Lab 3: Resistors and Bipolar Transistors

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1 Experiment 1: Bipolar Transistor Characteristics

1.1 Background and Procedure

The goal of this experiment was to measure the current-voltage characteristics of an npn bipolar transistor. We measure the base the current for the transistor (specifically, the 2N3904 bipolar transistor) as we sweep the base voltage over a range of values in order to vary the emitter current from 10nA to close to 20mA. We use one of the channels on the SMU to measure the emitter current as well, with the emitter voltage referenced at ground.

For computing the collector current using the two channels (measured emitter current and base current), we use the Equations 1, 2, 3, and 4:

$$I_c = I_s * e^{\frac{V_b - V_e}{U_T}} \tag{1}$$

$$I_b = \frac{I_s}{\beta} * e^{\frac{V_b - V_e}{U_T}} \tag{2}$$

$$I_e = \frac{I_s}{\alpha} * e^{\frac{V_b - V_e}{U_T}} \tag{3}$$

$$I_e = I_c + I_b \tag{4}$$

We used this suggested work around since the SMU becomes unstable and oscillates in the range of about 200 μA of collector current in this configuration shown in Figure 1.

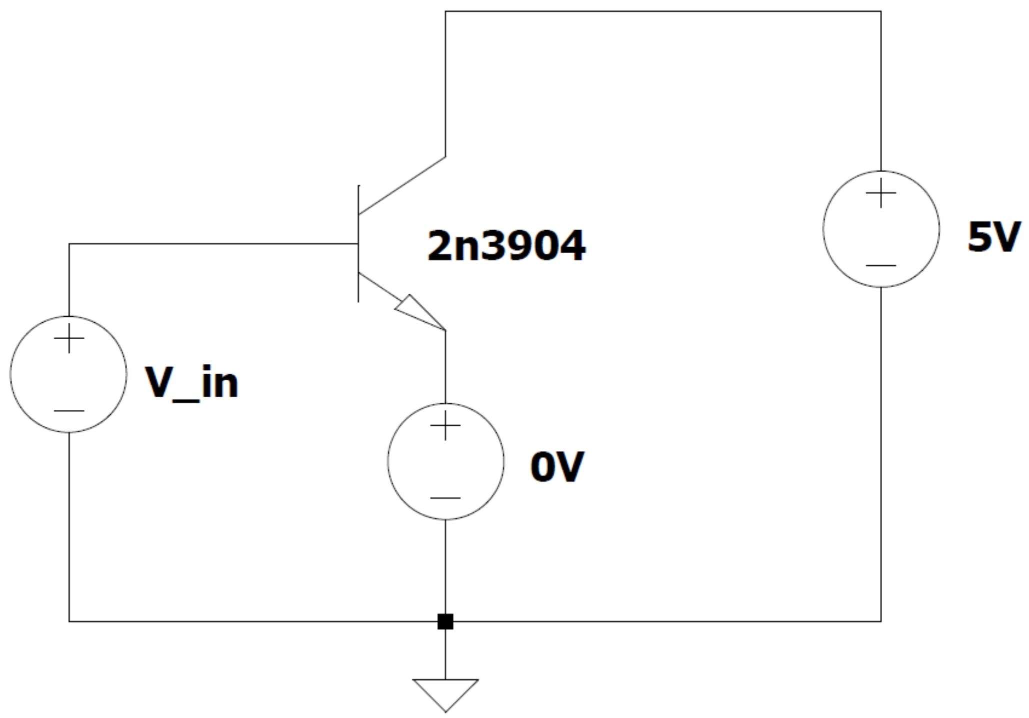

Figure 1: Schematic for circuit used in Experiment 1.

1.2 Results and Discussion

In order to account for the offset in the op-amp circuitry, we added 1.35e-09 A to the base currents that were measured as negative values. This allowed for the logarithmic plots to not have asymptotic behaviors with small input voltages.

Using linear regression, we found U_t and I_s for the transistor we used. The following figure shows experimental I-V characteristics which we used to extract the transistor parameter values.

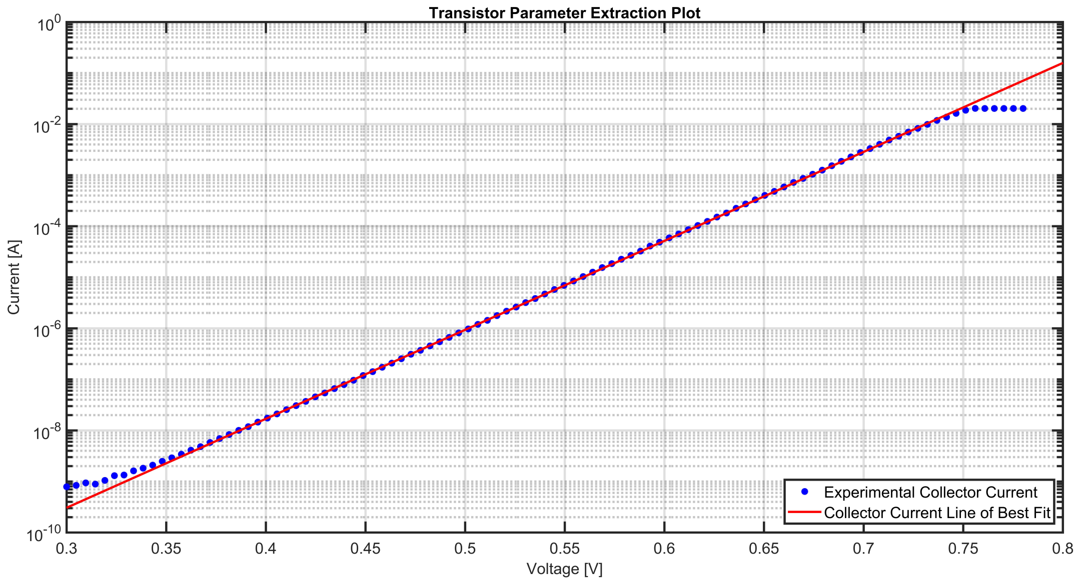

Figure 2: This figure shows experimental I-V characteristics for the diode we used during this experiment. We used a line of best fit to find U_t and I_s for our transistor.

