ENGR 2420 Lab 2 Report

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February 26, 2024

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1 Experiment 1 - Diode-Connected Transistor Characteristics

1.1 Process

In the first experiment, we used an SMU to run current and voltage sweeps to determine the corresponding currents and voltages respectfully. Due to its sensitivity, we encountered instances where we attempted to measure values beyond the SMU's range, resulting in clumps of data that we decided to remove from the final figures for clarity. Where this has been done, we have made a note under the figure caption.

The exponential model that we used to fit theoretical lines to our experimental data was created utilizing the ideal diode equation. In general, we were able to attain strong results from this, with our theoretical fit line passing through most of our experimental data points. It was not perfect however, as we needed to truncate some noisy data for the model to plot an accurate line, and our results for the extracted values did not match the theoretical expectations. We extracted our parameters by taking the coefficients from the model generated in MATLAB and using them as follows:

$$\ln I = \frac{1}{U_t} \cdot V_{in} + \ln I_s$$

We can see that $m = \frac{1}{U_t}$ and $b = \ln I_s$.

We explain below that in our case, it is best to simply not use the CV characteristic in any parameter calculations due to the amount of data that had to be truncated. In other cases, we would take some form of average between the 2 datasets, or use a shortest-distance method to plot a line between the 2 datasets and extract parameters from the new fitted line.

1.2 Figures

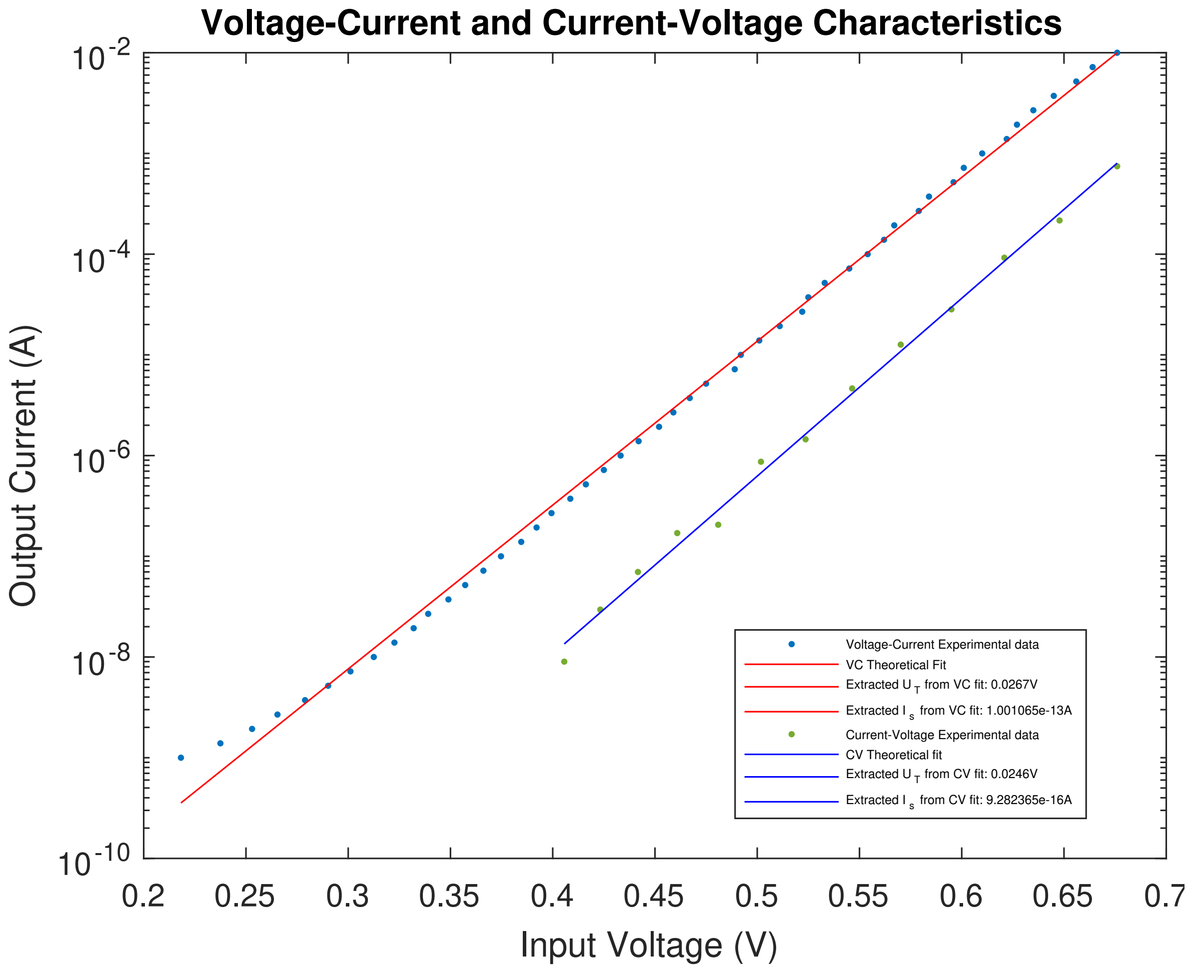

Figure 1: Semilog plot showing voltage-current and current-voltage characteristics, and theoretical fits with extracted parameters. Note that the voltage-current and current-voltage characteristics are slightly different. We have a few explanations as to why this might be the case. Firstly, the CV characteristic data contained many negative values during the sweep that are ignored when plotting on a log scale for mathematical continuity. The CV data may also be shifted because of the variance in the tolerances of the components we used, they are not exact and even within the SMU any discrepancies can lead to vastly different results. Because of these reasons, the remaining data that was not truncated did not exactly match the VC characteristic. The legend shows that the extracted parameters from the VC characteristic yielded a value of $0.0267V$ for the thermal voltage U_T, and $1.001 \times 10^{-13}A$ for the saturation current I_s. We also extracted the parameters from the CV characteristic shown in the legend, but because of the amount of data we had to truncate, they are less reliable and we did not use them for future calculations. The exponential model fits the data relatively well, besides the slight variance in the lower input voltages. We suspect that the model would better fit the data if the SMU could handle lower currents better.

