Circuits Lab 2 Report

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1 Experiment 1: Diode-Connected Transistor Characteristics

This experiment investigates the characteristics of a diode-connected 2N3904 bipolar junction transistor (BJT). In the experiment, we measure its voltage–current (V-I) and current–voltage (I-V) characteristics over a wide range of currents.

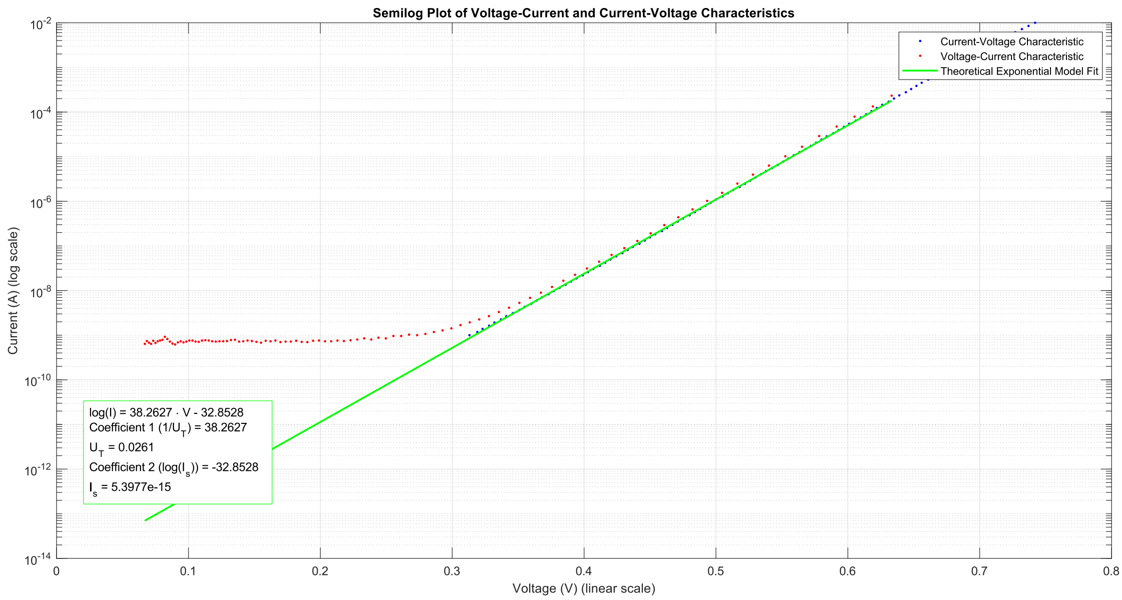

Figure 1: A semilog plot overlaying the current-voltage and voltage-current characteristics, as well as the theoretical exponential model fit and the derived thermal voltage and the reverse-bias saturation current.

In order to derive the values of U_T and I_S, we need to linearize the ideal diode equation. For a diode with a forward bias, the ideal diode equation given is:

$$I = I_S e^{\frac{V}{U_T}}$$

We can take the natural log of the equation and get:

$$log(I) = log(I_S e^{\frac{V}{U_T}})$$

$$= log(I) = log(I_S) + log(e^{\frac{V}{U_T}})$$

$$= log(I) = log(I_S) + \frac{V}{U_T}$$

Now, if the voltage and current values are given, we know that U_T is the inverse of the slope of the linear relation between the voltage and the natural log of the current, and that I_s is given as e raised to the power of the y-intercept of that relation.

There don't appear to be significant differences between the voltage–current characteristic and the current–voltage characteristic. The current-voltage characteristic doesn't extend towards the lower voltage ratings, and we see a little bit of a diversion at that point, but the two characteristics are very consistent under higher voltage and current inputs. The exponential model fits the data very well for the same higher voltage/current inputs, but diverges from the voltage-current characteristic under lower voltage inputs. This divergence could be the product of the limitations of the instrumentation used, very slight series resistance present within the diodes, or measurement error.

