Lab Report 3 by Jamie O'Brien, Sabrina Pereira, and Shyheim Russell

1 Introduction

In this lab, we examined the current-voltage characteristics of an npn bipolar transistor over many decades of current along with checking this characteristics with a resistor connected in series with the emitter.

2 Experiment 1: Bipolar Transistor Characteristic

For this section, we looked at how the bipolar transistor behaves when one sweeps the base voltage to cause a 10 nA to 20 mA change in the emitter current. We measured the emitter current while the emitter voltage is fixed to ground in order to use the base and emitter current to find the collector current.

From the changes in base current, we were able to compute the collector current because $I_c = I_e - I_b$, so we can find the collector current as shown in Figure 1. This plot shows that there is an exponential relationship between the collector current, I_c, and the base voltage, V_b, that eventually turns linear, as shown by the linear fit in the plot. Because $log(I_B) = log(I_s) + \frac{1}{U_T} * V_b$, we could find values for the saturation current, I_s, and the thermal heat, U_T. Because the linear fit for I_B is of the form $y = mx + b$ and our plot is plotting the log of the base current, $log(I_b)$, we solved that $I_s = e^b = 2.07 * e^{-16} A$ and $U_T = \frac{1}{m} = 0.0284V$.

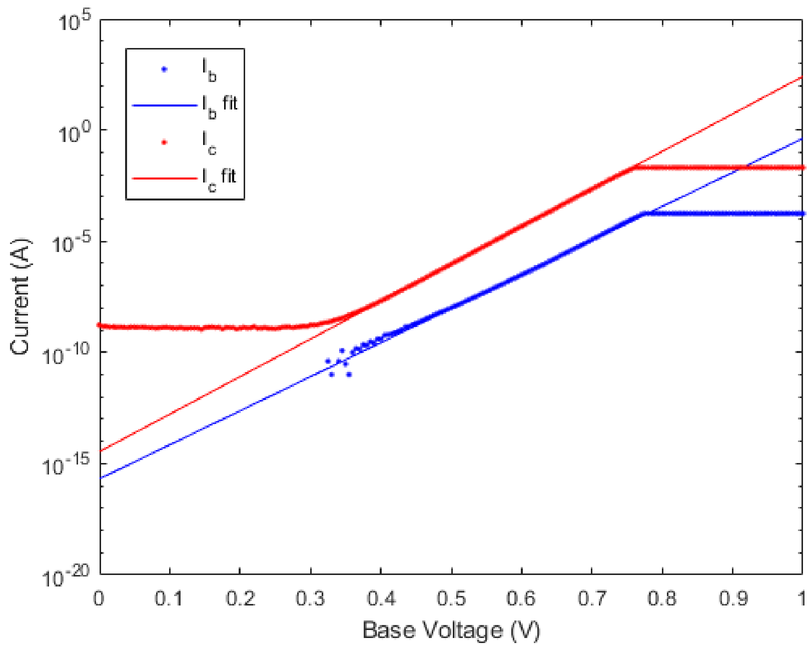

Figure 1: Experiment 1 data showing the relationship between the I_c and I_b with V_b swept to cause a 10 nA to 20 mA change in Ie

We found the current gain, β, which is the ratio between I_C and the base current, I_b, or $\frac{I_c}{I_b}$. Figure 2 shows the relationship between base current and the current gain. The current gain is not constant with the base current, but it is reasonable to assume that this is constant when the transistor is in the forward active mode. For this reason, later on in the lab we assumed $\beta = 150$.

