EXPERIMENT NUMBER 5
Characterization and Use of Bipolar Junction Transistors

Preface:

- Preliminary exercises are to be done and submitted individually.
- Laboratory hardware exercises are to be done in groups.
- Work done in notebooks to be submitted individually.
- The laboratory notebooks to be submitted immediately following the laboratory.
- The laboratory notebooks must include all settings, steps and observations in the exercises. All statements must be in complete sentences and all tables and figures must have a caption.
- This laboratory requires technical memorandum to be submitted individually. The technical memorandums require a specific format, must include specific appendix tables, and must address the listed questions. Review the associated guidelines.
- Review the guidelines for plagiarism to be aware of acceptable laboratory and classroom practices.

Bipolar junction transistors (BJTs) are common in many digital and analog applications. The following laboratory explores BJTs characteristic and their use in digital switching applications.

Objectives:

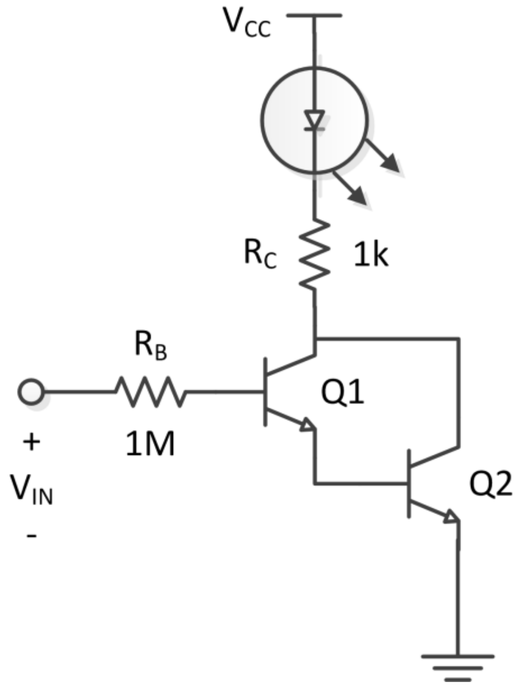
- Observe the I-V characteristics of both types of BJTs,
- Learn how to use a BJT as a switch, and
- Demonstrate the significance of the Darlington Pair configuration

References:

- EE 121 Handouts
- EE 151 and EE 153 text: Cunningham and Stuller, *Circuit Analysis*, 2nd Ed. (Houghton Mifflin Company, Boston, 1995).
- Neamen, Donald A., Electronic Circuit Analysis and Design, 2nd ed., (McGraw-Hill, New York, New York, 2001), Chap 4.

Background:

Switches are needed in electronics to turn-on a voltage or current of sufficient power to operate a circuit. Many digital and analog applications use transistor circuits for amplifying the output current of a microcontroller. The outputs from microcontrollers often can sink current well but cannot source current. One of the most common circuits to handle this application is a Darlington pair shown in Figure 1. (The LED is included to provide an indication of I_C.) While a single transistor has a gain of β, a Darlington pair has a gain of approximately β^2, which means a small base current can control a larger collector current than with a single transistor.



Current Gain

One transistor $I_c = I_b \beta$

Two transistors $I_c = I_b\beta(1+(\beta+1)) \cong I_b\beta^2$

Figure 1 – Dual-Transistor Darlington Circuit

To illustrate this concept, say a 1 MΩ resistor is placed in series with the base, and V_{in} is set to 5 V. If the ground connection was moved to the first transistor, Q_1 so that only a single transistor is used in the circuit, the current into the base should approximately be $\frac{5\ V - 0.7\ V}{1\ M\Omega} = 4.3\ \mu A$. Assuming β to be 100, the collector current should be about $100 \times 4.3\ \mu A = 430\ \mu\text{A}$. This current is not enough to turn on the LED. If the ground were connected at the emitter of Q_2, implementing the Darlington pair, the gain is approximately $100^2 = 10^4$, the base current is about $\frac{5\ V - 0.7\ V - 0.7\ V}{1\ M\Omega} = 3.6\ \mu A$, and the collector current is about $10^4 \times 3.6\ \mu A = 36\ \text{mA}$.