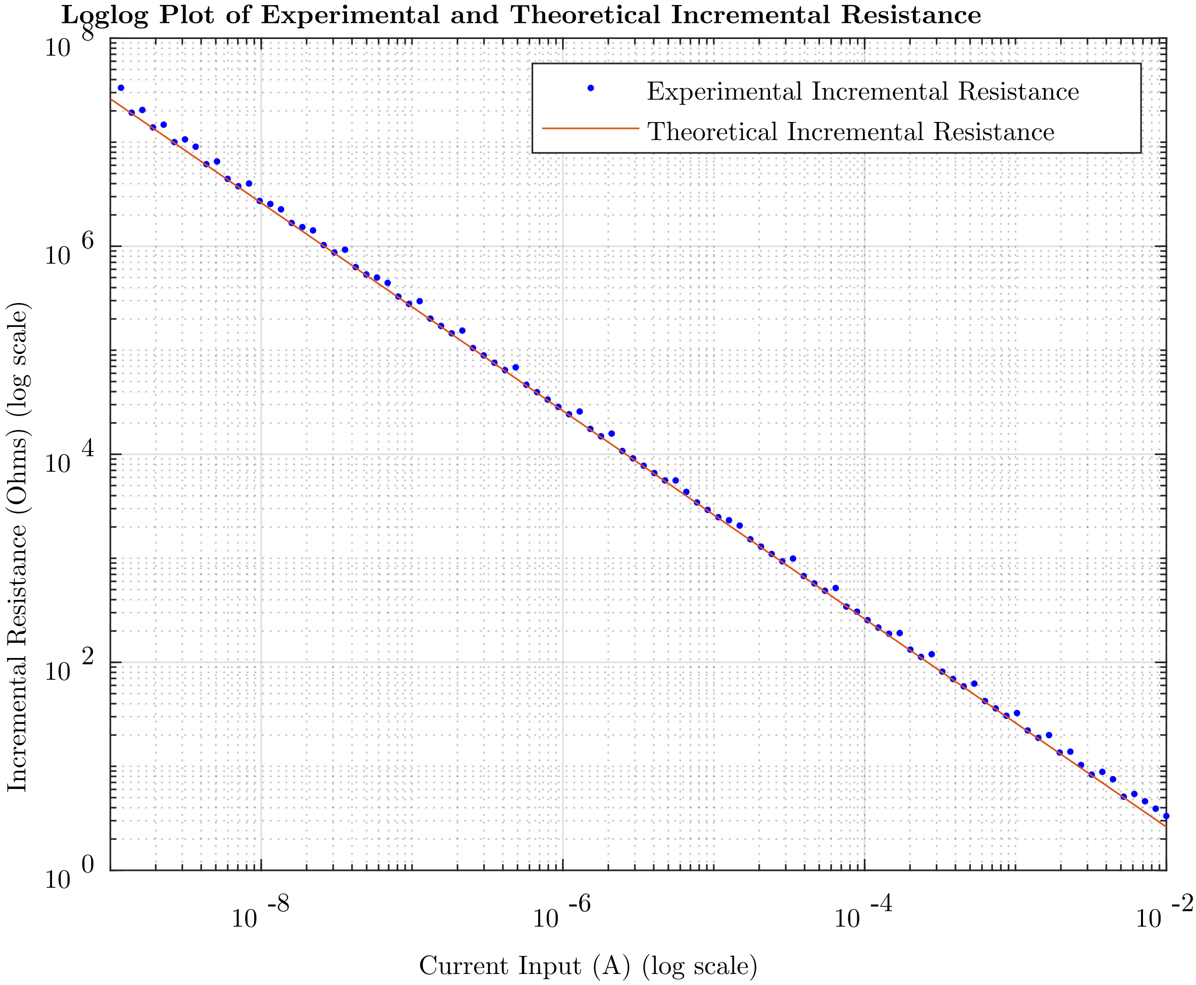

Figure 2: A loglog plot overlaying the experimental calculated and the theoretical values of the incremental resistance of the diode.

