Lab 2: Resistors and Diodes

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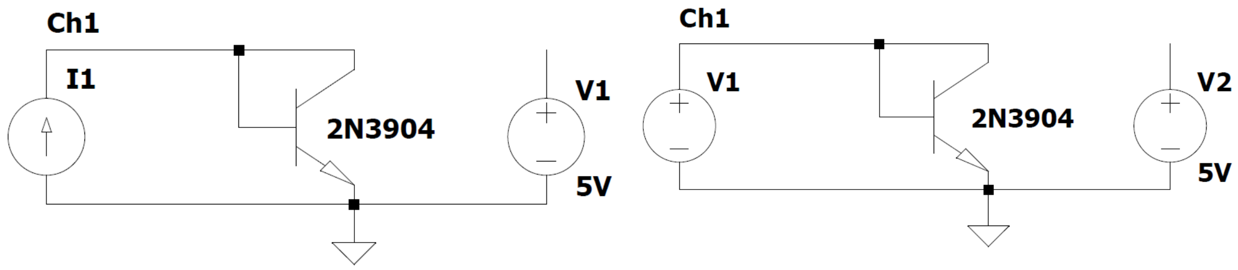
1 Experiment 1

1.1 Background and Procedure

For this experiment, we found the I-V characteristics of a diode. To do this, we input a current between 1 nA and 10 mA and measured the input voltage. For this characterization, we also input voltage (over an equivalent input current range) and measured the current flowing into the circuit. With this characterization, we computed a line of best fit to extract the saturation current (I_s) and thermal voltage (U_T) for the diode. Finally, from the data, we extracted the incremental resistance of the diode. For this experiment the following schematics were used,



(a) Input Current

(b) Input Voltage

Figure 1: Schematics for circuits used during Experiment 1.

1.2 Expectations

We expect the I-V characteristics to match the ideal diode equation approximation,

$$I = I_s * e^{\frac{V}{U_T}} \tag{1}$$

Where I is the current flowing through the diode, I_s is the saturation current, V is the voltage across the diode, and U_T is the thermal voltage of the diode. We suspect I_s is on the order of 10^{-15} A, and U_T is roughly 25 mV in the temperatures we are measuring.

1.3 Results

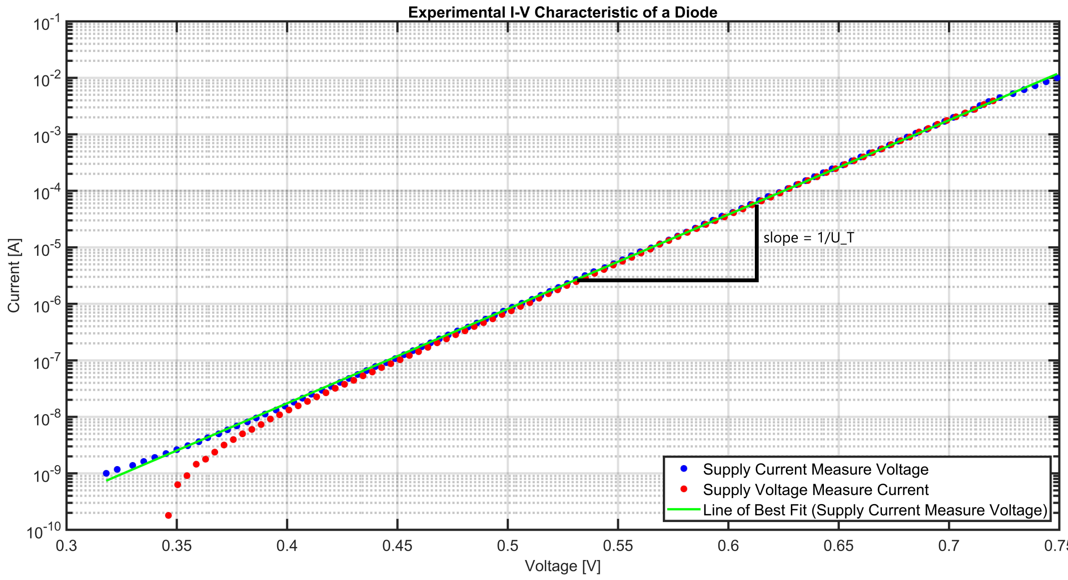


Figure 2: Experimental I-V Characteristic of a Diode

In Figure 2, we have plotted the exponential fit curve to the current-voltage characteristic which we then use to extract the values of the saturation current I_S, and the thermal voltage, U_T.