Light Emitting Diodes (LEDs)

A light emitting diode (LED) is a diode that emits light for forward bias conditions. The light emission increases as the diode current increases. Practically, a minimum current is required to clearly see the light. LEDs are often used as indicators, e,g, the light appears when a current threshold is reached.

Preliminary:

(Work on separate paper and turn in at the beginning of the laboratory session.)

- Print the data sheets for Fairchild 2N3904 (npn) and 2N3906 (pnp) transistors. Using these data sheets, find the DC current gain, collector saturation voltage, the maximum voltage rating, and the maximum current ratings. Put the results in a table.
- Consider a common-emitter, single-transistor npn-BJT circuit with R_b = 1 MΩ, R_c = 1 kΩ, and R_e = 0. Assume the base-emitter turn-on voltage is 0.7 V and the gain is 100. Calculate the value of V_{CC} for which the operating point at V_{BB} = 5 V is at the edge of the saturation region (about V_{CE} = 0.2 V). Calculate the corresponding collector current value. The circuit design is of a transistor switch that turns an LED "on" when the input is 5V and turns the LED "off" when the input is 0V.

Equipment:

- I-V Curve Tracer
- DC Power Supply
- Breadboard
- Signal Generator
- Oscilloscope
- Fairchild 2N3904 (npn) Transistor
- LED
- Resistors

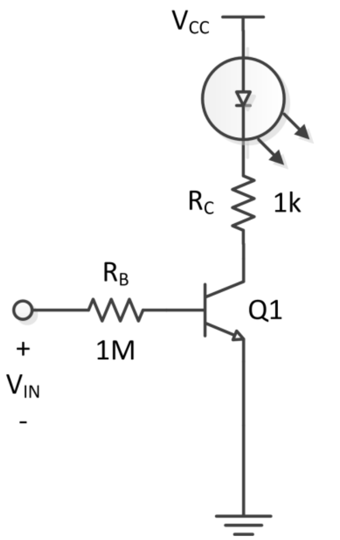


Figure 1 - Single BJT Circuit

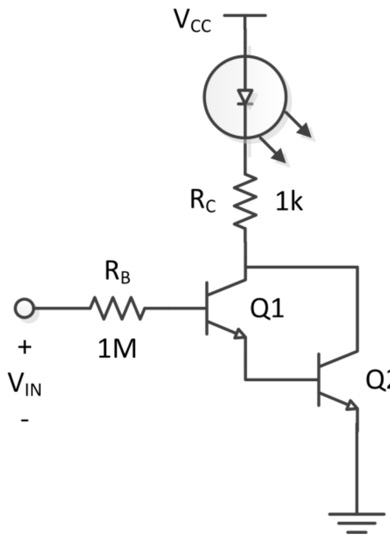


Figure 2 - Darlington Pair w/ LED

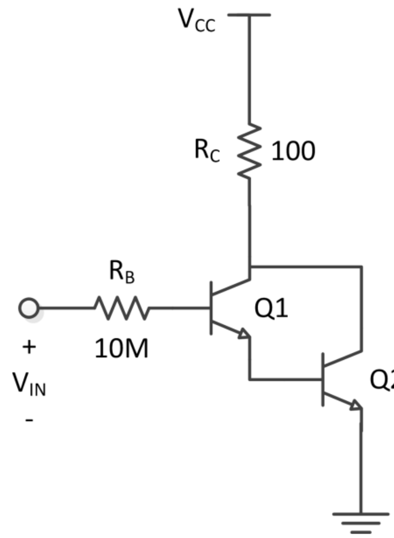


Figure 3 - Darlington Pair w/o LED

Experimental Procedure

1. Use the curve tracer to determine the I-V curves of the 2N3904 npn transistor. Record these curves.

   Q1: What are the approximate collector-emitter voltages at the transition between the saturation and active regions?