The theoretical fit matches the extracted incremental resistance calculated from the voltage and current readings.
In this lab, our findings validated our theoretical measurements for the incremental resistance, thermal voltage, and reverse-bias saturation current, but we also deviations between the ideal diode equation model and the observed behavior from our diode.

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

For the next experiment, we examine how a Resistor and a Diode-Connected Transistor act in series. We chose three resistors valued at 3kΩ, 30kΩ, and 300kΩ. Next, we put each of these resistors, in turn, in series with our 2N3904 and measured the current flowing into the series combination and the voltage across the diode-connected transistor, sweeping the input voltage from zero to five volts.

First, let's examine the current across the resistor/diode-connected transistor circuit as a function of the applied input voltage for each resistors that we used. From the prelab, we know the theoretical current when $V_{in} << V_{on}$ (the transistor is in the off state) for this type of circuit changes exponentially with V_{in} and is equivalent to:

$$I_{in} = I_s \left(e^{\frac{V}{U_T}} - 1 \right) \text{ amps}$$

In experiment one, we found U_T to be 0.02673... volts, and we know I_s to be $e^{-32.1846}$ amps. With these constants, we can calculate the theoretical current through our resistor/transistor circuit. In Figure 3, we plot our measured data for each of our resistors and our theoretical current fit in the transistors' off state.

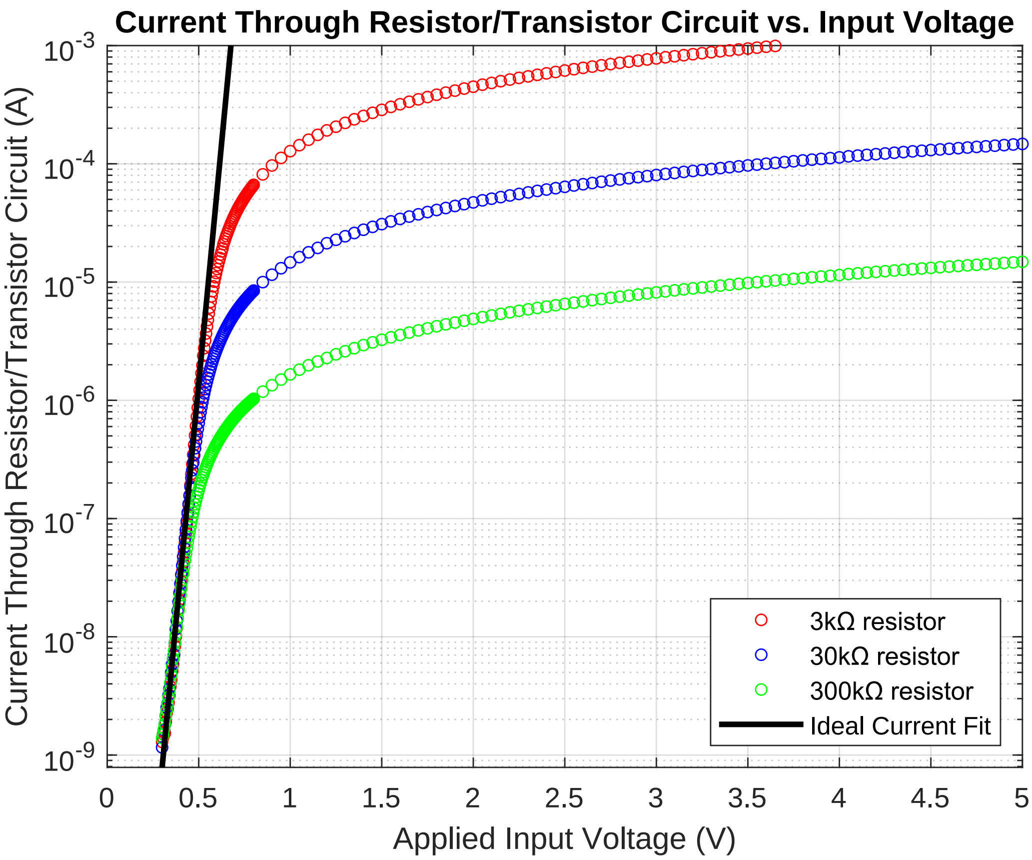

Figure 3: The current through the Resistor/Transistor circuit as a function of input voltage for three different resistors valued at 3kΩ, 30kΩ, and 300kΩ. The ideal current fit is plotted for the off state of the transistor, when $V_{in} << V_{on}$. V_{in} is swept from 0.3 volts to 5 volts. Note that the y-axis is logarithmic.