Extracted Values	
Constant	Extracted Value
I_S	1.4e-15 [A]
U_T	0.026 [V]

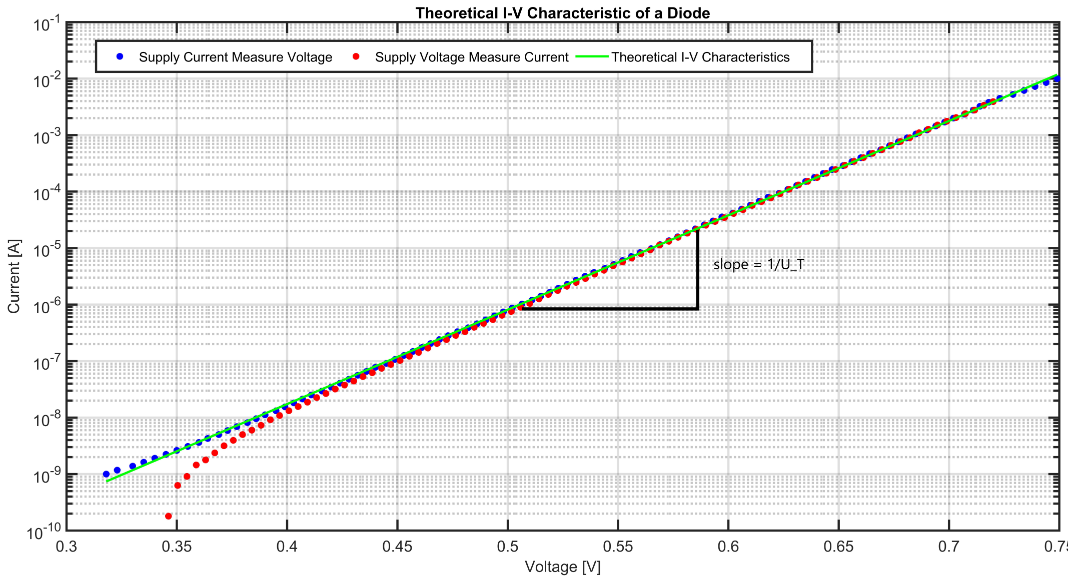


Figure 3: Theoretical I-V Characteristic of a Diode

In Figure 3, we have plotted the theoretical fit curve against the voltage-current characteristic, and the current-voltage characteristic on a semilog axis [y] plot.