From the line of best fit, we extracted

Extracted Transistor Parameters	
Constant	Extracted Value
I_S	$1.813 * 10^{-15}$ [A]
U_T	0.0249 [V]

For our transistor, we made a Gummel plot to show the relationship between the collector and base current as the base current varied.

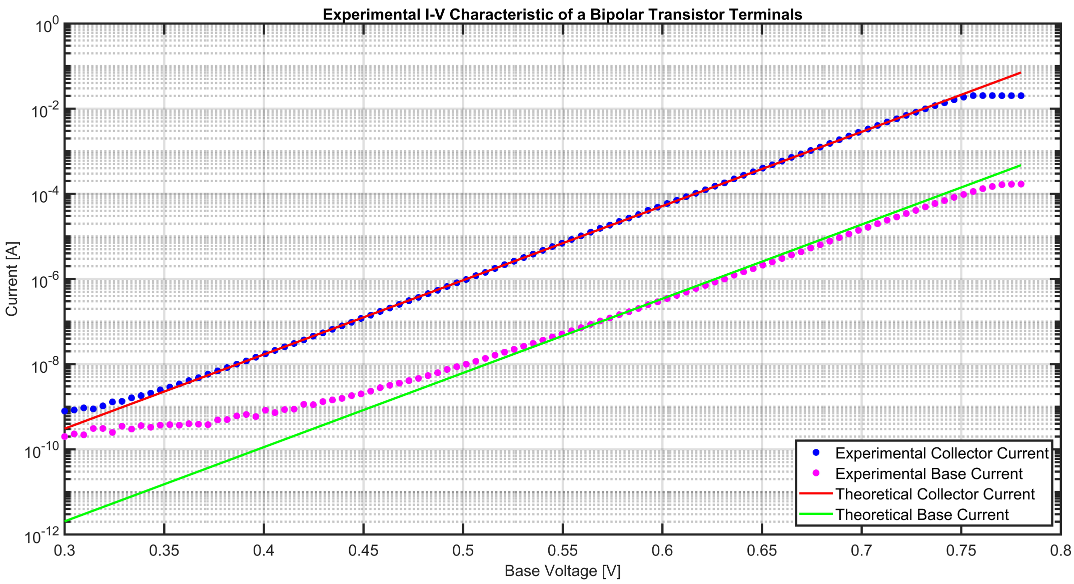

Figure 3: This figure shows a Gummel plot for our transistor.

From this, we can see that both the current through the collector varies exponentially with the base voltage. There is an exponential relationship when V_{be} is between 0.3 V to 0.75 V. From the theoretical fit, we can extract the slope to be 40.1233 S. The slope corresponds with $\frac{1}{U_t}$.

We then considered how the forward current gain (β) varies as the base current varies. The following figure shows this relationship,

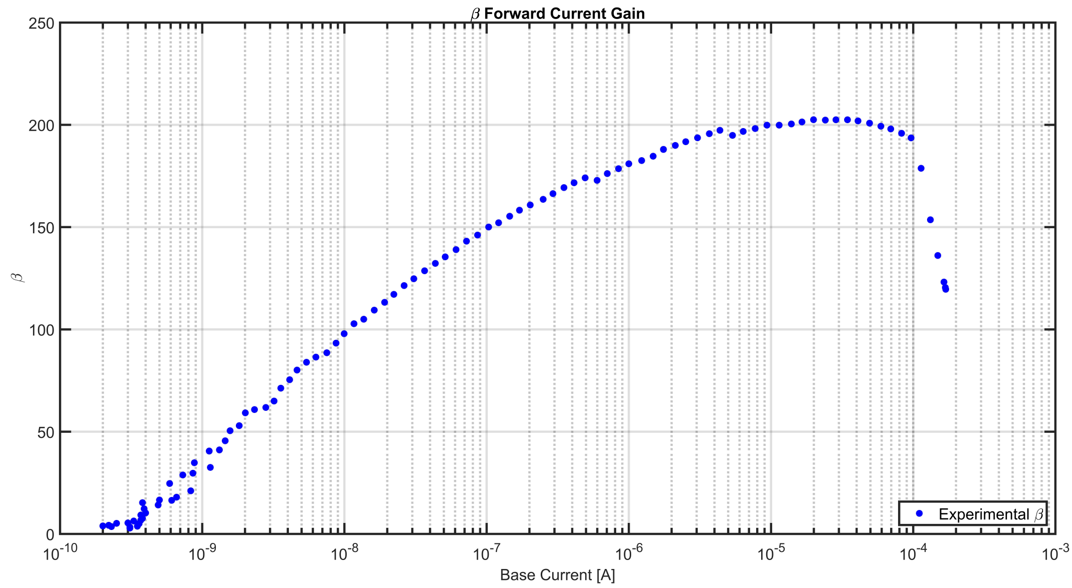

Figure 4: This figure shows the forward current gain (β) as the base current changes.

We can see that β varies as the base current varies. We can see that the value of β is only relatively constant when the base current is between $5 * 10^{-6} A$ and $10^{-4} A$, and thus for those base current values it is a reasonable assumption to say that $\beta = 200$.