As seen in Figure 3, our resistor/transistor behaves as expected. When the transistor is off ($V_{in} << V_{on}$), the current is exponentially proportional to V_{in}. Once the transistor is on ($V_{in} >> V_{on}$), the current increases linearly in proportion to V_{in}/R.

Next, let's examine the voltage across the diode-connected transistor as a function of the applied input voltage for each of the resistors that we used. We can again reference the prelab and find our ideal transistor voltage for $V_{in} << V_{on}$:

$$V_{out} = U_T \ln\left(\frac{I_{in}}{I_s} + 1\right) \text{ volts}$$

Since we already found the ideal current as a function of applied input voltage, we can then calculate voltage across the transistor as a function of applied input voltage. Substituting in $U_T = 0.02673...$ volts, and $I_s = e^{-32.1846}$ amps, we can calculate the theoretical voltage across our resistor/transistor circuit. In Figure 4, we plot our measured data for each of our resistors and our theoretical voltage fit in the transistors' off state.

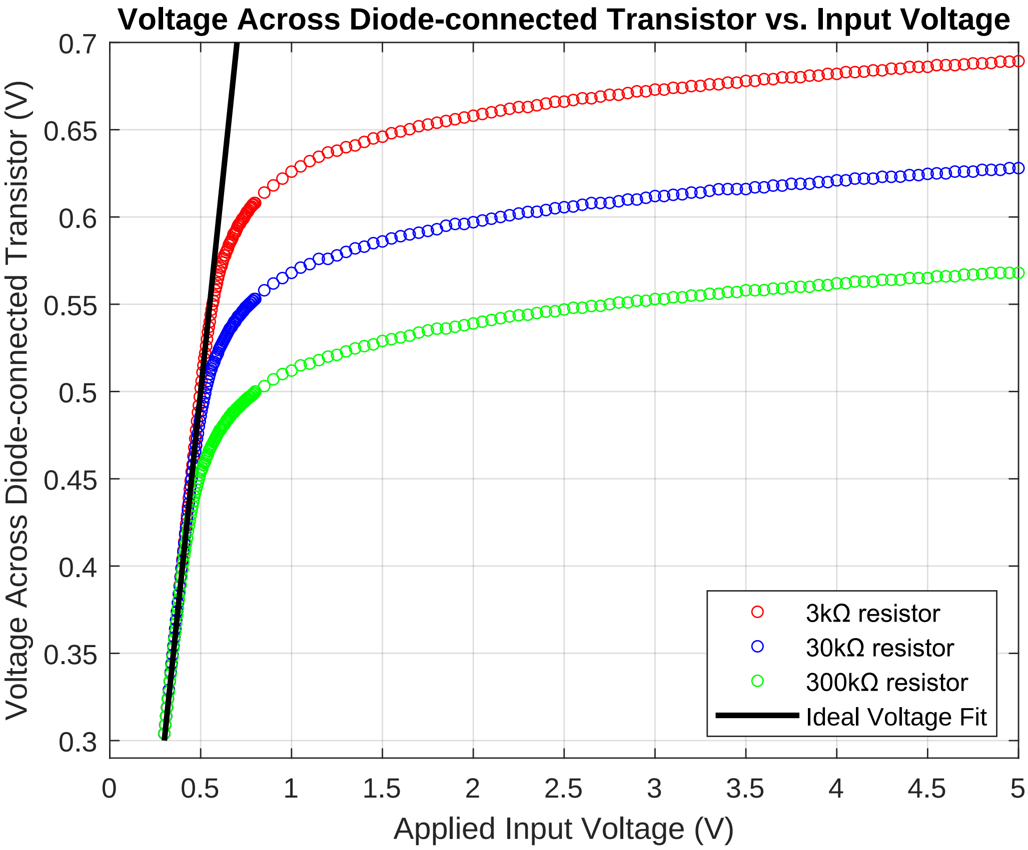

Figure 4: The voltage across our transistor as a function of input voltage for three different resistors valued at 3kΩ, 30kΩ, and 300kΩ. The ideal voltage fit is plotted for the off state of the transistor, when $V_{in} << V_{on}$. V_{in} is swept from 0.3 volts to 5 volts.

Once again, we can see in Figure 4 that the ideal voltage fit matches nicely with the predicted fit for the transistor's off state. Additionally, the voltage across the transistor does quantitatively behave as expected; it is linearly related to V_{in} when $V_{in} << V_{on}$, and logarithmically related to V_{in} when $V_{in} >> V_{on}$.

Next, we created linear plots showing the current as a function of the applied input voltage for each of the three resistors. This allows us to analyze current as a function of voltage after $V_{on} << V_{in}$. After $V_{on} << V_{in}$, the transistor reaches its "on" state, allowing current to flow through it. As such, the current then changes linearly to Vin and dependant on the resistance. From the prelab, we can estimate the ideal current as:

$$I_{in} = \frac{V_{in} - V_{on}}{R} \text{ amps}$$

This is due to the assumption that after $V_{on} << V_{in}$, $V_{transistor} \approx V_{on}$. We can solve for V_{on} as:

$$V_{on} = U_T \log(\frac{I_{on}}{I_s}) \text{ volts, where } I_{on} = \frac{U_T}{R} \text{ amps.}$$

Plugging in our values for U_T, I_s, and our three resistors, we get the results displayed in table 1.

Resistor	$I_{on}(A)$	$V_{on}(V)$
3kΩ	$8.91 * 10^{-6}$	0.5496
30kΩ	$8.91 * 10^{-7}$	0.4880
300kΩ	$8.91 * 10^{-7}$	0.4265

Table 1: A table with the $I_{on}(A)$ and $V_{on}(V)$ values for each resistor.

Finally, we can plot our current as a function of the applied input voltage for each of the three resistors (Figures 6, 7, and 7).