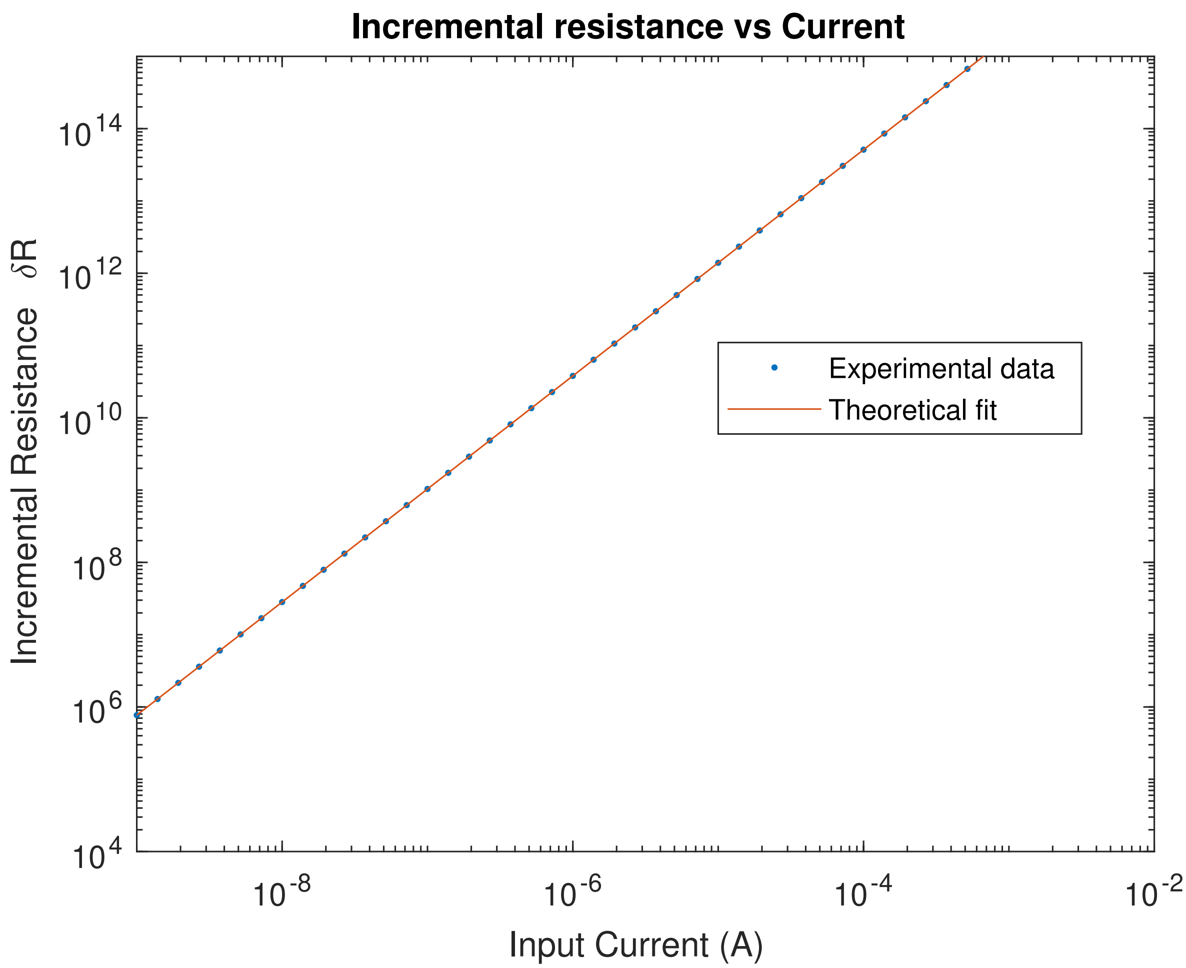

Figure 2: Log-log plot showing incremental resistance of diode-connected transistor as current flows through it. Note that the incremental resistance (δR) is still a resistance, just a small change in resistance. It is still measured in ohms, the lack of units on the y-axis is a misinput. We can see here that the theoretical line fits the experimental data very well, representing a high precision and accuracy in our data, as there are few outliers and the data lies close to the theoretically true value.

2 Experiment 2 - Characteristics of a Resistor and Diode in Series

2.1 Process

For this experiment, we placed a diode-connected transistor in series with resistors of different values. We chose the nominal values of 500Ω, 5000Ω and 50000Ω. We swept through voltages logarithmically from 5 volts down to 0 volts, as this provided more accuracy than sweeping up from 0 volts to 5 volts. We measured the total current through the circuit as well as the voltage drop across the diode-connected transistor and plotted them as functions of the input voltage.