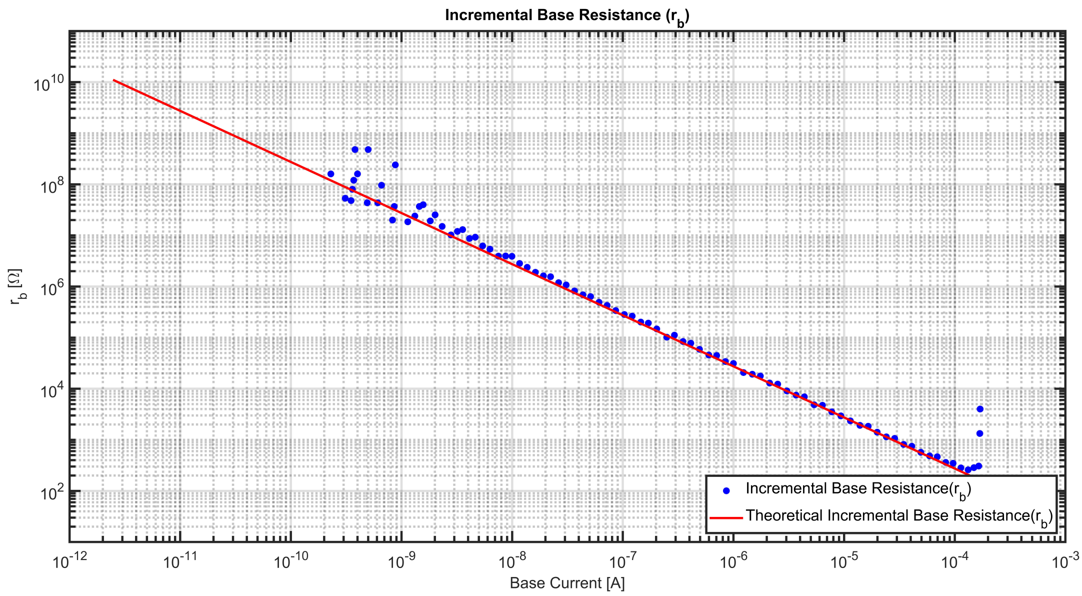

Figure 5: This figure shows the incremental base resistance of the transistor as the base current varies.

The theoretical fit for the incremental base resistance matches the experimental data very well for the range 1e-8 [A] to 1e-4 [A], and is only an average fit for the spread of data values in the range 1e-10 [A] to 1e-8 [A] where it deviates due to some outliers. The mean error for the theoretical fit is within 11.14 %. Although this error is fairly high, we are comparing it to points generated with matlab's diff function. Thus, any small measurements errors are exacerbated.

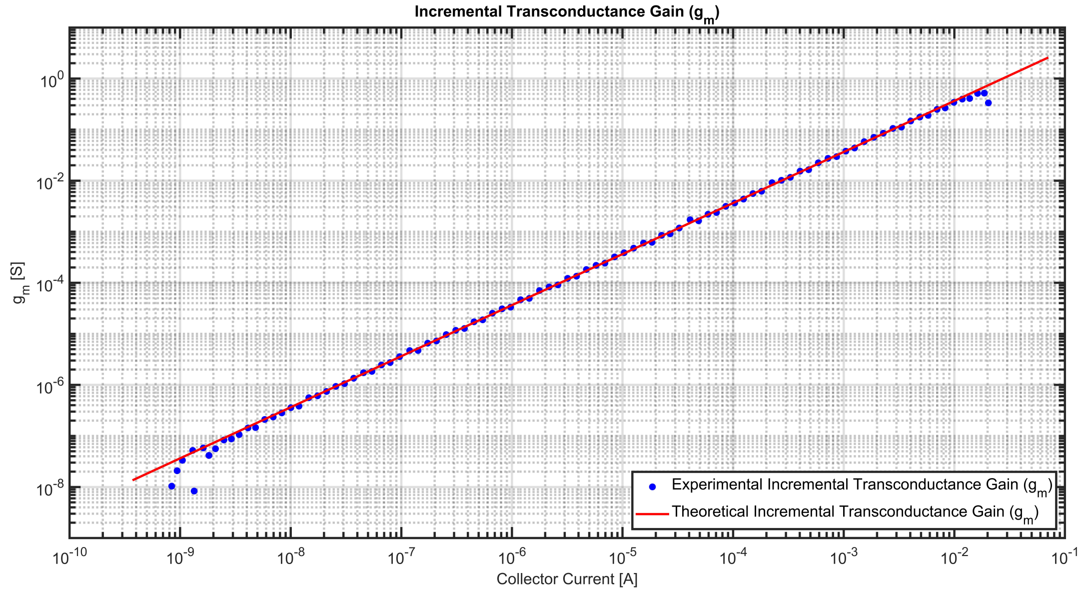

Figure 6: This figure shows the incremental transconductance gain of the transistor as the collector current varies.

The theoretical fit for the incremental transconductance gain matches the experimental data very well for the vast majority of the current range 5e10-8 [A] to 5e-2 [A]. There is slight deviation from the general trend of the data in the 1e-9 [A] to 5e-9[A] which is averaged out as is visible in the plot. The mean error for the theoretical fit is within 3.306 %. This fit is much better than the incremental resistance fit, yet is still fairly high. We believe the inconsistency between the fit and measured values can be attributed to the crudeness of matlab's diff function, as any measurement errors are emphasized.

2 Experiment 2: Emitter-Degenerated Bipolar Characteristics

2.1 Background and Procedure

For this experiment, we found the emitter current for a bipolar transistor that was Emitter-Degenerated. Using the SMU we swept input voltages between 0 V and 5 V, for three resistor values (200Ω, 2kΩ, and 20kΩ) that varied by an order of magnitude each. The circuit used for this experiment is shown below.

