EXPERIMENT NUMBER 5
Characterization and Use of Bipolar Junction Transistors

Preface:
- Preliminary exercises are to be done and submitted individually and turned in at the beginning of class
- Laboratory hardware exercises are to be done in groups
- The Lab Report is the Lab Notebook, and it can be written by any one member of the group
- The student-group MUST have the data and answers acquired during the lab and entered in the Lab Notebook verified by the TA before they leave the class
- Failure to show the Lab Notebook to the TA, will result in no score for Lab Report for the entire group
- Tech Memo to be done in Word Doc according to the format uploaded on CANVAS and submitted by individual students at the beginning of the next class
- 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
- Demonstrate the significance of the Darlington Pair configuration

References:
- EE 121 Handouts

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 Ic.) While a single transistor has a gain of $\beta$, a Darlington pair has a gain of approximately $\beta^2$, which means a small base current can control a larger collector current than with a single transistor.
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 $\beta$ to be 100, the collector current should be about $100 \times 4.3 \, \mu A = 430 \, \mu A$. 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 $10^4 \times 3.6 \, \mu A = 36 \, mA$.

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 (nnp) 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 $R_b = 1 \, M \Omega$, $R_c = 1 \, k \Omega$, 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

**Experimental Procedure:**
(Record specifics in the Laboratory Notebook.)

1. TA to setup the Oscilloscope and Curve Tracer at one station. Each group then takes a turn. Use the curve tracer to determine the I-V curves of the Fairchild 2N3904 (npn) and 2N3906 (pnp) transistors. Plot or sketch the common-emitter I-V curves.

**King Instruments Curve Tracer (KI-3020A) and Oscilloscope settings for Diode Measurement:**

**OSCILLOSCOPE:**
- Save/Recall Button -> Default Setup
- Menu/Zoom Button -> XY

**KI-3020A:**
- Horizontal -> X or Oscilloscope Channel 1
- Vertical -> Y or Oscilloscope Channel 2
- Polarity Knob -> PNP or NPN
- V Knob -> 20V
- Bias Knob -> 0.2V
- H Length Knob fully Clock Wise
- Connect Transistor following diagram on tracer panel
- Selector Switch to side using
- Current Limit Switch -> signal
- Transistor Type Switch -> Trans
- Power ON
Adjust Oscilloscope V/div, Time/div, and Horizontal Position accordingly XY Origin denoted on the oscilloscope display at the left and top

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.

Q2: Keeping $V_{IN}$ the same, find the value of $V_{CC}$ that the LED stops blinking.

Q3: How does the experimental value of $V_{CC}$ compare to the calculated value?

Q4: Set $V_{CC}$ back to 5 V, adjust the frequency so that the LED stops blinking? Why do you think this is?

3. 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.

Q5: 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?

4. 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.

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 multi-meter at your station, not the oscilloscope.

Q6: 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. (Q5) What is the expected theoretical gain of the single transistor circuit? What is the expected theoretical gain of the Darlington pair circuit?