2.2 Hypothesis' (Prelab recap)

We calculated the change in voltage across the transistor to be:

$$\frac{\delta V_d}{\delta V_{in}} = \frac{I_{on}}{I_{in} + I_{on}} \tag{1}$$

When I_{in} is much greater than I_{on}, this value is almost 1, and for the inverse case, the value is approximately 0. We expect to see this in our figures, and we will be able to verify this by fitting a line to the initial linear slope of the voltage across the diode-connected transistor as a function of the applied input voltage for all of the resistors that we used. We expect to see this value approach 0 as the voltages across each transistor begin to diverge.

According to our calculations in the prelab, before the turn-on voltage is reached, the current flowing through the circuit should be very small. We should be able to easily see this visually by inspecting the relevant figures. Since 0 cannot be plotted on a log scale, and the SMU has issues dealing with extremely small currents, we are expecting to see very small values or no data initially. We made sure to take dense datasets for this reason, although this did not fully resolve the visual issues.

After the turn-on voltage is reached, the resistor should become the dominant force, as the incremental resistance of the diode approaches 0. The voltage across the diode is not expected to drop, as the incremental resistance is not negative at any point. We are therefore expecting to see an Ohm's Law-like relationship. We can estimate the current through the circuit as a function of the applied voltage as shown:

$$I_{in} = \frac{V_{in} - V_{on}}{R} \tag{2}$$

We should be able to see this relationship in the linear plots showing the input current as a function of the applied input voltage.

We were able to calculate experimental turn-on currents and voltages using the following equations:

$$I_{on} = \frac{U_T}{R} \tag{3}$$

$$V_{on} = U_T \cdot ln\left(\frac{I_{on}}{I_s}\right) \tag{4}$$

Where:

- I_{on} is the turn-on current in amps
- U_T is the thermal voltage in volts
- R is the resistance in ohms
- V_{on} is the turn-on voltage in volts
- I_s is the saturation current in amps

We are also expecting I_{on} and V_{on} to remain the same throughout, as we are using the same transistor. This can easily be checked by comparing the theoretically calculated values to those extracted from our experimental data.