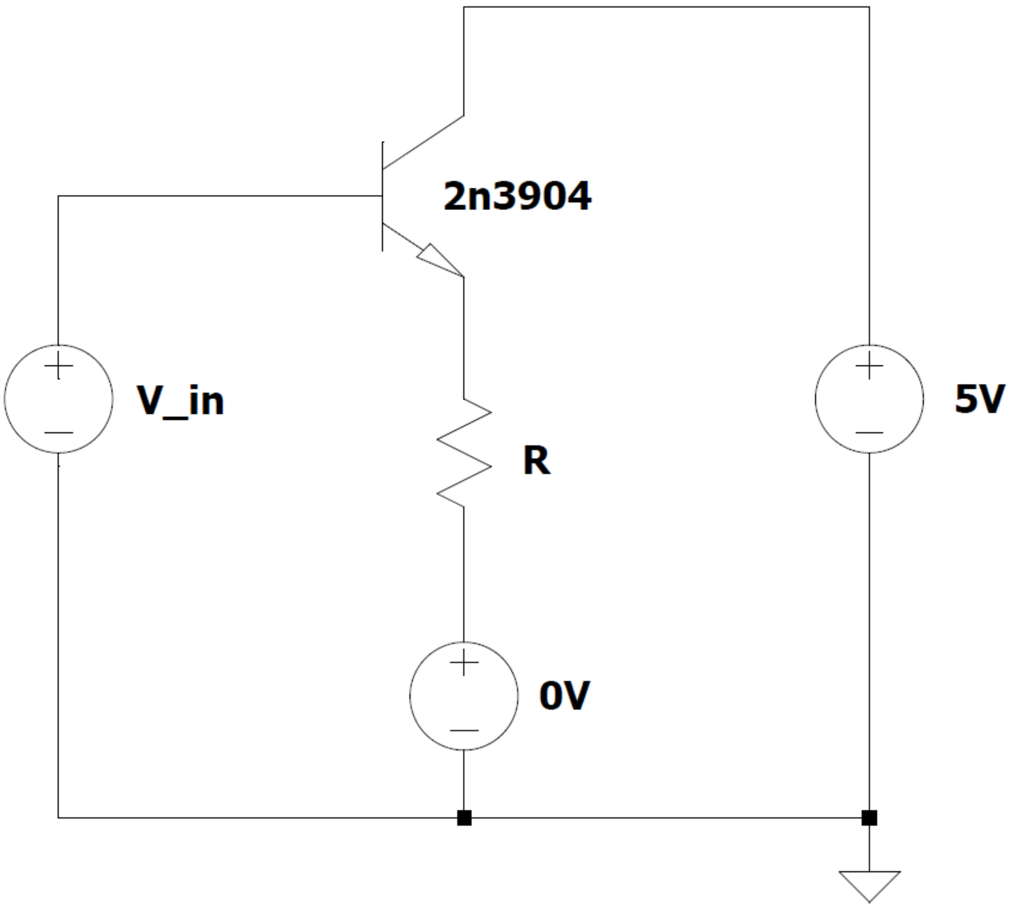

Figure 7: Schematic for circuit used in Experiment 2.

In this circuit, R was each of the resistor values used. To find the I-V characteristics for this circuit, we swept the input voltage from 0V to 5V.

2.2 Results and Discussion

Using the circuit in Figure 7, we used three resistance values as the degenerating resistor. The measured resistance values we used are shown below,

Experimental Values for Resistors			
Manufacturer Provided Value	Measured Value	Error Percentage	Given Tolerance
200 Ω	199.57 Ω	-0.215%	+/-1%
2 $k\Omega$	1.99 $k\Omega$	-0.5%	+/-1%
20 $k\Omega$	19.86 $k\Omega$	-0.7%	+/-1%

Using these resistor values, we looked at the collector current characteristics of the circuit with each of the resistance values as the degenerating resistor. These characteristics are shown below,

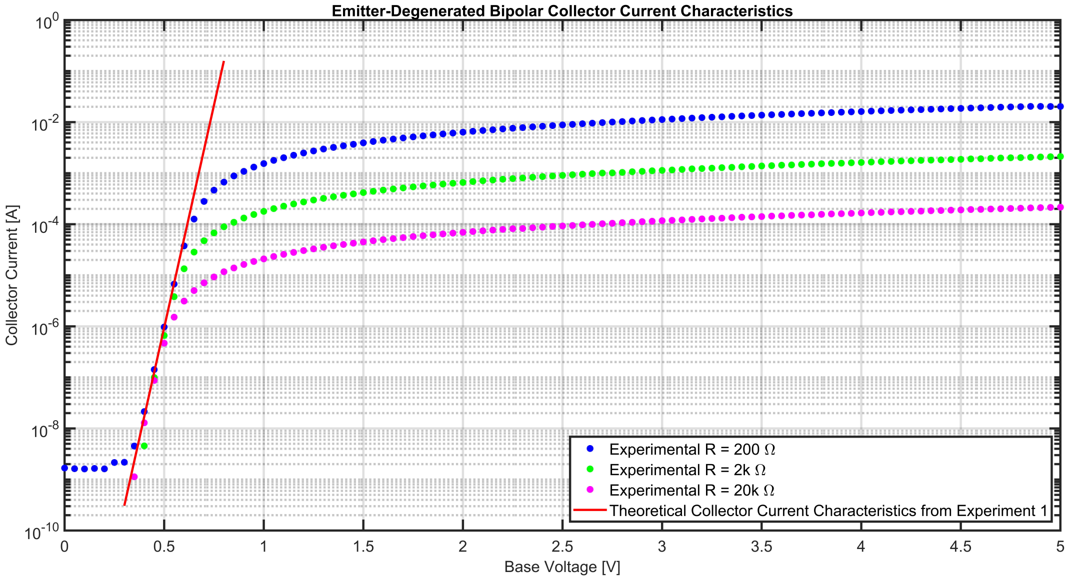

Figure 8: This figure shows the collector current characteristics of a emitter-degenerated bipolar transistor for three different values of resistors.

Along with the experimental I-V characteristics of the circuit, we compared these characteristics to the case without a degenerated emitter terminal (Experiment 1). The theoretical fit from Experiment 1 is shown as the red line on this figure. The slope of this fit is 40.1233 S. This value is the same as $\frac{1}{U_t}$.

By isolating each resistor, we plot the I-V characteristics on a linear scale. Following plots show this relationship.