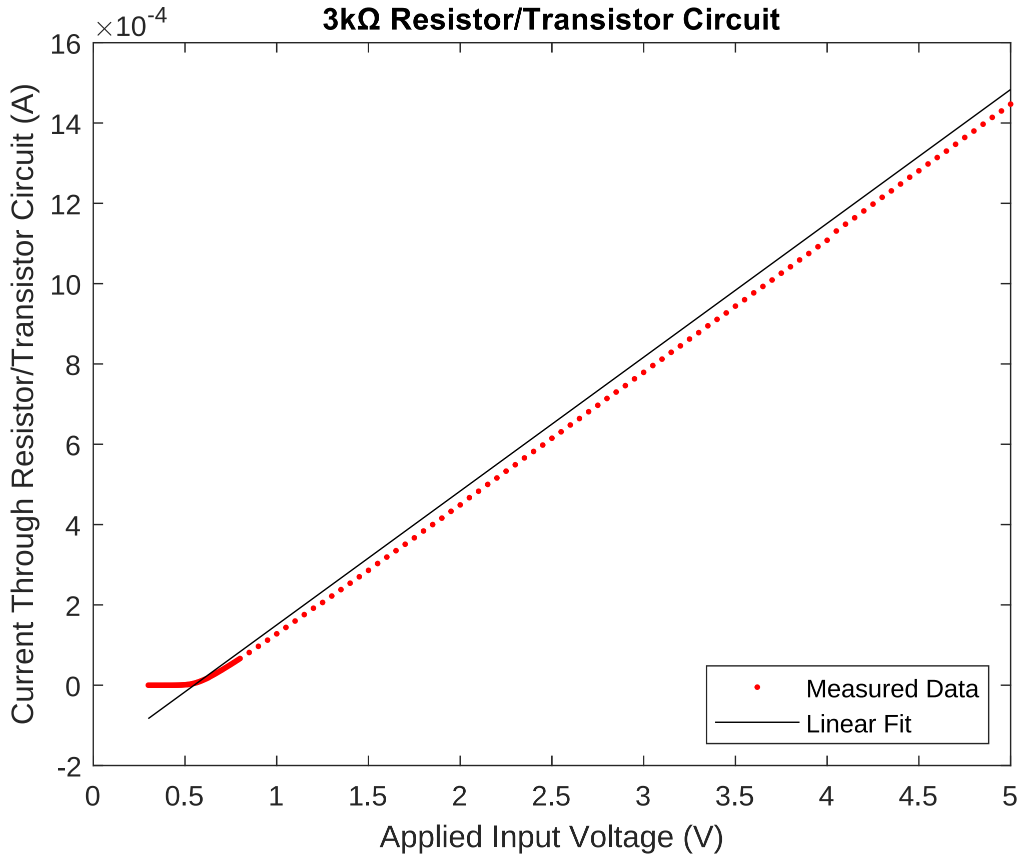

Figure 5: A graph of current through the circuit over applied voltage for our 3kΩ Resistor/Transistor Circuit.