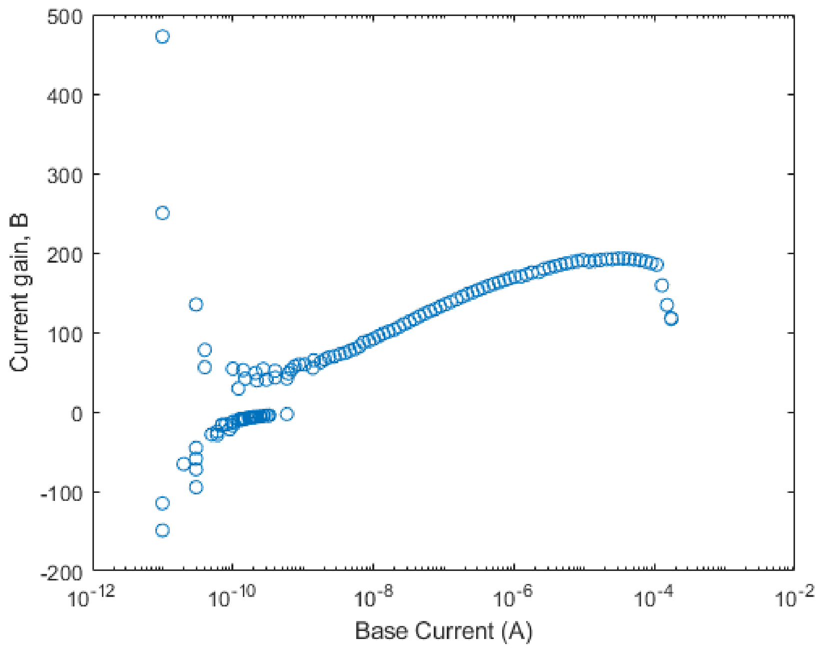

Figure 2: Current gain in respect to base current

From here, we found the incremental base resistance, r_b from our base current-voltage characteristics by solving for $r_b = \frac{\delta V_b}{\delta I_b} = \frac{U_T}{I_b}$. We plotted our incremental resistance with respect to base current. Figure 3 below demonstrates this relationship from our data in comparison with what it theoretically should look like, and it fits quite well.

Finally Figure 4 shows the incremental transconductance gain, g_m, with respect to out base-voltage/collector current. We found that $g_m == \frac{\delta I_c}{\delta V_b} = \frac{I_c}{U_T}$. When the collector current is very low, there is some fluctuation in g_m, and this is likely due to the small amount of current and potential limitations in the SMU. In comparison to the theoretical line, we can see that it fits entirely with the data collected for this section.

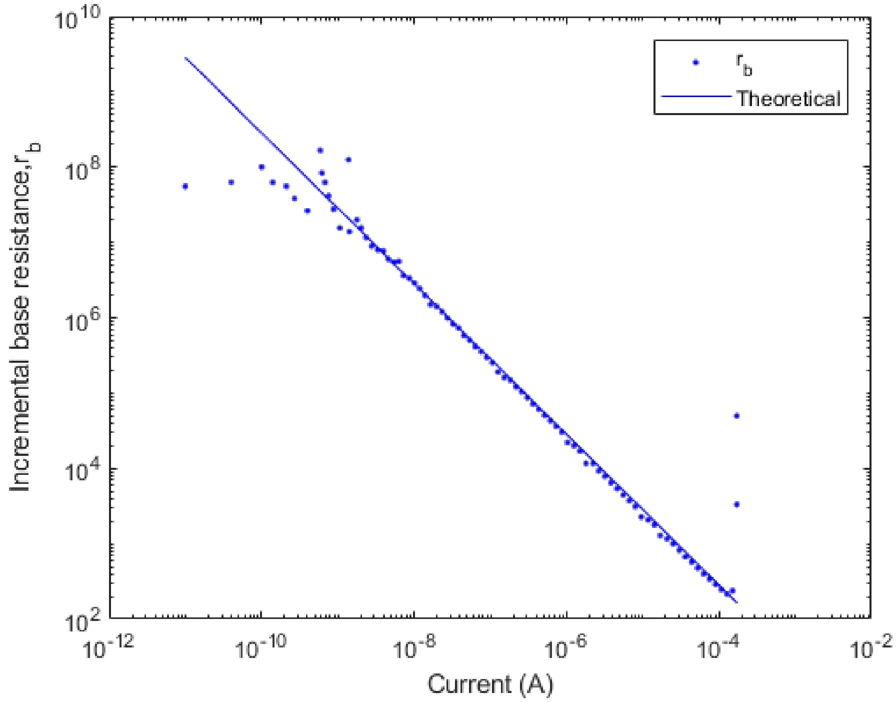

Figure 3: Incremental Resistance in respect to base current in comparison to the theoretical fit