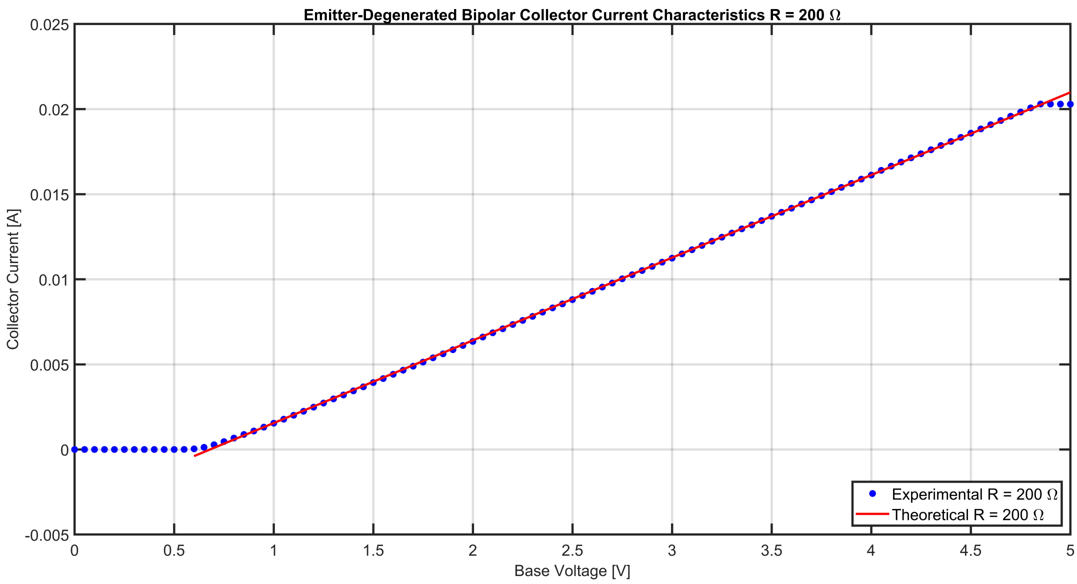

Figure 9: The figure shows the collector current characteristics for an emitter-degenerated bipolar transistor with R = 200 Ω as the base voltage varies.

From the theoretical line of best fit, we can extract the slope to be 0.0049 S. The slope value corresponds with $\frac{1}{R}$. We can extract the x-intercept to be 0.6802 V. This value corresponds with the turn on voltage for the transistor. The line of best fit had a absolute percent error of

0.573% in the region when V_{in} is greater than V_{on}. Thus, this is a good fit for the region we consider it in. We considered this region specifically as this is where the transistor is operating in the forward active region.

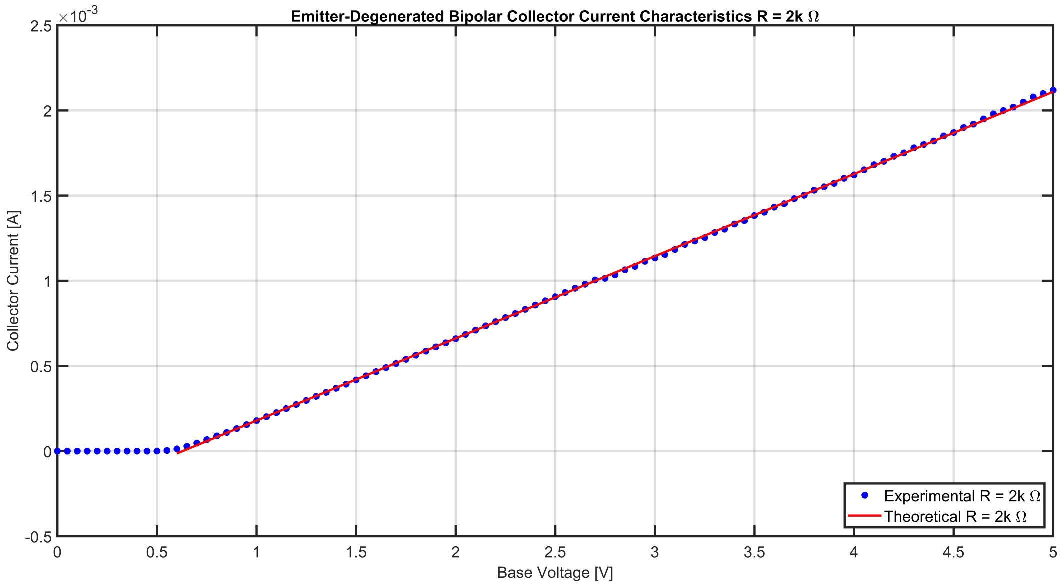

Figure 10: The figure shows the collector current characteristics for an emitter-degenerated bipolar transistor with R = 2 kΩ as the base voltage varies.

From the theoretical line of best fit, we can extract the slope to be 4.826e-04 S. The slope value corresponds with $\frac{1}{R}$. We can extract the x-intercept to be 0.6286 V. This value corresponds with the turn on voltage for the transistor. The line of best fit had a absolute percent error of 0.494% in the region when V_{in} is greater than V_{on}, as this is where the transistor is operating in the forward active region. Therefore, there is a good fit within this region.

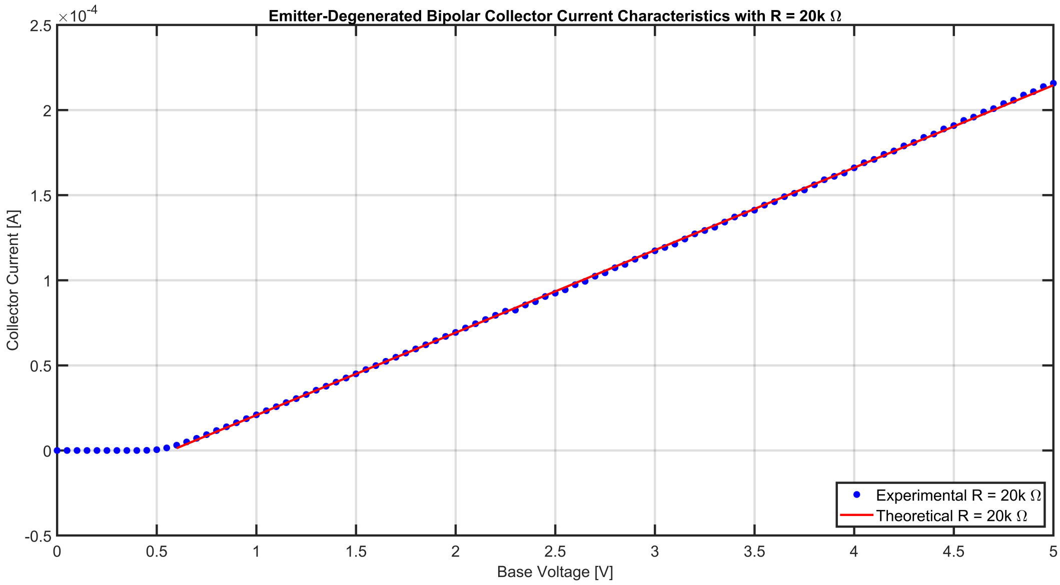

Figure 11: The figure shows the collector current characteristics for an emitter-degenerated bipolar transistor with R = 20 kΩ as the base voltage varies.