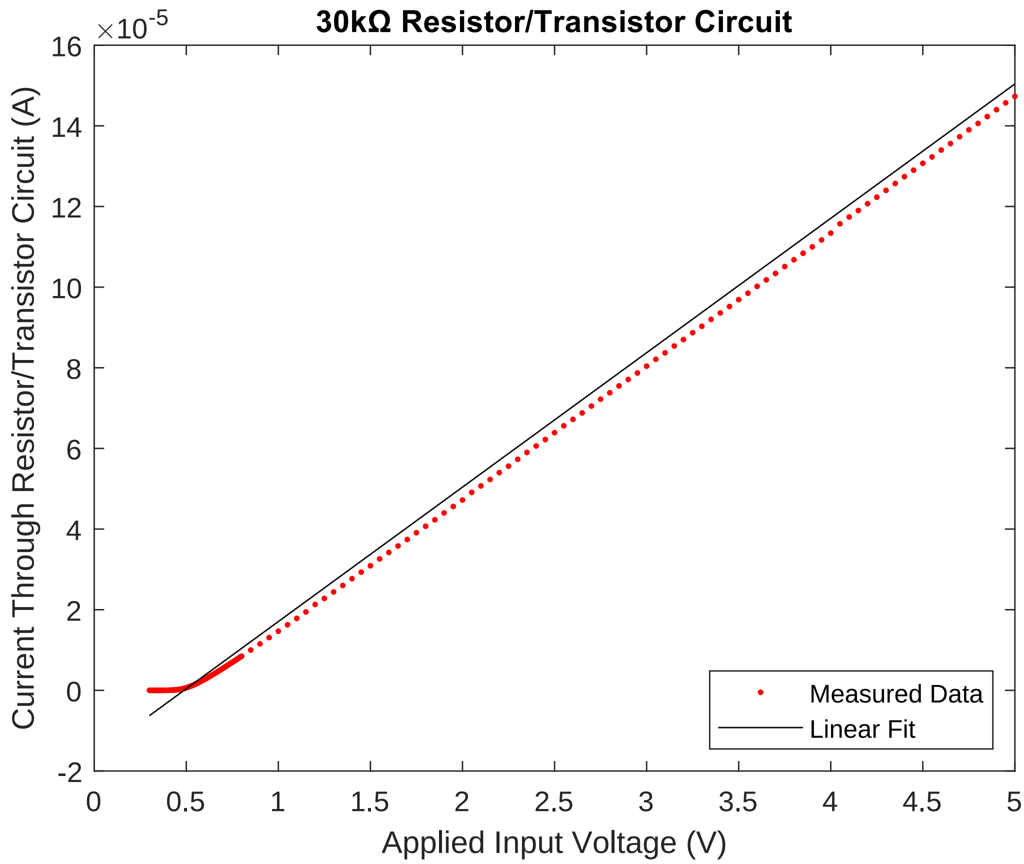

Figure 6: A graph of current through the circuit over applied voltage for our 30kΩ Resistor/Transistor Circuit.