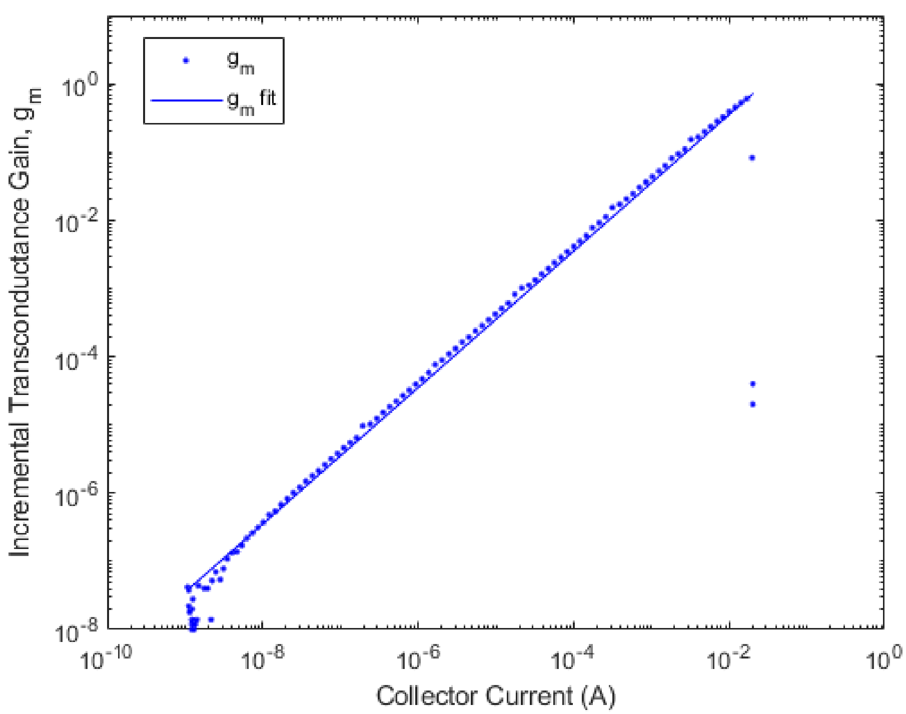

Figure 4: Incremental transconductance gain in respect to collector current

3 Experiment 2: Emitter-Degenerated Bipolar Characteristics

For this section, we started out by sweeping the base voltage from ground to +5V while measuring the current through the emitter and keeping the emitter voltage fixed to ground. While doing this, we connect a resistor in series with the emitter, using 3 resistors, each a magnitude of 10 away from each other - a 100Ω, 1kΩ, and 10kΩ resistor. After performing this measurement of emitter current, we then computed the collector current for each resistor value. The following figures show the collector current as a function of base voltage for each resistor value, including the theoretical fit we would expect to see based on the saturation current I_s and the thermal voltage U_t found in experiment 1. The close fit of the theoretical line indicates that the plots with each resistor are consistent with the transistorâs collector characteristics.

