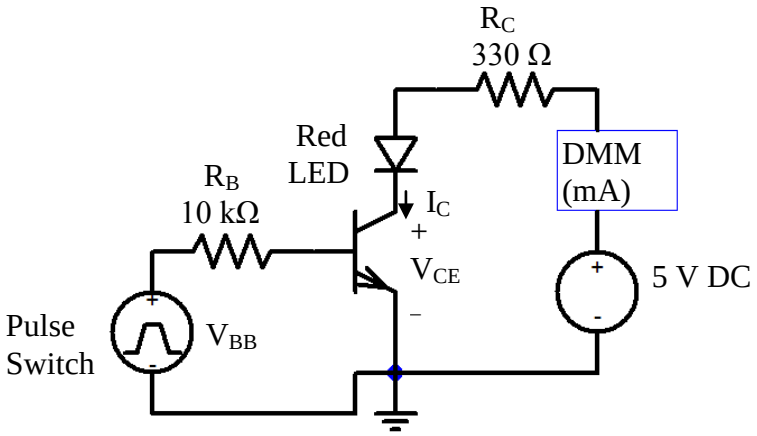


Figure 5. Circuit for switching an LED.