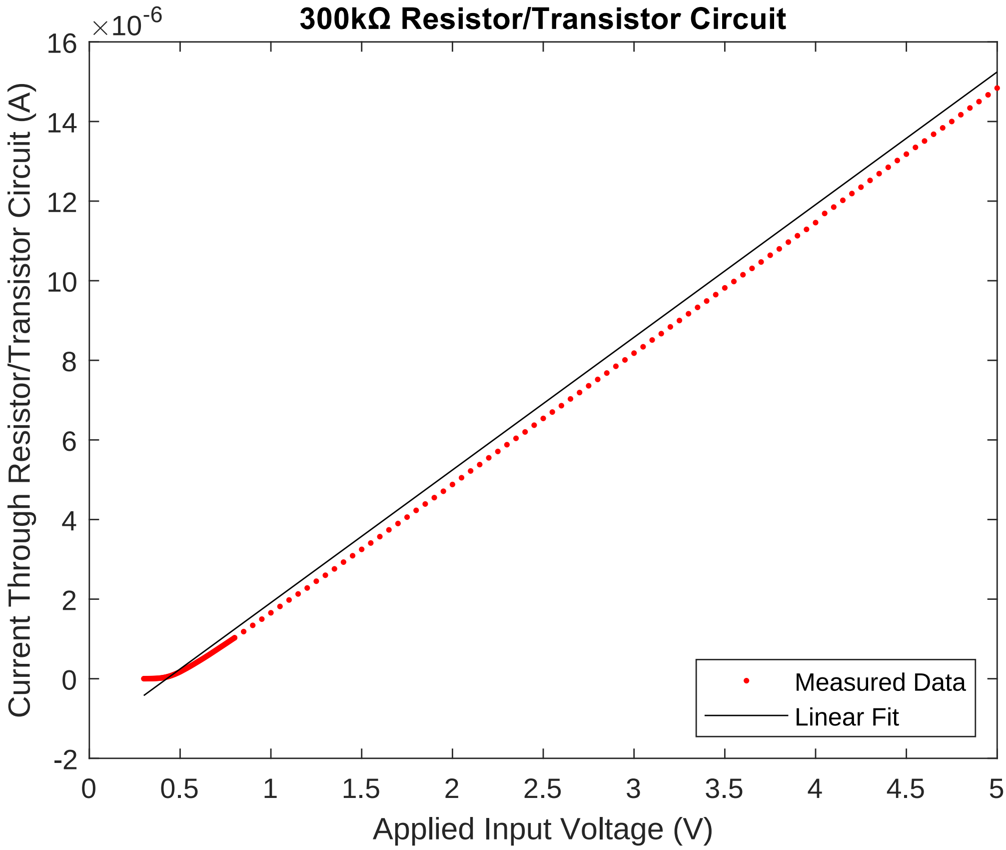

Figure 7: A graph of current through the circuit over applied voltage for our 300kΩ Resistor/Transistor Circuit.

We can see in Figures 5, 6, and 7, that our linear fit is very close to our measured current, but is slightly above in all cases. This could be due to the fact that the voltage across the transistor still slightly increases (logarithmically) after reaching V_{on}, or it could be slight variance in our resistor values.

For the last part of our experiment, we want to compare the values of I_{on} and V_{on} for each resistor. Referencing Table 1, we can plot the values as a function of resistance in Figures 8 and 9.