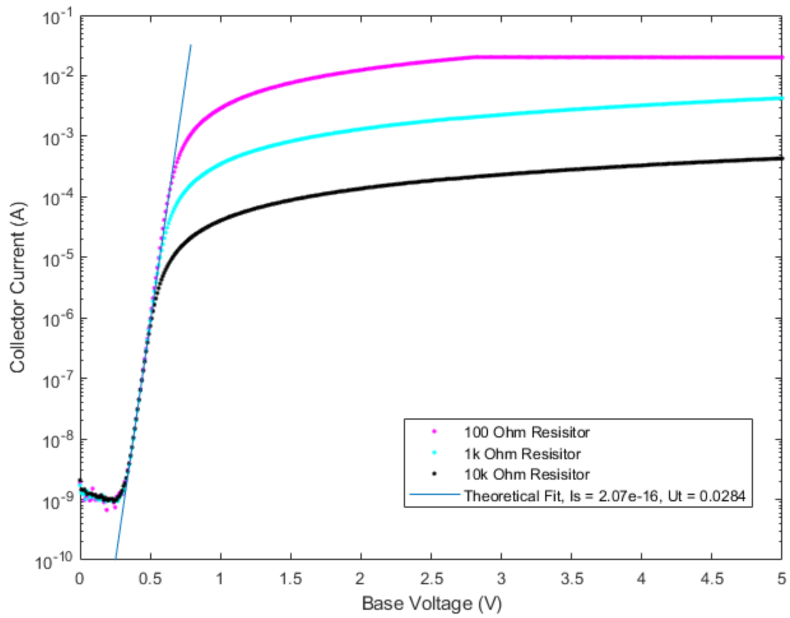

Figure 5: Collector Current vs. Base Voltage, and theoretical fit obtained in Experiment 1

The inverse of the slope for each of the graphs in Figures 6, 7, and 8 are very closely matched to the values of the resistors we chose, which we would expect as these regions of operation should follow Ohm's Law, $V = IR$.

Following this, we extracted the incremental resistance of the base terminal with emitter degeneration by using our experimental data and the equation $R_b = \frac{\delta V_b}{\delta I_b}$. We plotted the incremental resistance with respect to the base current for each resistor value along with the theoretical fits for the data using the equation derived in the prelab, $R_b = \frac{U_t}{I_b} + \beta R$.

As seen in Figure 9, the theoretical lines fit closely with the data recorded, and this same trend can be seen with the incremental transconductance gain of the emitter degeneration. We applied the equation $G_m = \frac{\delta I_c}{\delta V_b}$ to our experimental data, and used the equation derived in the prelab, $G_m = \frac{1}{R} * \frac{1}{1+U_t/I_c R}$.