2.3 Figures

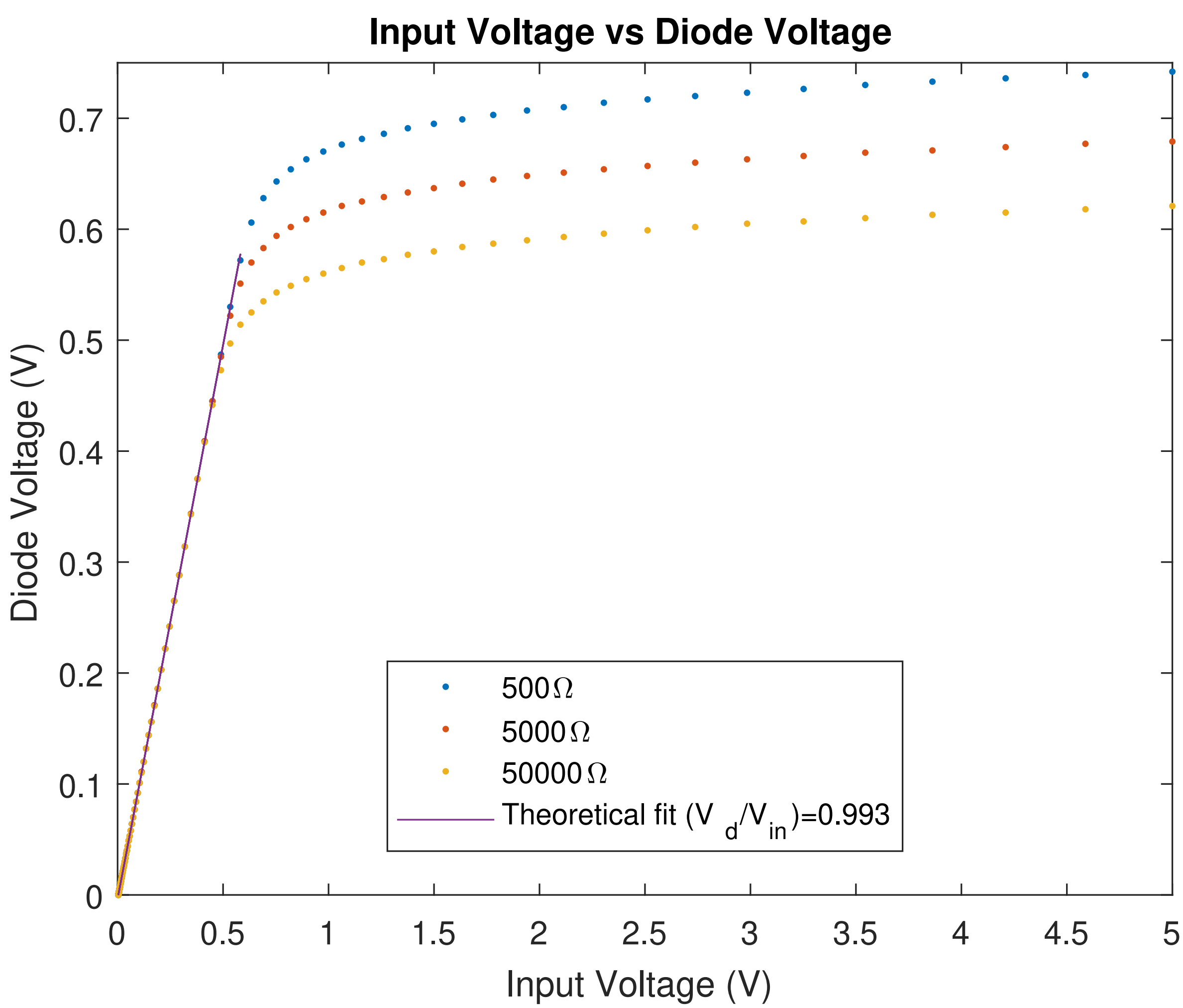

Figure 3: Plot showing the voltage across the diode-connected transistor as a function of the applied input voltage at 500Ω, 5000Ω and 50000Ω. We used the *polyfit* function to fit a line to all three linear parts of each voltage relationship, and as we expected, we can see that the theoretical gives us a $\frac{\delta V_d}{\delta V_{in}}$ of 0.993, which is very close to one and certainly within the range of error that using non-ideal components would lead us to expect.

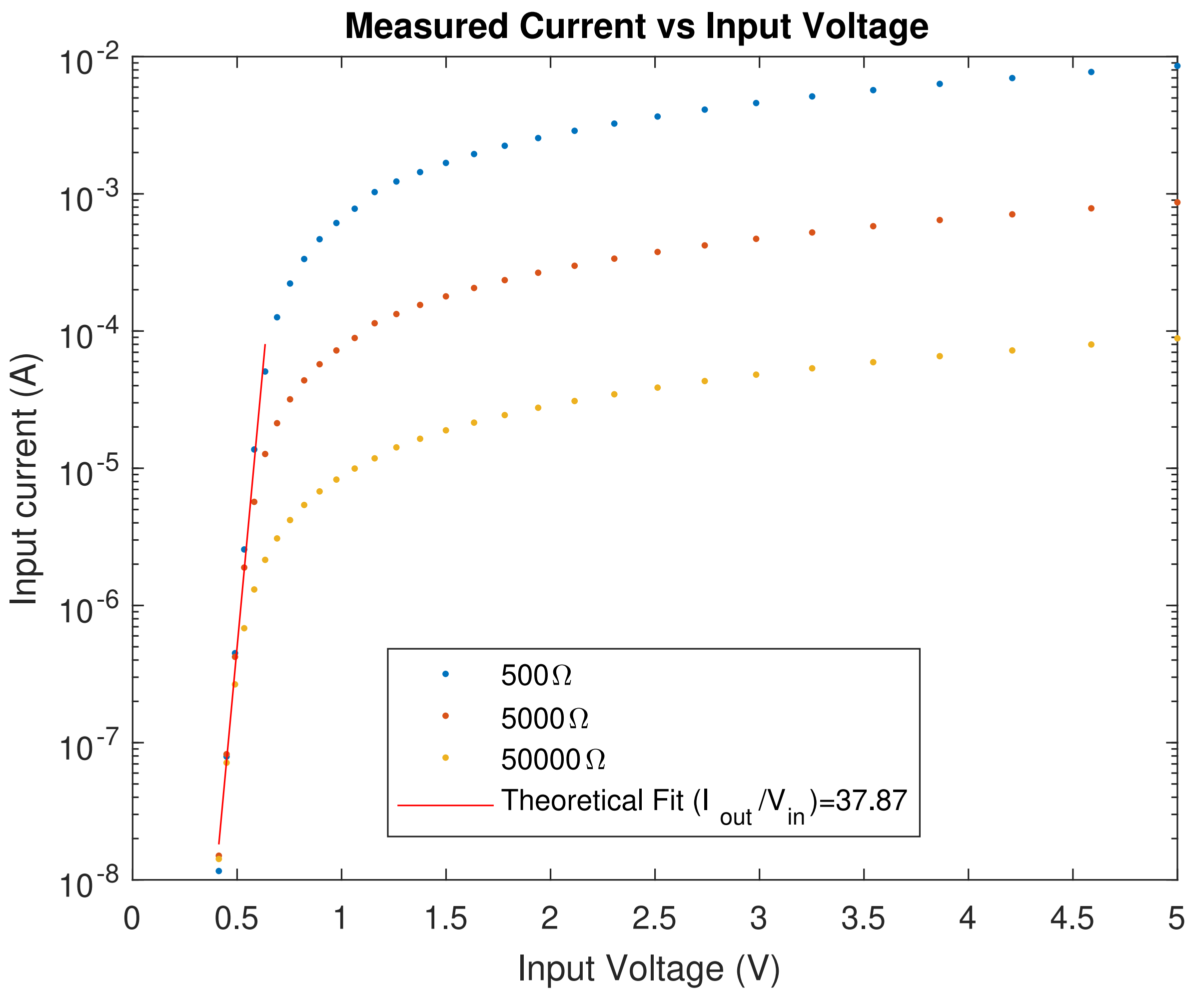

Figure 4: Semilog plot showing measured current flowing into the circuit as a function of applied voltage. We can see here that despite our dense dataset, the number of points truncated to plot a linear line of best fit means that the amount of experimental data used in our plots is very little. This was due to the majority of our very low voltage data being noise, and at voltages and currents that low and that close to 0, there was unexpected behaviour within the SMU that caused some of our data to be skewed. Because of this, our data set was truncated for line-fitting and plotting purposes. We were still able to see a clear relationship between current and voltage with the few data points, however, the accuracy of the extracted parameter is questionable due to the lack of experimental data points that the model was fitted to.