2. Build circuit shown in Figure 1. Set V_{CC} to 5 V using a DC voltage supply. For V_{IN}, use a function generator to create a low frequency (<10 Hz) square wave. Use a T-junction to attach the signal generator output to the oscilloscope before attaching it to your circuit. Using the measurement functions on your oscilloscope, view the maximum and minimum voltage of the signal from the function generator. By manipulating the amplitude and offset knobs of the function generator, create a square wave with a minimum voltage of ~0 V and a maximum voltage of 5 V. Note that you will have to pull the offset knob towards you to turn it. When you have the correct input voltage, connect the function generator to your circuit. The LED should be blinking at this point.

3. Keeping V_{IN} the same, decrease V_{CC} until the LED stops blinking.

   Q2: At what voltage V_{CC} does the LED stop blinking?

4. Set V_{CC} to back to 5 V. Increase the frequency of V_{IN} until the LED stops blinking and is constantly on. Record the frequency at which this happens.

   Q3: At what frequency does the LED stay constant? Why do you think this is?

5. Build the Darlington Pair circuit shown in Figure 2. Set the frequency of V_{IN} back to something less than 10 Hz, and make sure V_{CC} is still 5 V. Observe the change in brightness of the LED.
   Q4: How does the brightness of the LED in the Darlington Pair circuit compare to that of the LED in the previous circuit? Why are they different?

6. Alter the Darlington Pair circuit so that it matches the circuit shown in Figure 3. This will involve removing the LED, changing R_B to 10 MΩ, and R_C to 100 Ω. Set V_{CC} to 10 V. Disconnect the function generator and use a DC supply for V_{IN}. Set V_{IN} to 5 V.

7. Vary V_{IN} from 2 V to 6 V in increments of 0.5 V. Measure the voltage across R_C (V_O) at each point using the digital multimeter at your station, **not the oscilloscope**.
   Q5: Put these values in a table, where V_{IN} is in one column and V_O is in the other.

Technical Memorandum

1. Describe, based on your observations, the I-V curves of the Fairchild 2N3904 npn transistor. At approximately what collector-emitter voltage (V_{CE}) does the transition from saturation to active region occur? (Q1) Does this match theoretical expectations?

2. Describe the necessary conditions operation in the active region in terms of V_{BE} and V_{CE}. Why does the transistor not work correctly as a switch when V_{CE} is below a certain voltage? (Q2)

3. Describe the differences in operation of the Darlington Pair circuit and the single transistor circuit. Specifically address why you would use a Darlington Pair instead of the single transistor circuit. (Q4) What is the expected theoretical gain of the single transistor circuit? What is the expected theoretical gain of the Darlington pair circuit?

- Appendix 1: Record the sketch or plot of the I-V curves from the 2N3904 transistor. State the approximate collector-emitter voltage (V_{CE}) at which the transition from saturation to active region occurs and mark this transition on the plot.

- Appendix 2: Record the minimum voltage of V_{CC} found in Q2. How does this value of V_{CC} compare to the value calculated in class? What is the percent difference?

- Appendix 3: Using the equation shown below (which is simply repeated from the background section of the lab manual), calculate the base current for each of the input voltages in the table from Q5. Calculate the current through the 100 Ω resistor from the output voltages in the table.
  $$I_{B1} = \frac{V_{IN} - V_{TO} - V_{TO}}{R_B} = \frac{V_{IN} - 0.7 - 0.7}{10\ M}$$
  Note that only one example of these calculations needs to be shown in the appendix. Put the calculated values in a plot, where input current is on the x-axis and output current is on the y-axis.

Extra Credit: Calculate the gain values of the Darlington Pair circuit from the input currents and output currents determined in Appendix 3. How do these values compare to the theoretical gain of a Darlington Pair circuit?