Lab Three
Fundamentals of Electronics
EECE2412/3

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Abstract

The goal of this laboratory experiment is to orient the performing individual with bipolar junction transistors (BJTs). Common regions (active, saturated, and cut-off) are explored, in addition to the effects of temperature variance on BJT performance. Finally, a light-emitting diode (LED) light-sensing circuit is constructed with a photocell.

KEYWORDS: BJT, active, saturated, cut-off, temperature variance, LED, photocell

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1 Equipment

Available equipment included:

- 2N3904 Bipolar Junction Transistors
- Light-Emitting Diodes (varying colors)
- Basic Circuit Components (Wires, Inductors, Capacitors, etc.)
- Keysight EDU36311A Dual DC Power Supply
- Photocell (Light-Varying Resistor)

2 Experimental Procedure

We begin by constructing the following circuit:

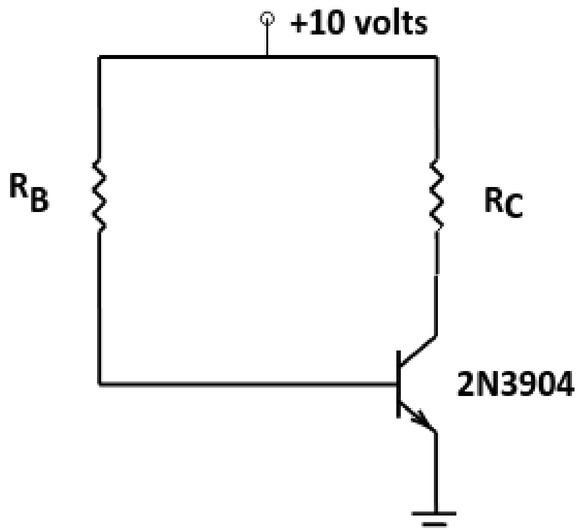

Figure 1: BJT Biasing Circuit

We proceed to test various configurations which place the 2N3904 in common regions, such as active, saturated, and cut-off.

2.1 The Forward-Active Region (with varying β)

Using the circuit shown in Figure 1, with $R_B = 316.7[\text{k}\Omega]$ and $R_C = 1.003[\text{k}\Omega]$, we place the BJT into its active region (supporting calculations are present in the pre-lab). Measuring V_{CE} and V_{BE} for both of our BJTs, we find:

$$V_{BE_1} = .708[\text{V}] \quad \text{and} \quad V_{CE_1} = 3.394[\text{V}]$$

$$V_{BE_2} = .704[\text{V}] \quad \text{and} \quad V_{CE_2} = 3.378[\text{V}]$$

We know the BJT is in its active region since, based on the above measurements, $V_{CE} > V_{BE}$ (or, alternatively $V_{BE} > 0$ and $V_{BC} < 0$).
Using the data from above, we may calculate I_B, I_C, and β:

$$I_{B_1} = \frac{10 - .708}{316.7k} \quad \text{and} \quad I_{C_1} = \frac{10 - 3.394}{1003}$$

$$\boxed{I_{B_1} = 29.34[\mu\text{A}] \quad \text{and} \quad I_{C_1} = 6.586[\text{mA}]}$$

$$I_{B_2} = \frac{10 - .704}{316.7k} \quad \text{and} \quad I_{C_1} = \frac{10 - 3.378}{1003}$$

$$\boxed{I_{B_1} = 29.353[\mu\text{A}] \quad \text{and} \quad I_{C_1} = 6.6022[\text{mA}]}$$

From this, we find the direct current (DC) gains:

$$\beta_1 = \frac{6.586}{.02934}$$

$$\boxed{\beta_1 = 224.47}$$

$$\beta_2 = \frac{6.6022}{.029353}$$

$$\boxed{\beta_2 = 224.92}$$

2.1.1 Using Curve Tracers

Per the curve tracer presented in class, we would expect $I_B = 40[\mu\text{A}]$ for our I_C value. This gives us a β of:

$$\beta_{curve} = \frac{6}{.04}$$

$$\boxed{\beta_{curve} = 150}$$

2.1.2 Tolerance and Standard Deviation of Gain

It would be difficult to design a circuit with $\beta = 150 \pm 1\%$ because, even within the same model of BJT, there is much variation; however, it should still be practical to meet this strict tolerance. This is further supported by the variance of β presented in the BJT data sheets attached to the laboratory experiment. Though the tested transistors are all within specification, there is a great amount of variance, which we can calculate using the standard deviation. We obtain two of each β value from other groups:

$$\beta_1 = 186, 196$$

$$\beta_2 = 201, 217$$

The average of the gains is:

$$\beta_1^{avg} = 202.16$$

$$\beta_2^{avg} = 214.31$$

Thus, we get standard deviations of:

$$\boxed{\sigma_{\beta_1} = 19.96 \quad \text{and } \sigma_{\beta_2} = 12.185}$$

We may see that these standard deviations are all, more or less, within 1% (for β_1 it is above for two of the three values), and, therefore, we should be able to design for such a tolerance.

2.1.3 Thermal Response

Using a can of refrigerant, we obtain new values:

$$V_{CE} = 3.78[\text{V}] \quad \text{and} \quad V_{BE} = .725[\text{V}]$$

This gives us:

$$\beta = \frac{\left(\frac{10-3.78}{1003}\right)}{\left(\frac{10-.725}{316700}\right)}$$

$$\boxed{\beta_{cold} = 211.48}$$

Per the data sheets, we would expect a drop in I_C, which would result in a decrease in β, as shown above. This would be unwanted in a car stereo system, as colder weather would mean that the amplification would not be as great, thus causing lower volumes.

2.2 BJT Saturation

As per the pre-lab, we know that $R_B \leq 208.66[\text{k}\Omega]$ will saturate the BJT. Thus, we select the closest available value: $R_B = 157[\text{k}\Omega]$. Measuring the saturation values, we find:

$$V_{CE_1}^{sat} = 45[\text{mV}] \quad \text{and} \quad V_{BE_1}^{sat} = .906[\text{V}]$$
$$V_{CE_2}^{sat} = 51.5[\text{mV}] \quad \text{and} \quad V_{BE_1}^{sat} = .94[\text{V}]$$

We see that there is a lot of variation between even the same model of BJT, and, thus, it is necessary to account for BJT-to-BJT variation. We may find the β values for this region:

$$I_{B_1} = \frac{10 - .906}{157000} \quad \text{and} \quad I_{C_1} = \frac{10 - .045}{1003}$$

$$\boxed{I_{B_1} = 57.92[\mu\text{A}] \quad \text{and} \quad I_{C_1} = 9.925[\text{mA}]}$$

$$I_{B_2} = \frac{10 - .94}{157000} \quad \text{and} \quad I_{C_2} = \frac{10 - .0515}{1003}$$

$$\boxed{I_{B_1} = 57.7[\mu\text{A}] \quad \text{and} \quad I_{C_1} = 9.9187[\text{mA}]}$$

This gives us:

$$\beta_1 = \frac{9.925}{.05792}$$

$$\boxed{\beta_1 = 171.36}$$

$$\beta_2 = \frac{9.9187}{.0577}$$

$$\boxed{\beta_2 = 171.90}$$

From this, we see that, if a high β is important in a circuit, we want to operate in the active, and not in the saturated region.

2.3 BJT Cut-Off

Using the different methods provided, we obtain:

$$V_{CE_1} = 10[\text{V}]$$

$$V_{CE_2} = 9.638[\text{V}]$$

$$V_{CE_3} = 4.572[\text{V}] \quad (\text{when } R = 470[\Omega])$$

2.4 BJT Touch-Sensitive Switch

We may create a touch-activated LED circuit by integrating an LED and replaced R_B with "touch points" as show in Figure 2 below:

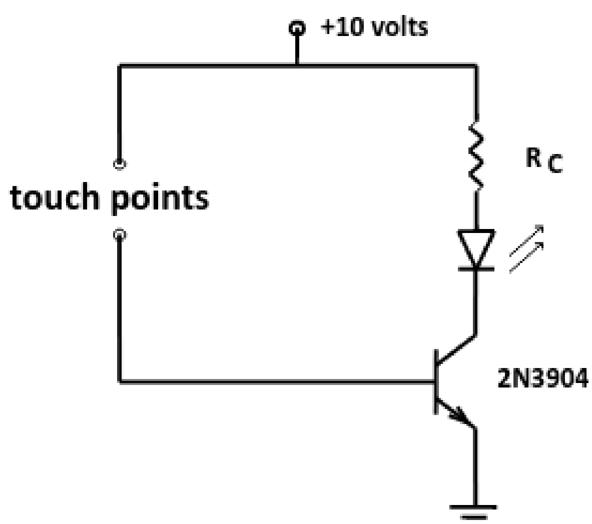

Figure 2: Touch-Activated Circuit

We may thus equate the initial resistance to the resistance of the finger, and call it R_f. We now perform all of the necessary BJT calculations:

$$V_{CE} = 7.549[\mathrm{V}] \quad \text{and} \quad V_{BE} = .653[\mathrm{V}]$$

$$V_{LED} = 1.76[\mathrm{V}] \quad \text{and} \quad V_{R_C} = .49[\mathrm{V}]$$

The measured values allow us to obtain:

$$\boxed{I_C = \frac{.49}{1003} = .48853[\mathrm{mA}]}$$

We can then write:

$$.653 = \frac{R_f}{R_f + 1003}$$

$$.347R_f = 653$$

$$\boxed{R_f = 1.882[\mathrm{M\Omega}]}$$

From here, we can get:

$$I_B = \frac{.653}{1.882 \cdot 10^6}$$

$$\boxed{I_B = .34697[\mathrm{\mu A}]}$$

We may observe that, for the circuit without the BJT, the LED would not light up. This is due to the fact that the BJT provides the amplification, which allows the LED to light up, whereas the circuit without the transistor would have very little current, and, therefore, the LED would not turn on.

2.5 Automatic Night Light

In this section, we construct two night light circuits: one with immediate response, and one with a one second time delay. First, we measure the resistance of the photocell:

$$\boxed{R_{light} = 5.9[\mathrm{k\Omega}] \quad \text{and} \quad R_{dark} = 51[\mathrm{k\Omega}]}$$

The constructed circuit may be seen below:

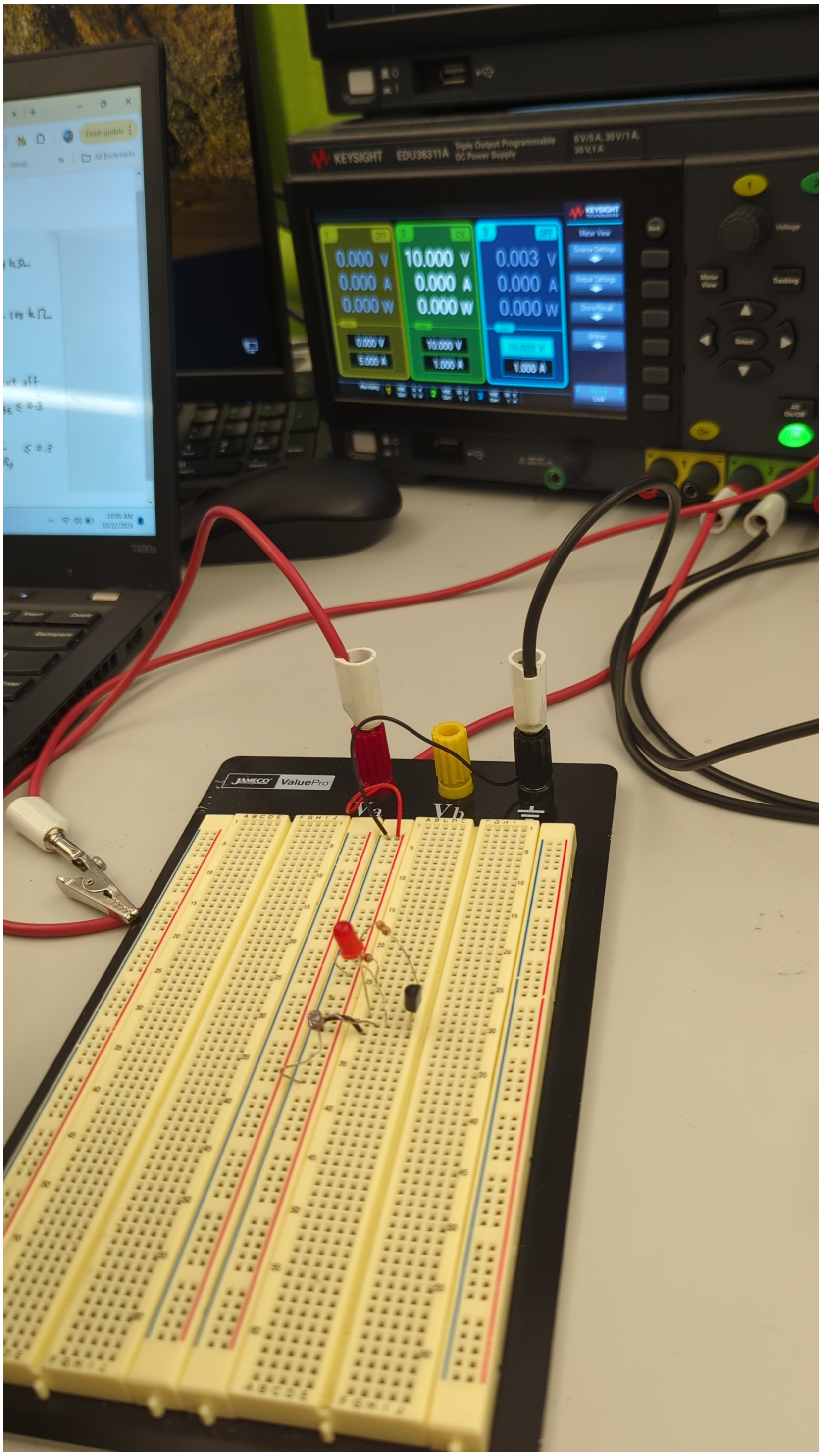

Figure 3: Night Light BJT Circuit

The immediate response circuit may be seen below:

Figure 4: Scan to See Response (or click here)

The circuit was then reconstructed with a 1[mF] capacitor in parallel with the photocell to ensure a time-delayed response. The circuit is shown below:

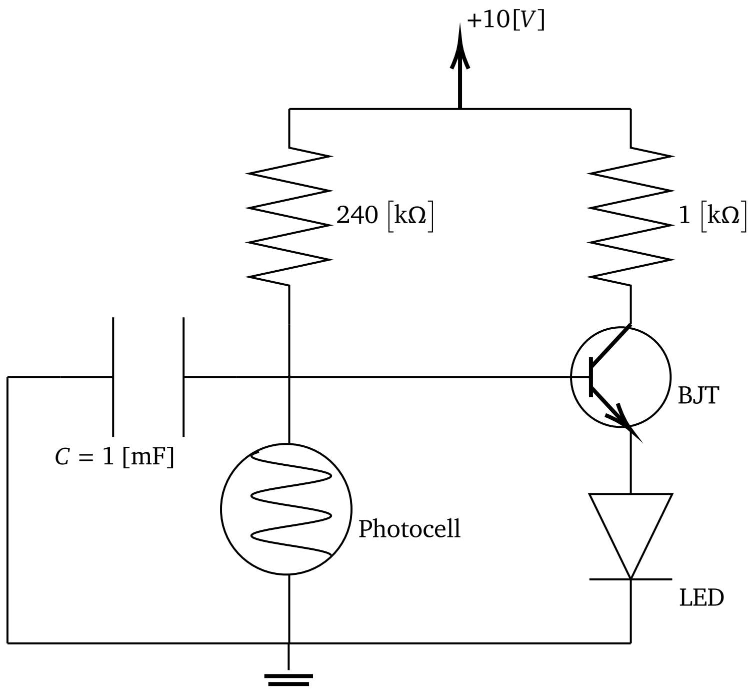

Figure 5: Modified Circuit (added Parallel Capacitor)

The response can then be seen below:

Figure 6: Scan to See Response (or click here)

2.6 Virtual Simulation

2.6.1 BJT Operation

We may simulate each of the cases analyzed physically. Let us begin with the active region:

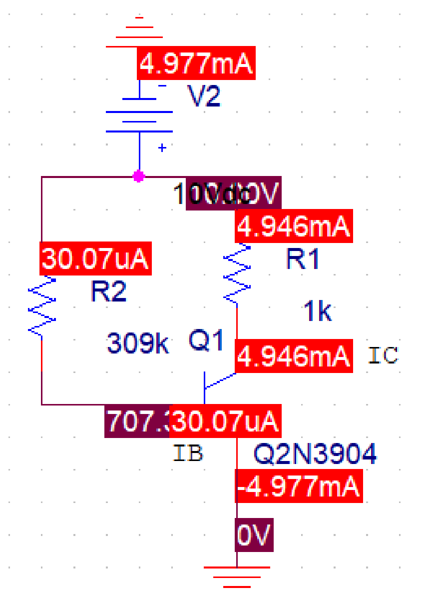

Figure 7: Active Region Simulation

From this, we may find the β value:

$$\beta = \frac{I_C}{I_B}$$

$$\beta = \frac{4.946}{.03007}$$

$$\boxed{\beta = 164.48}$$

We may observe that this value is lower than the one obtained experimentally; however it is still a bit similar. We now move on to the saturated case:

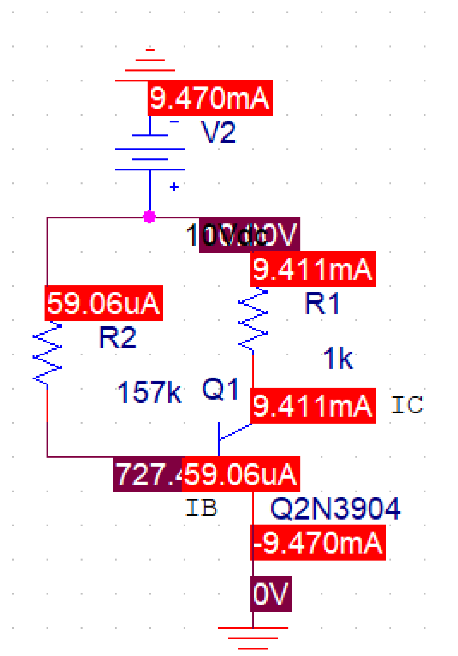

Figure 8: Saturated Region Simulation

From this, we find:

$$\beta = \frac{9.411}{.05906}$$

$$\boxed{\beta = 159.35}$$

We may observe that this value is close to the experimentally obtain value; more importantly, however, it shows that β drops in the saturated region. Finally, we simulate the cut-off region:

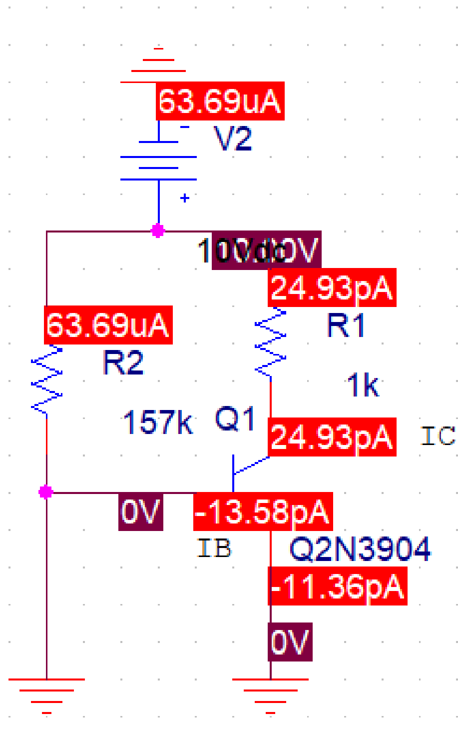

Figure 9: Cut-Off Region Simulation

We may observe that the current flow is practically zero throughout the circuit. Given that there is nearly no current flow through the resistor R_C, we may obtain the same value as we obtained experimentally:

$$V_{CE} \approx 10[\text{V}]$$

For the touch-sensitive circuit, we may see:

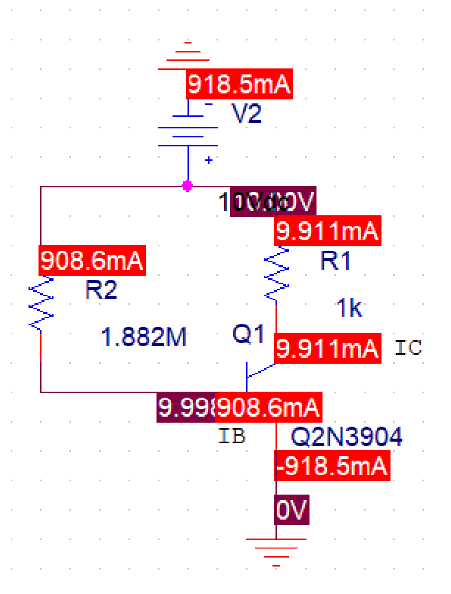

Figure 10: Touch-Sensitive Equivalent Simulation

We may observe that the voltage drop across the resistor makes:

$$V_{CE} = 10 - (9.911)(1)$$
$$V_{CE} = .089[\mathrm{V}]$$

Furthermore, we see that:

$$V_{BE} = 10 - (908.6)(1.882 \cdot 10^3)$$
$$V_{BE} = -1.71 \cdot 10^6$$

Therefore, because $V_{BE} < V_{CE}$, we may say that this BJT is in the active region.