From the theoretical line of best fit, we can extract the slope to be 4.847e-05 S. The slope value corresponds with $\frac{1}{R}$. We can extract the x-intercept to be 0.572 V. This value corresponds with the turn on voltage for the transistor. The line of best fit had a absolute percent error of 0.517% in the region when V_{in} is greater than V_{on}. We consider this region specifically because it is when the transistor is operating in the forward active region. The fit is good in this region.

We can then extract the incremental base resistance with each of the degenerating resistor values. The following plot shows the incremental base resistance as the base current varies.

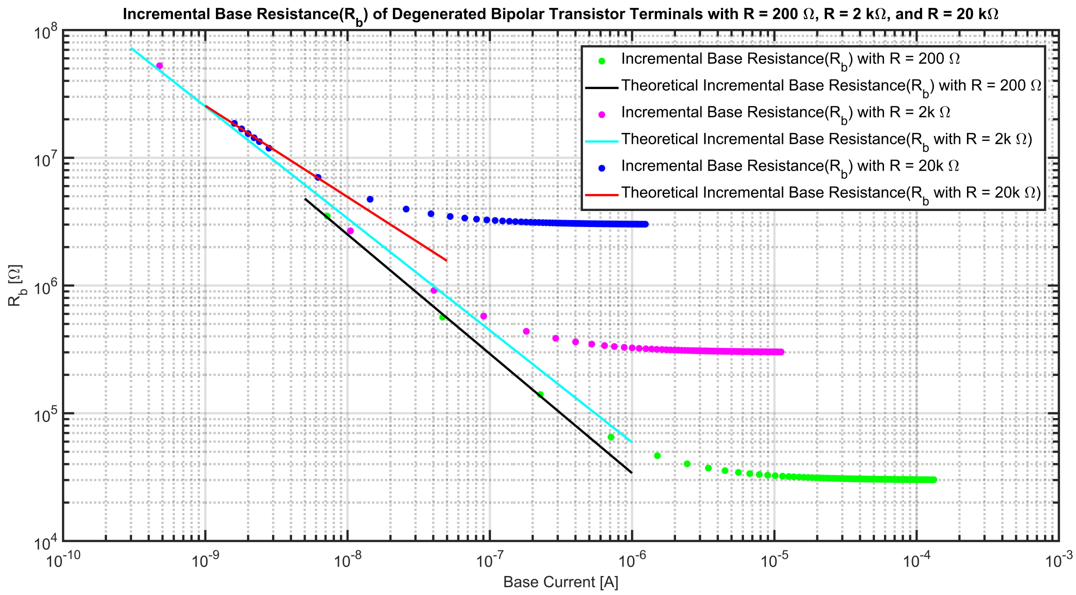

Figure 12: This figure shows the incremental base resistance (R_b) of a degenerated bipolar transistor as the base current varies.

We can see that the theoretical fit matches the data well in the first part of the curve. For the 200Ω resistor this range was from $10^{-8}A$ to $10^{-6}A$. For the $2k\Omega$ resistor this range was from $10^{-8}A$ to $10^{-7}A$. For the $20k\Omega$ resistor this range was from $10^{-9}A$ to $10^{-8}A$.

Finally, we can extract the incremental transconductance of the diodes with each of the degenerated resistors.

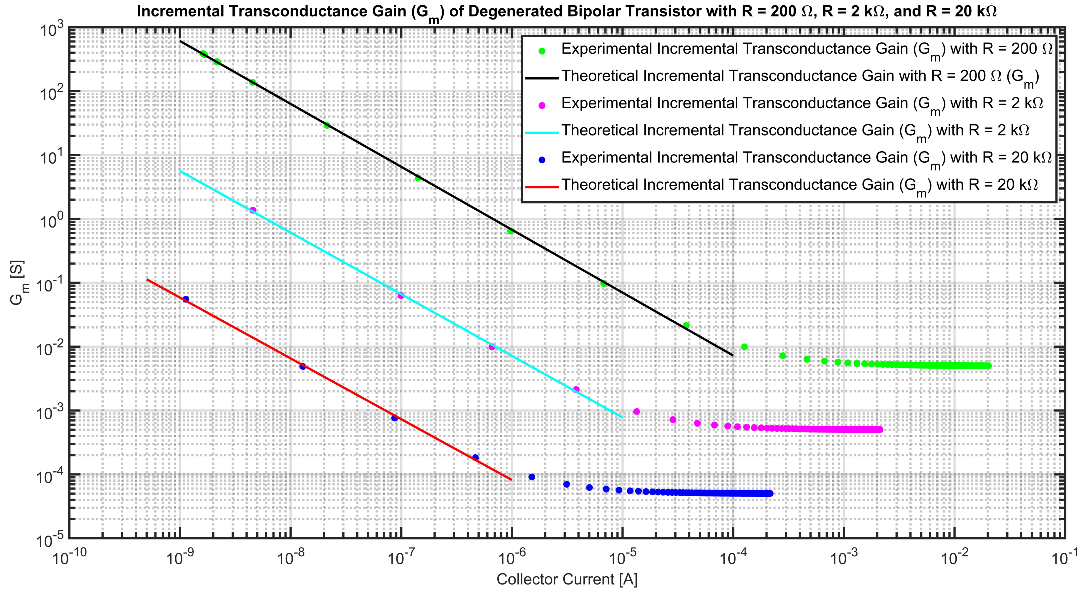

Figure 13: This figure shows the incremental transconductance (G_m) of a degenerated bipolar transistor as the collector current varies.

We can see that the theoretical fit matches the data well in the first part of the curve. For the 200Ω resistor this range was from $10^{-9}A$ to $10^{-6}A$. For the $2k\Omega$ resistor this range was from $10^{-8}A$ to $10^{-5}A$. For the $20k\Omega$ resistor this range was from $10^{-9}A$ to $10^{-4}A$.