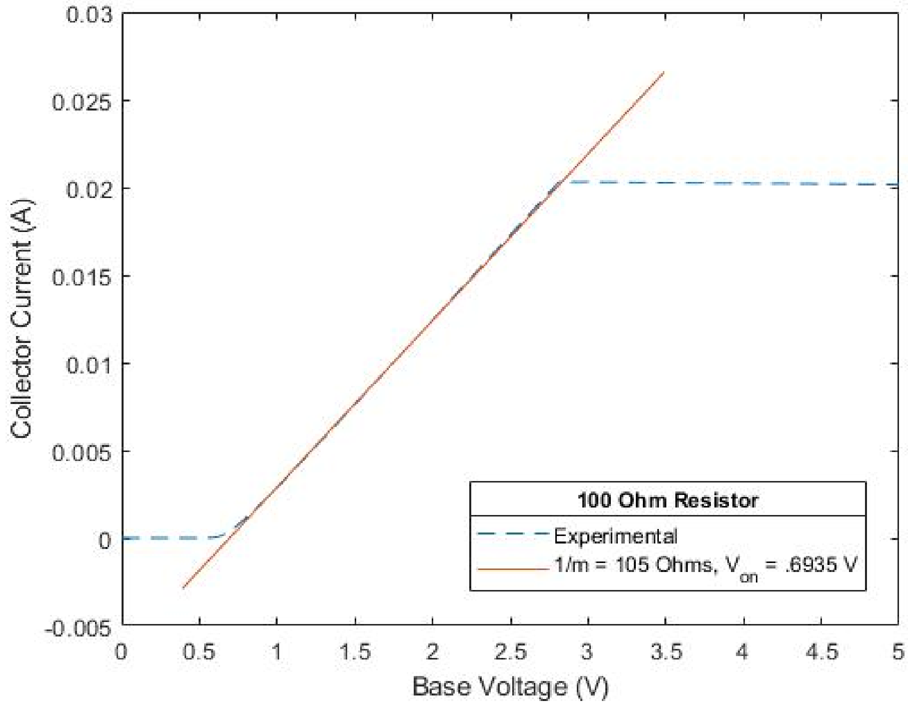

Figure 6: Collector Current vs. Base Voltage with a 100Ω resistor

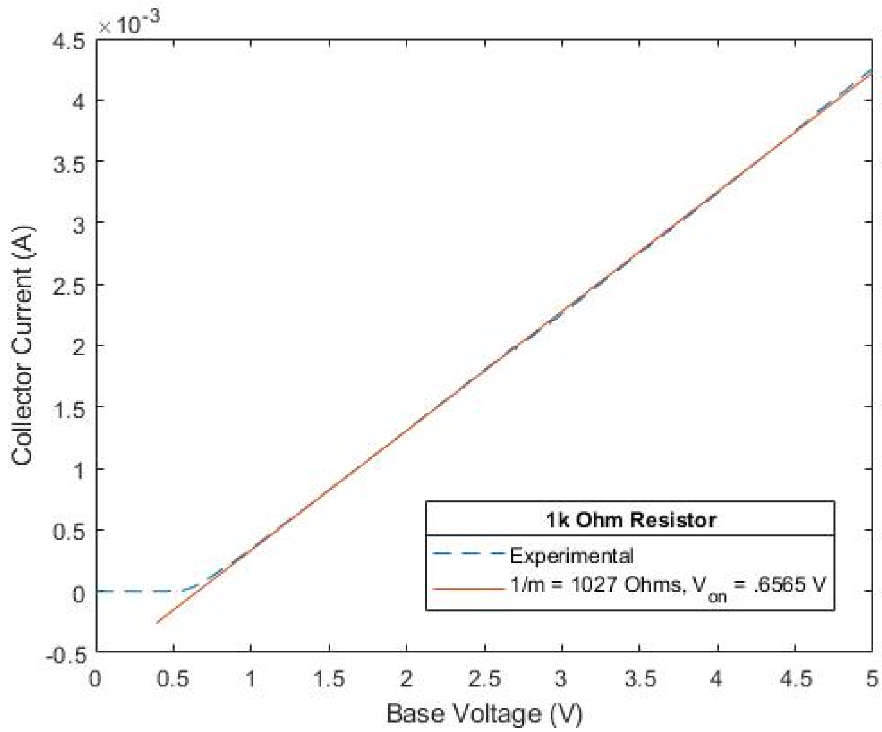

Figure 7: Collector Current vs. Base Voltage with a 1kΩ resistor

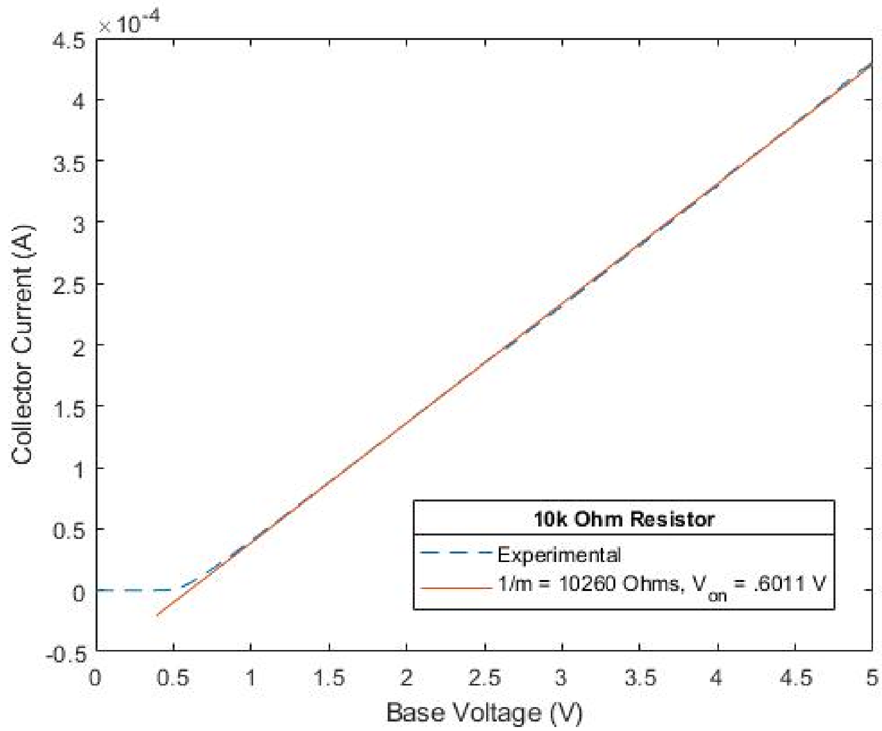

Figure 8: Collector Current vs. Base Voltage with a 10kΩ resistor

4 Experiment 3: Follower Voltage Transfer Characteristics

For this experiment, we created a common-collector amplifier putting a 100Ω resistor in series with the emitter and swept the input voltage from ground to +5V to find the output voltage. We then plotted the Voltage Transfer Characteristic (VTC) in Figure 11, which is the output voltage V_{out} as a function of V_{in}. The line of best fit has a slope of approximately 1, which is the incremental voltage gain. It's approximately 1 because the voltage isn't scaled in the system. The voltage difference is determined by the voltage at which the transistor turns on, or V_{on}, which in our case is about $V_{on} = 0.63$. This is the x-intercept of the VTC, as shown in the plot. When $V_{in} = V_{on}$, the transistor enters forward active mode and the slope of the VTC changes from 0 to 1, as shown in Figure 11. The slope becomes zero again, and this is likely because we chose a small resistor value, which probably caused us to hit some current limit on the Source-Measurement Unit (SMU).

5 Experiment 4: Inverter Voltage Transfer Characteristics

For this experiment, w used a 100Ω resistor in series with the emitter and then used three resistors that are small integer multiples of the 100Ω in between the collector and +5V power supply to create a simple inverting voltage amplifier, commonly known as an inverter or common emitter amplifier.

The Figure 12, shows the VTC that's in the Figure 11 as well as the output voltage as a function of input voltage for each of the inverter circuits we measured. We