2.6.2 Night Light Simulation

We now move on to simulating the night light. We simulate once for a "light" case, and once for a "dark" case:

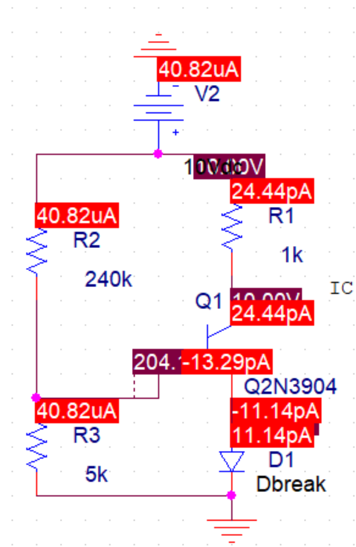

Figure 11: Immediate Response "Light" Case

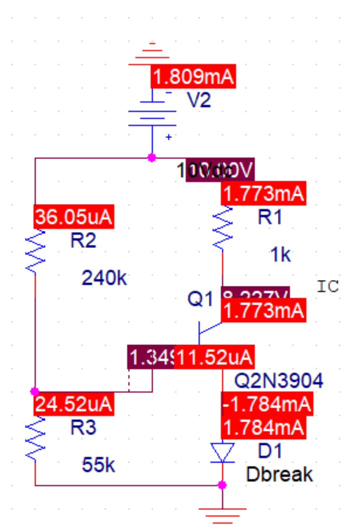

Figure 12: Immediate Response "Dark" Case

We may write the gains as:

$$\beta_{light} = \frac{24.44}{-13.29}$$

$$\boxed{\beta_{light} = -1.839}$$

$$\beta_{dark} = \frac{1.773}{.01152}$$

$$\boxed{\beta_{dark} = 153.91}$$

We may observe that, as intended, there is current flow through the LED when it is dark, which turns it on, and no (or, rather, limited) current flow when it is light. As we see, the circuit behaves as expected. Adding a parallel capacitor we get:

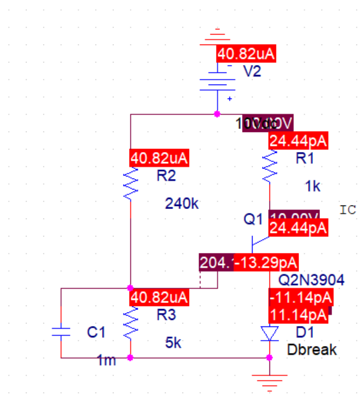

Figure 13: Time-Delayed Response “Light” Case

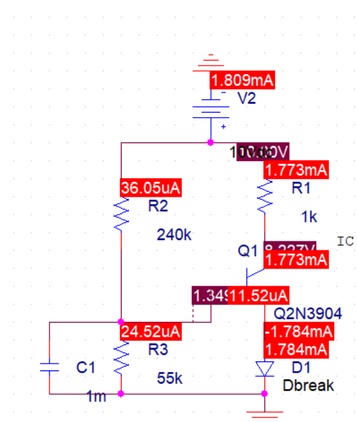

Figure 14: Time-Delayed Response “Dark” Case

Since we are not running a time-sweep (transient analysis), we see that, because there is only DC input, the capacitor is treated as an open circuit, and the values remain the same. We can observe, however, that, by calculating the time constant, there is a delay for the LED to charge or discharge:

$$\tau = RC$$

$$\tau = \frac{1}{(1)(5)}$$

$$\boxed{\tau = .2[s]}$$

This is a bit less than intended, since the measured photocell resistance values were less than expected; however, the time-delay still worked.

3 Conclusion

Throughout this laboratory experiment, we familiarized ourselves with the operations of bipolar junction transistors in their standard regions (active, saturated, and cut-off). We then synthesized our knowledge by constructing a touch-activated and light-sensitive circuit.