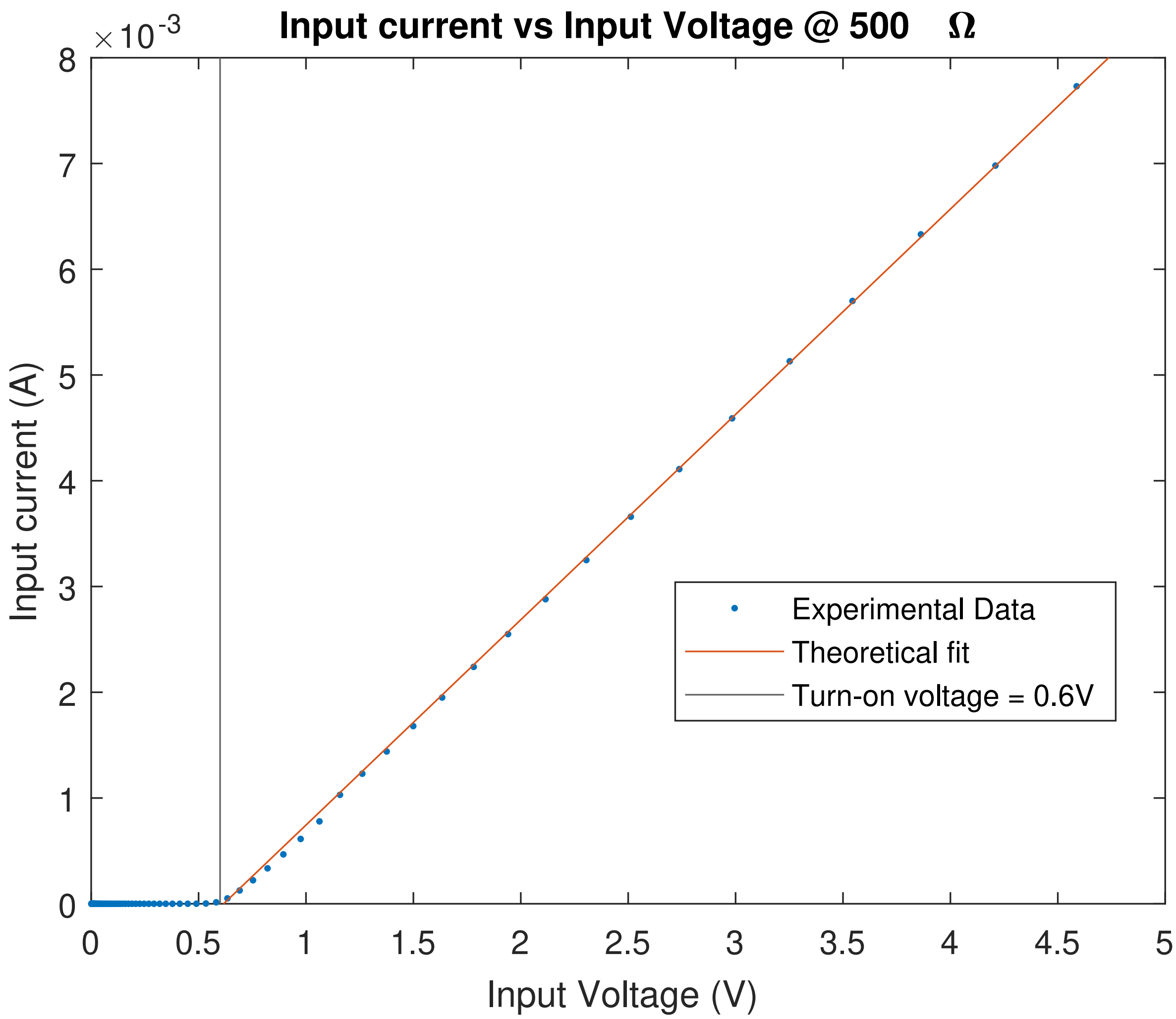

Figure 5: Plot showing input current as a function of applied input voltage for the 500 ohm resistor. A grey vertical line was added at the estimated turn-on voltage based on the experimental data, in this case, $V_{on} = 0.6V$. The theoretical fit shows the expected linear relationship between the current and the voltage once the turn-on voltage is reached, and before the turn-on voltage is reached the current is effectively zero. Both these results line up perfectly with our quantitative analysis. For the theoretical fit, a model was fit to the experimental data according to our prelab analysis described above.