3 Experiment 3: Follower Voltage Transfer Characteristics

3.1 Background and Procedure

For this experiment, we considered the voltage transfer characteristics of a common-collector amplifier. The circuit used for this experiment is shown below,

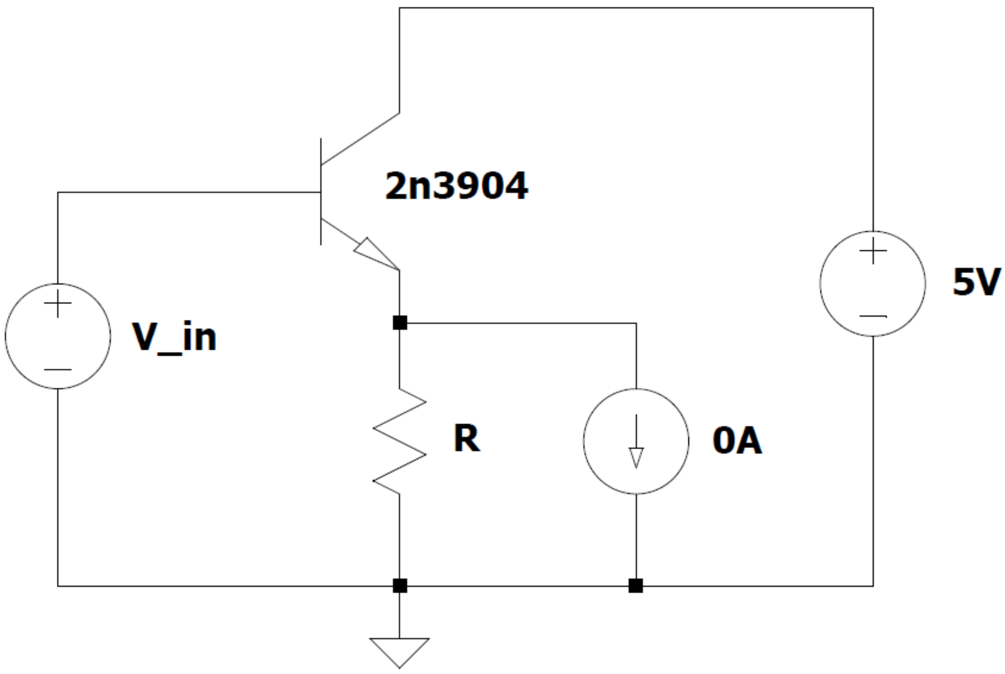

Figure 14: Schematic for circuit used in Experiment 3.

In this circuit, the resistor we used was 20 $k\Omega$. To find the voltage transfer characteristics for this circuit, we swept the input voltage from 0V to 5V.

In theory and practice, this configuration of transistors 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. The emitter voltage follows the base voltage's lead.

3.2 Results and Discussion

We measured the transistor parameter values from this experiment to be,

Extracted Transistor Parameters	
Constant	Extracted Value
I_S	$3.8464 * 10^{-15}$ [A]
U_T	0.0265 [V]

For this experiment, we used a 20 $k\Omega$ as the degeneration resistor. Instead of measuring the current as we did in Experiment 2, we measured V_e. The following figure shows the voltage transfer characteristics for the circuit shown in Figure 14.

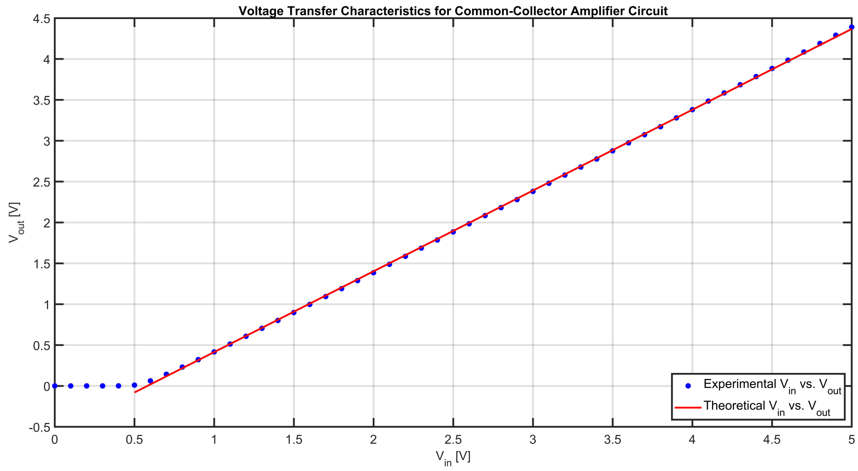

Figure 15: Experimental and Theoretical voltage transfer characteristics of a Common-Collector Amplifier circuit.

From this plot, we can extract an incremental voltage gain of the emitter follower is 0.975 V. The gain is less than one because of inefficiencies on the terminals of the transistor such as incremental resistances on the terminals. The overall average difference between V_{in} and V_{out} is 0.57 V. However, if we only consider the region when V_{in} is above 0.6 V, the average difference of V_{in} and V_{out} is 0.606 V. More specifically, V_{out} is $\sim$ 0.606 V less than V_{in}. We consider this region specifically, because it is when the transistor is operating in the forward active mode. We believe this is determined by turn on voltage of the transistor. We can see in the plot that the linear relationship begins when V_{in} is roughly 0.6 V, which is where the forward active mode begins. When V_{in} is less than 0.6 V, the transistor is operating in saturation mode.

From this plot, we are able to use the theoretical line to find the slope and x-intercept,

Extracted Values	
Parameter	Value
Slope	0.9883
y-intercept	-0.5739 V

From this, we can find that the y-intercept is $-V_{bias}$ and the slope is the incremental voltage gain of the circuit.