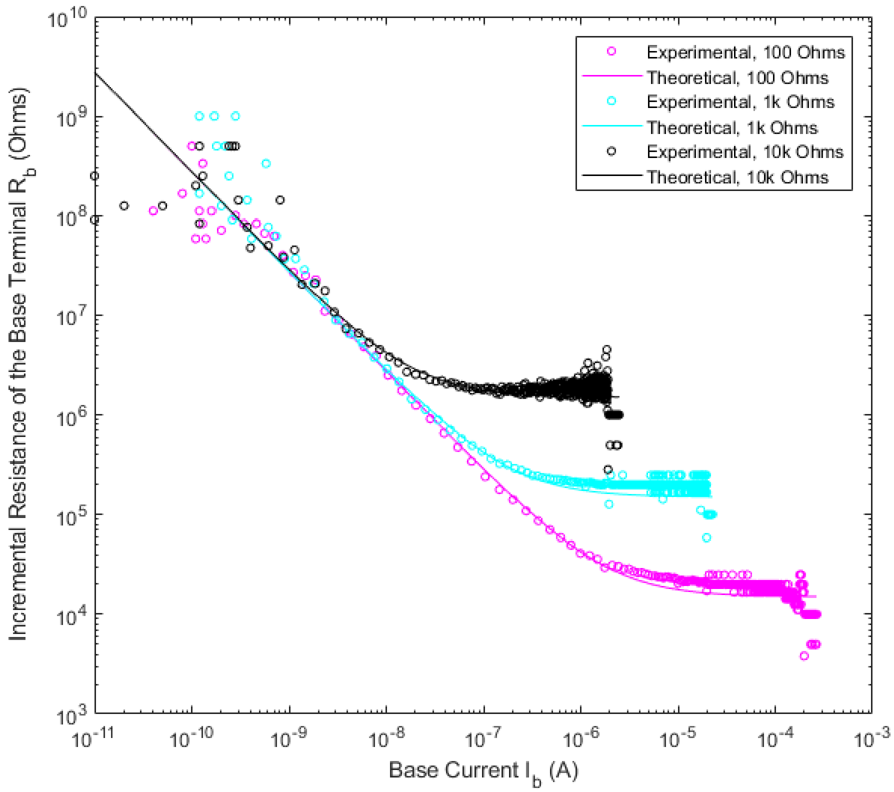

Figure 9: Incremental Resistance using 100Ω, 1kΩ, and 10kΩ resistors

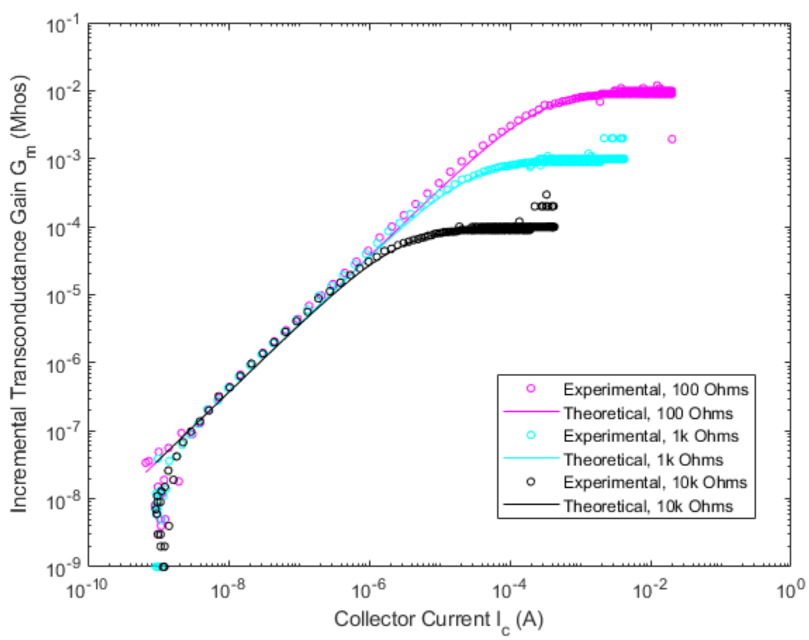

Figure 10: Incremental Transconductance Gain using 100Ω, 1kΩ, and 10kΩ resistors

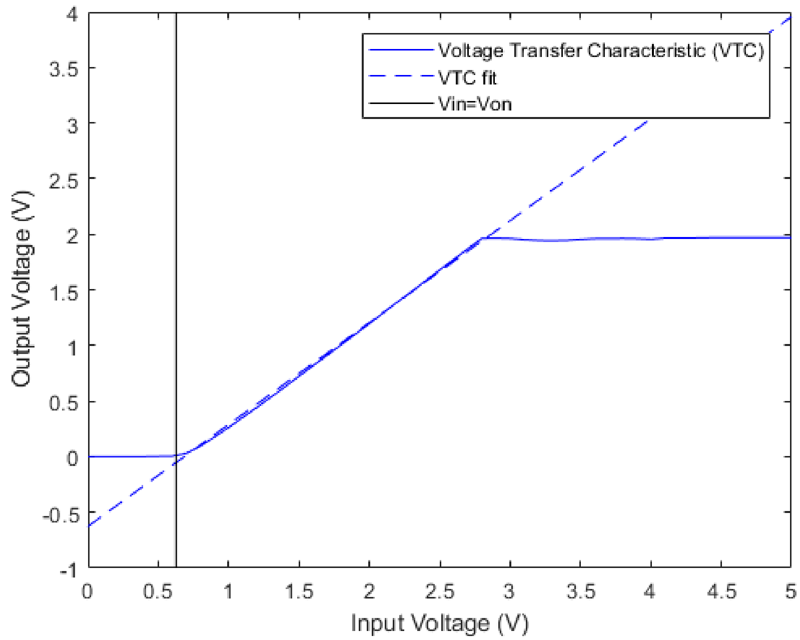

Figure 11: VTC in respect to the input voltage

plotted theoretical fits for each line, and for each of the inverters, the slope began as zero, became negative, switched to positive, and then returned to zero. The slope is zero when the input voltage, V_{in}, is very small because V_{in} is still less than the voltage at which the transistor turns on, V_{on}. When V_{in} becomes greater than V_{on}, the transistor enters forward-active mode. This is where the slope becomes $-m$, where m is the ratio between the first 100Ω resistor in series with the emitter and the second resistor that is in between the collector and the +5V supply. This means that using the second resistors in each of our inverter circuits, the slopes of our