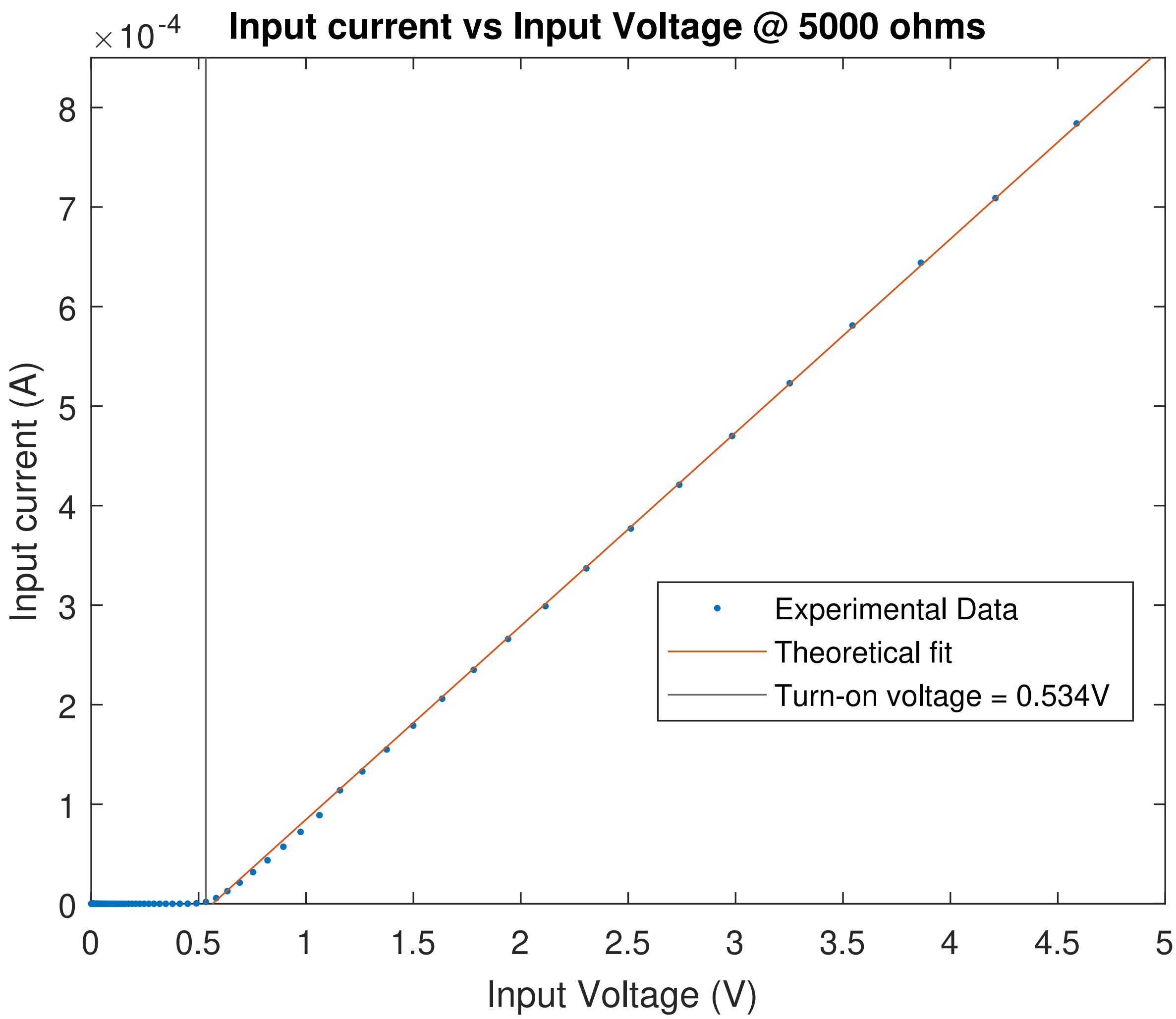

Figure 6: Plot showing input current as a function of applied input voltage for the 5000 ohm resistor. A grey vertical line was added at the estimated turn-on voltage based on the experimental data, in this case, $V_{on} = 0.534V$. The theoretical fit shows the expected linear relationship between the current and the voltage once the turn-on voltage is reached, and before the turn-on voltage is reached the current is effectively zero. Both these results line up perfectly with our quantitative analysis. For the theoretical fit, a model was fit to the experimental data according to our prelab analysis described above.