4 Experiment 4: Inverter Voltage Transfer Characteristics

4.1 Background and Procedure

We measured the transistor parameter values from this experiment to be,

Extracted Transistor Parameters	
Constant	Extracted Value
I_S	$3.8464 * 10^{-15}$ [A]
U_T	0.0265 [V]

For this experiment, we measured the voltage transfer characteristics for a inverting voltage amplifier which is sometimes called a common-emitter amplifier. The schematic used for this experiment is shown below,

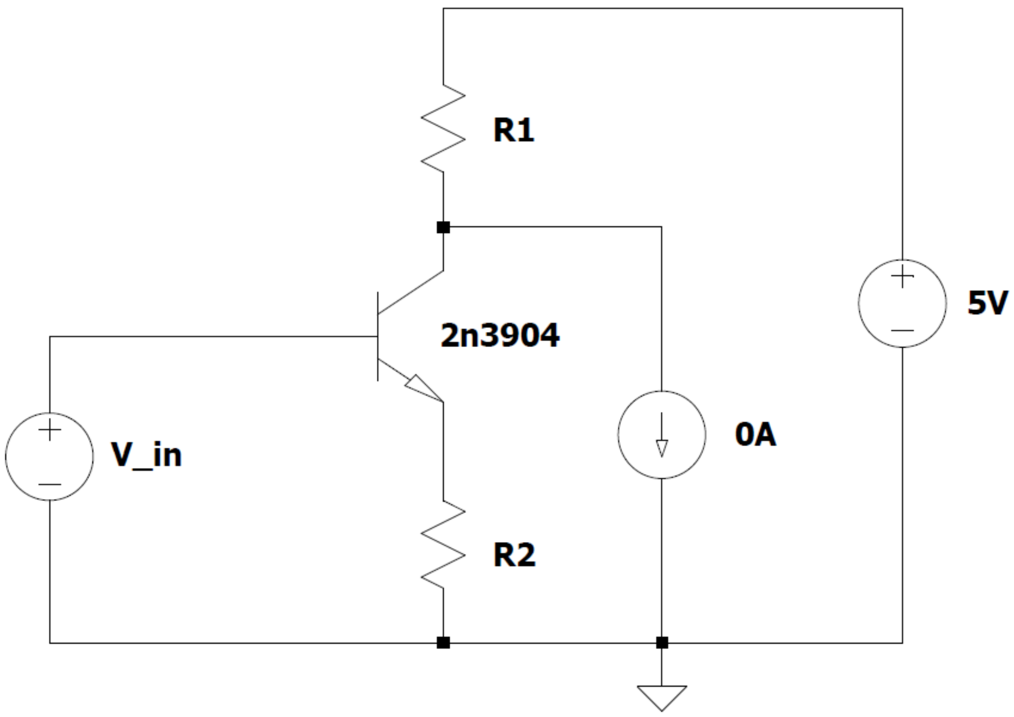

Figure 16: Schematic for circuit used in Experiment 4.

In this circuit, R1 was a resistor value that was a integer multiple of R2. For this experiment, we used a 20 $k\Omega$ resistor for R2. To measure the voltage transfer characteristics, we swept the input voltage from 0V to 5V.

In theory and practice, this configuration of transistors is known as a common-emitter amplifier (with emitter degeneration). The base voltage serves as the circuit's input and the collector voltage is its output.

4.2 Results and Discussion

Using the circuit in shown in Figure 16, we measured the voltage transfer characteristics with different resistance values of R1. The theoretical value of R2 was 20 $k\Omega$; however, we measured this resistor to be 19.65 $k\Omega$. The voltage transfer characteristics are shown in the plot below.

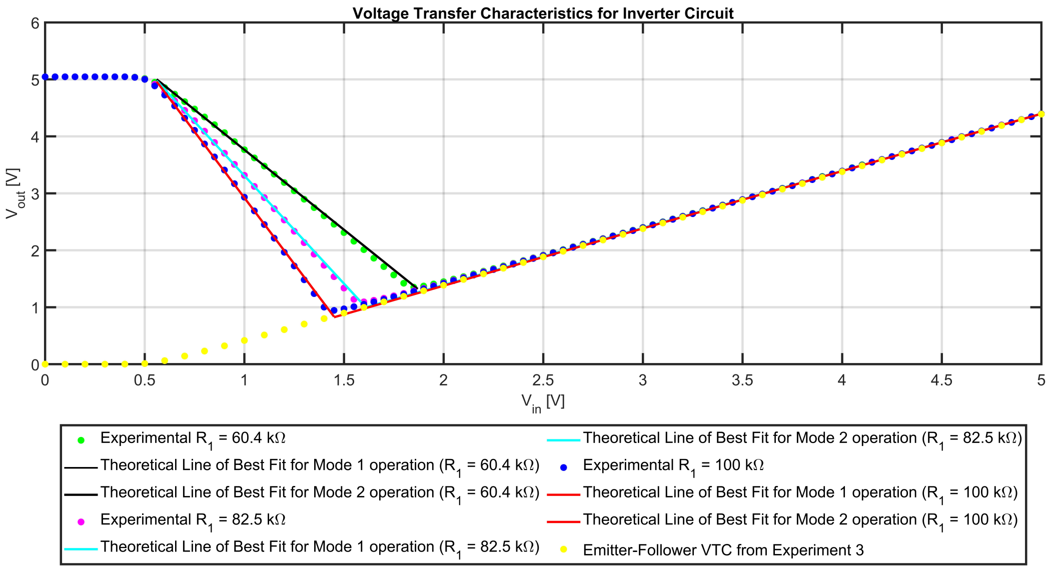

Figure 17: Experimental and theoretical voltage transfer characteristics for inverter circuit.

To find the incremental voltage gain, we only considered the region when V_{in} was between $\sim$ 0.6 V and $\sim$ 1.6 V (this value varies with each resistor as we only considered the region before the output begins to follow the input). The incremental voltage gain characteristics are shown in the table below along with the measured resistance values for each of the resistors.

Incremental Voltage Gain with Different Resistor Values		
Theoretical R1 (In schematic Figure 16) Value	Measured R1 (In schematic Figure 16) Value	Incremental Voltage Gain
60.4 $k\Omega$	60.45 $k\Omega$	-2.81
82.5 $k\Omega$	81.44 $k\Omega$	-3.89
100 $k\Omega$	100.38 $k\Omega$	-4.64

We can see that as we increase R1 the incremental voltage gain increases in magnitude. As this circuit is an inverter, the incremental voltage gain is a negative value. The voltage gain is determined by the reciprocal of the integer multiple of R1 to R2. For example, when R1 is 60 $k\Omega$, it is 3 times R2 (20 $k\Omega$). Similarly, we can see that the incremental voltage gain is -2.81. We believe the inefficiencies due to resistance in the transistors terminals is what accounts for the difference between the resistance value multiple and the measured incremental voltage gain. The tests with other resistance values matches this pattern with the inefficiency exacerbated as we increase the multiple.