inverter VTCs are $R = 200, m = 2$, $R = 300, m = 3$, and $R = 400, m = 4$. These slopes are shown in the figure by the fit lines for the appropriate resistance values. While the slope is $-m$, the transistor moves from forward-active mode to soft-saturation. The slope switches from $-m$ to 1 as the output voltage, V_{out}, becomes greater than V_{in} and the transistor leaves soft-saturation and enters deep-saturation. Here, the slope is approximately 1, which is the same as the slope of the follower circuit VTC. This is determined by the current gain, which is also approximately 1, as the voltage isn't scaled, only offset by V_{on}. This slope of 1 is shown by the fit line for the $R = 100$ inverter VTC. The slope becomes zero again as V_{in} continues increasing, and this is likely because we chose small resistor values, so we must have hit some type of current limit on the SMU.

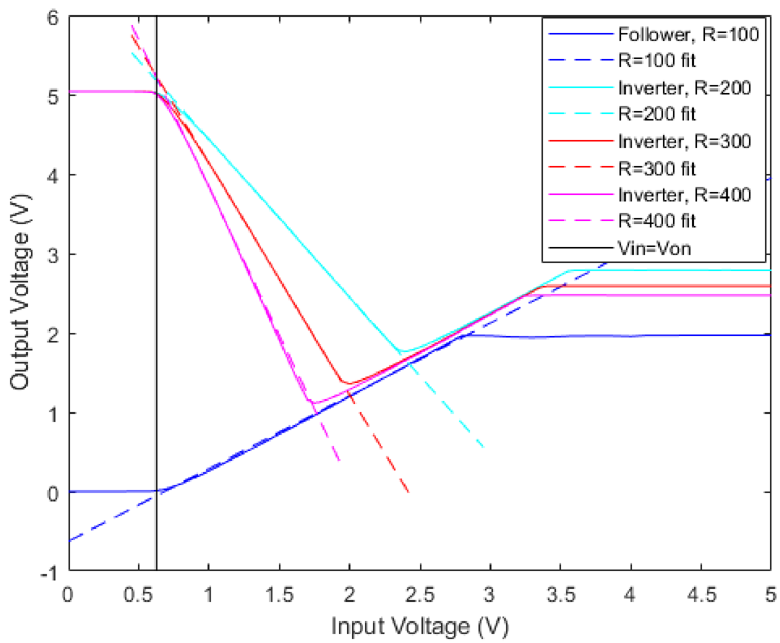

Figure 12: Incremental voltage gain for $200\Omega, 300\Omega, 400\Omega$ resistors