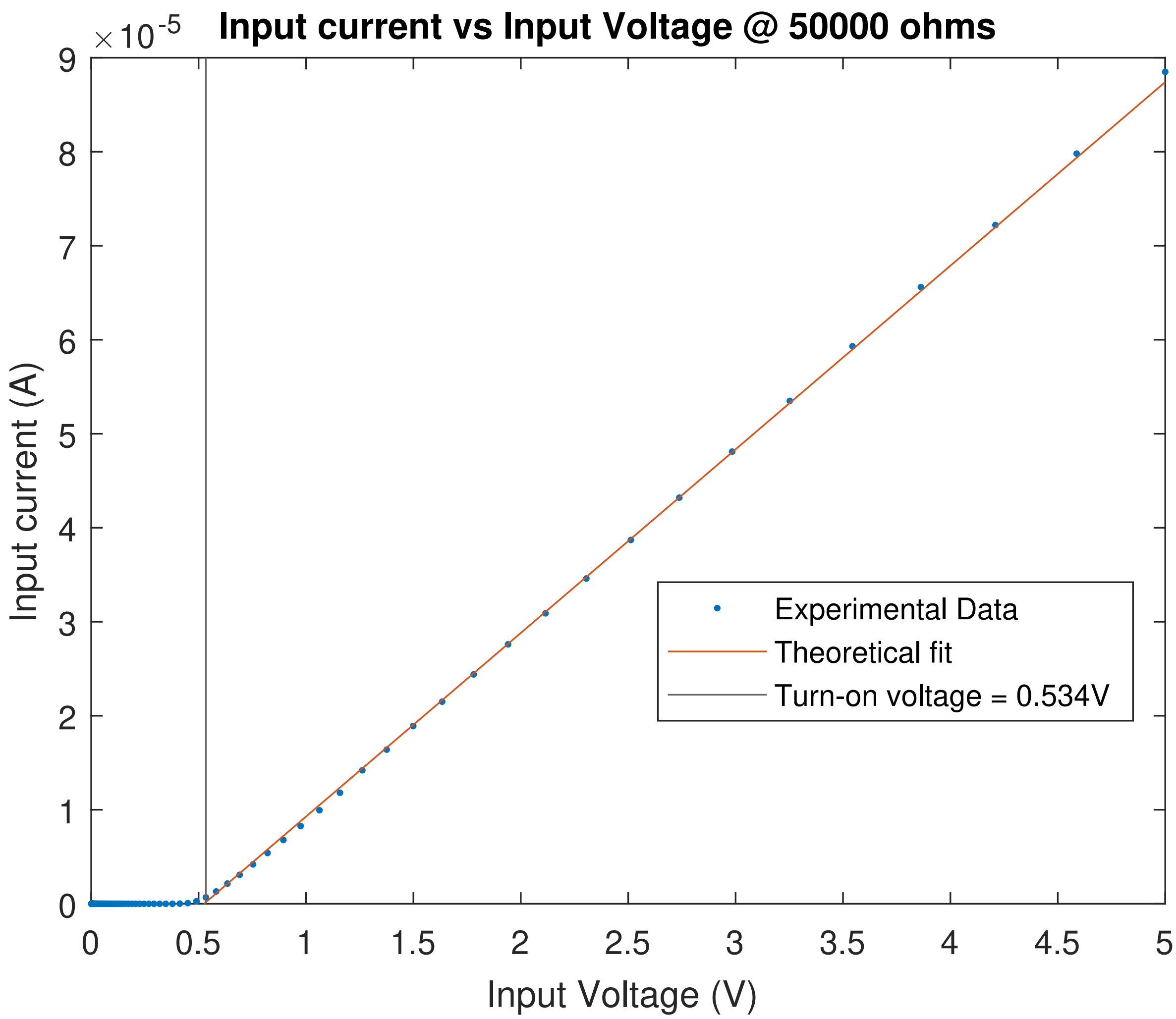

Figure 7: Plot showing input current as a function of applied input voltage for the 50000 ohm resistor. A grey vertical line was added at the estimated turn-on voltage based on the experimental data, in this case, $V_{on} = 0.534V$. The theoretical fit shows the expected linear relationship between the current and the voltage once the turn-on voltage is reached, and before the turn-on voltage is reached the current is effectively zero. Both these results line up perfectly with our quantitative analysis. For the theoretical fit, a model was fit to the experimental data according to our prelab analysis described above.