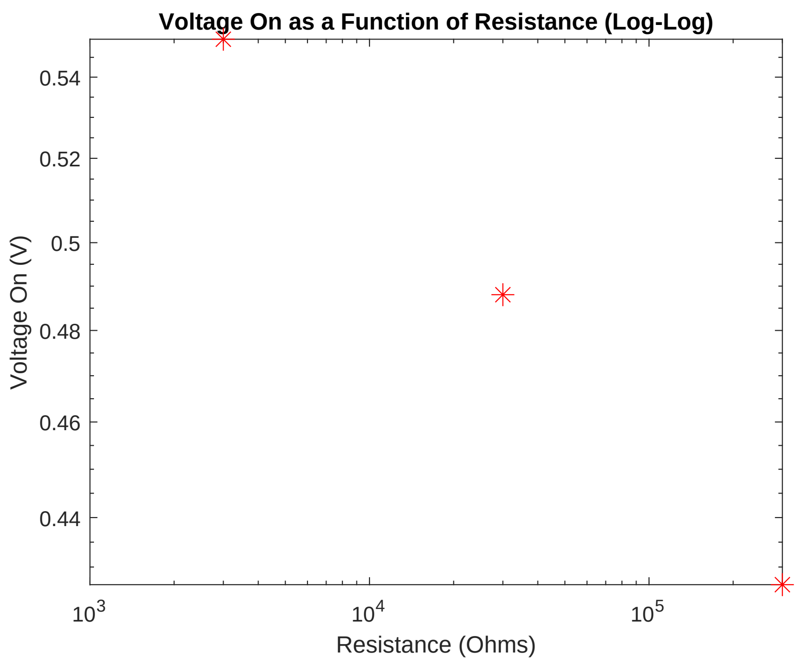

Figure 8: Turn-on Voltage Values through the diode-connected transistor/resistor over resistance on a log-log scale.

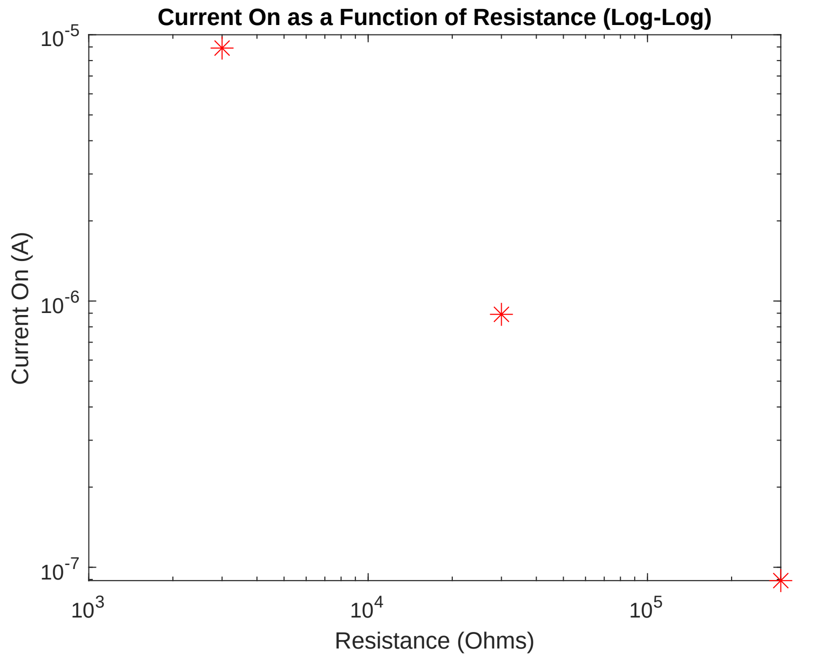

Figure 9: Turn-on Current Values through the diode-connected transistor/resistor over resistance on a log-log scale.

As shown in Table 1, we expected V_{on} and I_{on} to be calculated as:

$$V_{on} = U_T \log(\frac{I_{on}}{I_s}) \text{ volts, where } I_{on} = \frac{U_T}{R} \text{ amps.}$$

We expect I_{on} to be inversely proportional to resistance, which would be a negative linear slope on a log-log scale. Additionally, we expect V_{on} to be proportional to the negative log of resistance, which would be a negative logarithmic slope on a log-log scale. Based on our extracted values for I_{on} and V_{on}, these parameters vary with R as we expected from our prelab analysis.