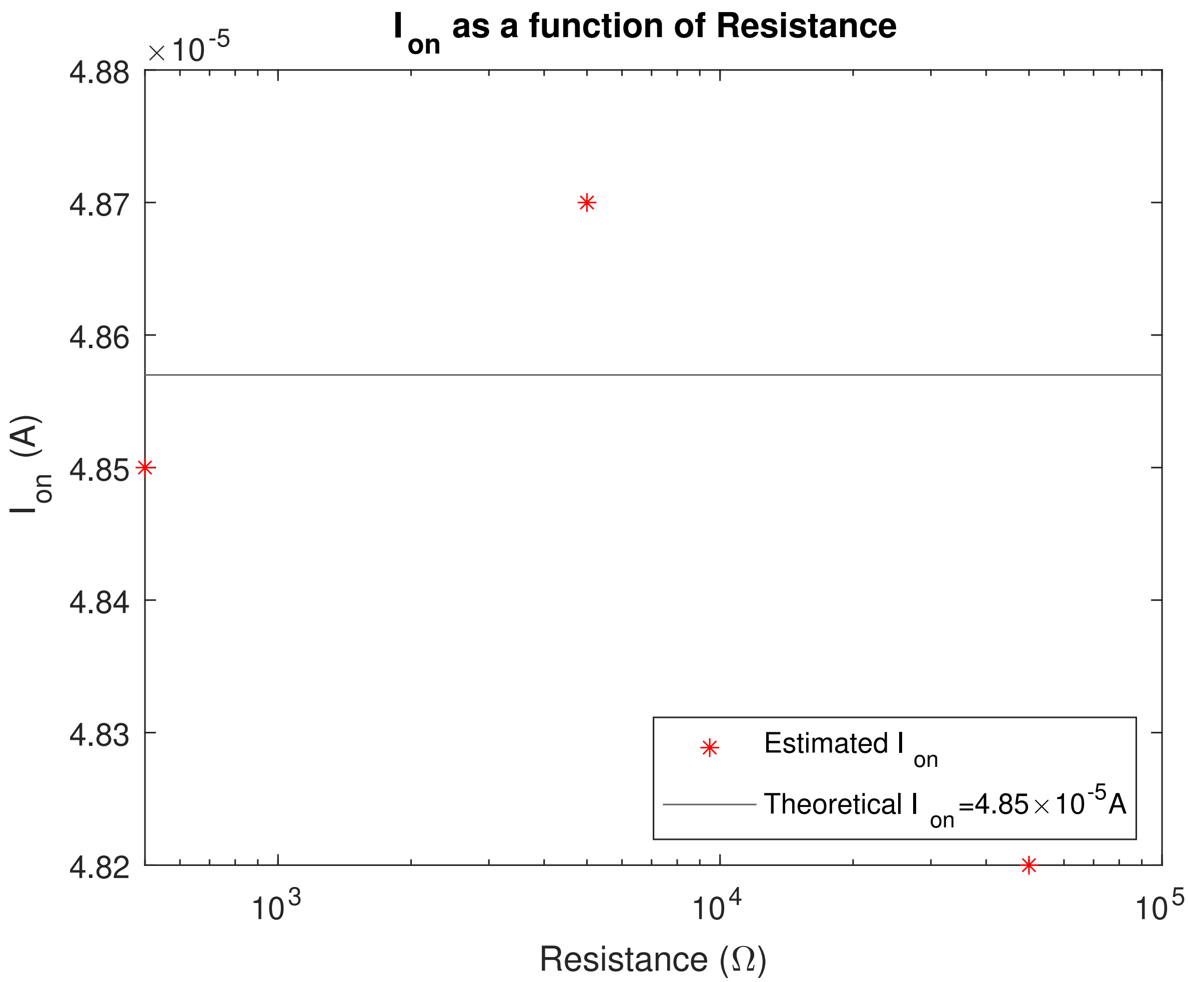

Figure 8: Plot showing the turn-on current I_{on} as a function of resistance. For each of the resistance values we used our experimental data to calculate the corresponding turn-on current using the equations in our hypothesis, and compared them to the expected theoretical turn-on current which we calculated to be 4.85×10^{-5} amps. We can see that while the estimated I_{on} from our experimental data varies slightly, we are on the scale of micro amps, meaning any recorded variances in current can be purely instrumental rather than experimental, and the tolerances of the resistors we used mean there will be some natural variances in our results. Overall, the experimental turn-on current lines up well with expectations.

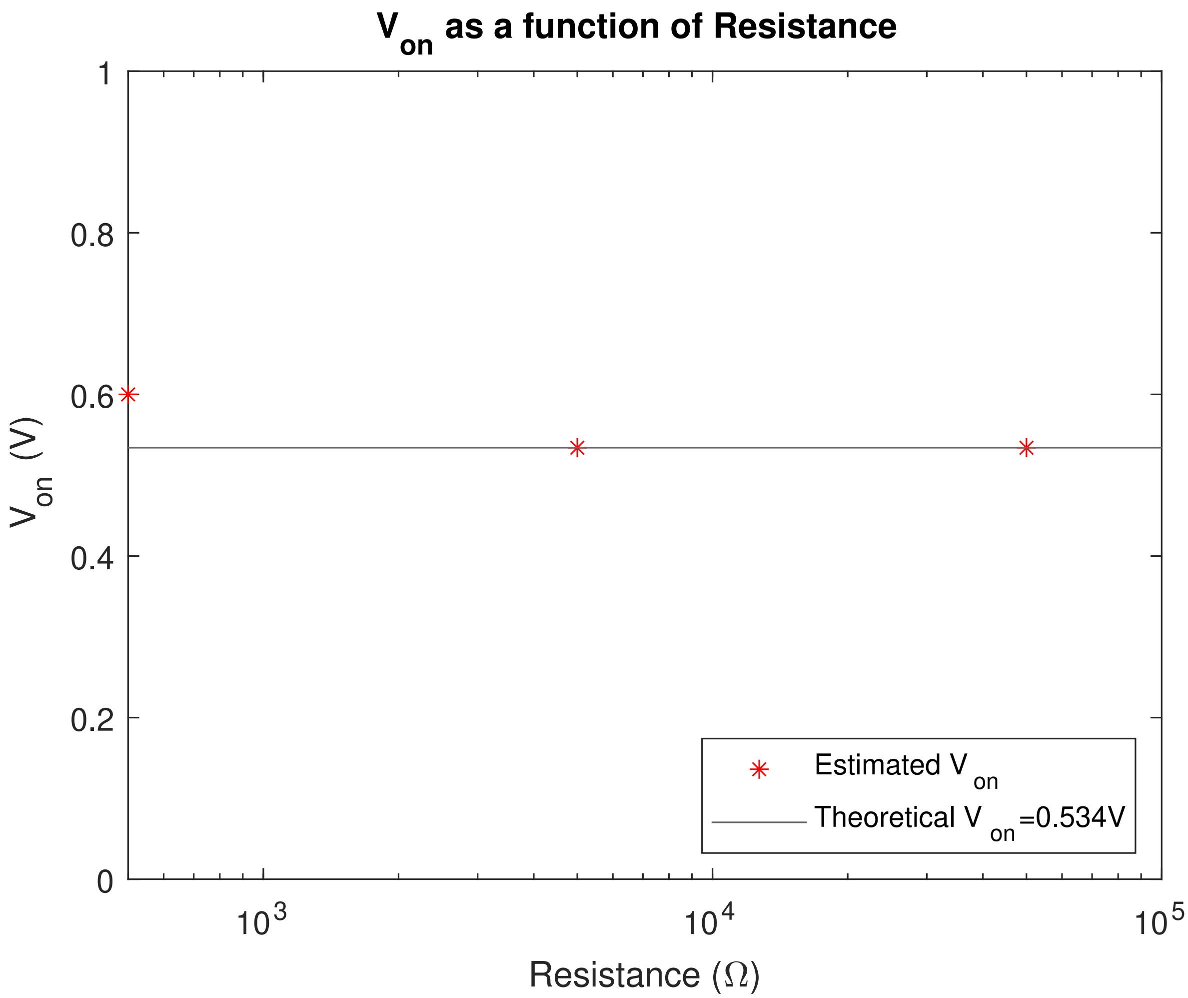

Figure 9: Plot showing the turn-on current V_{on} as a function of resistance. For each of the resistance values we used our experimental data to calculate the corresponding turn-on voltage using the equations in our hypothesis, and compared them to the expected theoretical turn-on voltage which we calculated to be 0.534 volts. We can see that while the estimated V_{on} from our experimental data varies slightly, our results are all accurate to the theoretical value, accounting for the tolerances of the resistors we used. Overall, the experimental turn-on voltage lines up well with expectations.