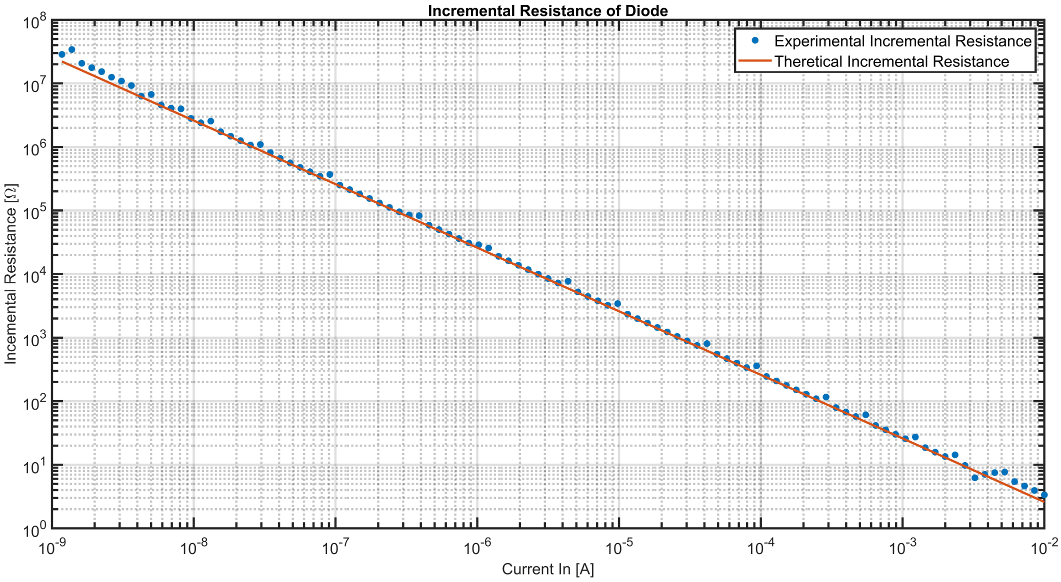


Figure 4: Incremental Resistance of a Diode

In Figure 4, we have plotted the incremental-resistance of the diode-connected transistor as a function of the current flowing through it against a theoretical fit to the data on a log-log plot. The theoretical fit very close characteristics. The result is a very small current (negative) that is effectively zero when supplying voltage.

Using the line of best fit, we extract the values of the saturation current I_S, and the thermal voltage, U_T to be as follows:

Extracted Values vs. Expected Values		
Constant	Extracted Value	Expected value
I_S	1.4e-15 [A]	1e-15 [A]
U_T	0.026 [V]	0.025[V]

To do this, we use linear regression on a log scale. The line of best fit follows the equation,

$$\log I = \log I_S + \frac{1}{U_T} * V \tag{2}$$

Thus, we can extract I_s as the y-intercept and U_T as the inverse slope of the line of best fit for the experimental data.

The exponential model fits the data very well. The absolute percentage error is 4.6% error between the experimental and line of best fit. This was computed using,

$$\text{Error} = \frac{|\text{Experimental - Theoretical}|}{\text{Theoretical}} * 100 \tag{3}$$

The theoretical model fits the data very well. It has an absolute percent error, using Equation 3, of 4.6% between the theoretical and experimental data. This is because for the theoretical fit we used the extracted saturation current and thermal voltage. Thus, the line of best fit is the same as the theoretical I-V characteristic.

For the incremental resistance, the theoretical fit matches the data fairly well. The absolute percent error was $\sim$ 12%, which can be accounted to the small spikes in the experimental r_d data. We believe this is due to inconsistencies in the SMU measurement device. This is because all of the spikes seem to be periodic and are approximately the same magnitude every time.

2 Experiment 2

2.1 Background and Procedure

For this experiment, we connected a resistor and the diode in series. In doing this, we measured the current flowing into the circuit and the voltage across the diode for a given input voltage. This process was repeated with three resistor values (200 Ω, 2 $k\Omega$, and 20 $k\Omega$). With these measurements, I_{on} and V_{on} were computed for the diode. The following schematic shows the circuit used for Experiment 2. To check if the resistor resistance values for the components are within tolerance, we cross-verify the resistance values using the Keithley 2400 SourceMeter. The following table shows the given vs. measures resistance values:

Observed 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%

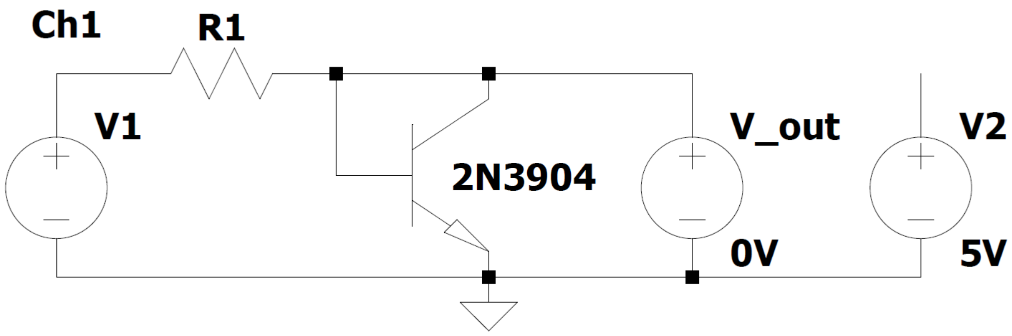


Figure 5: Schematic for circuit used in Experiment 2

Please note measurements were taken with all three resistor values in the position of R1 in the schematic above.

2.2 Expectations

The following equations express the theoretical values we expect to see for the experimental data throughout this experiment.

The voltage drop across the diode-connected transistor can be given by,

$$V = U_T * \log(I/I_s) \tag{4}$$

Where U_T is the thermal voltage, I is the current through the diode, and I_S is the saturation voltage of the diode-connected transistor.

The current through the circuit can be found using,

$$I_{in} = \frac{V_{in}}{R + r_d} \tag{5}$$

Where I_{in} is the current going into the circuit, V_{in} is the voltage across the circuit, R is the resistor in series with the diode-connected transistor, and r_d is the incremental resistance of the diode.

The turn on current can be found using,

$$I_{on} = \frac{U_T}{R} \tag{6}$$

Where I_{on} is the turn on current, U_T is the thermal voltage of the diode connected-transistor, and R is the resistance of the resistor in series with the diode.

We can find the turn on voltage through,

$$V_{on} = U_T * \log\left(\frac{I_{on}}{I_s}\right) \tag{7}$$

Where V_{on} is the turn on voltage, U_T is the thermal voltage, I_{on} is the turn on current, and I_s is the saturation current.

2.3 Results

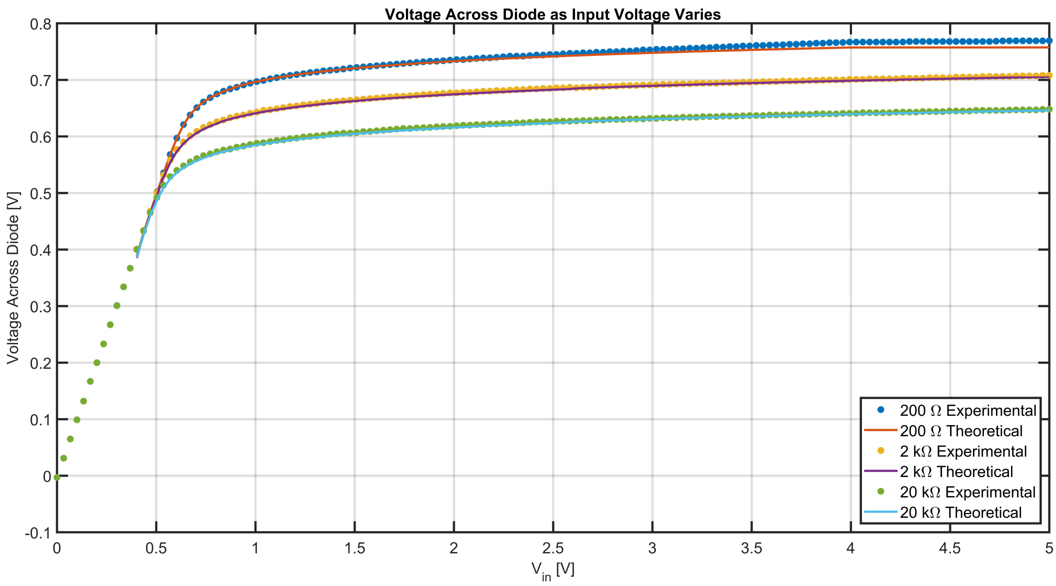


Figure 6: Voltage across diode as input voltage varies

In Figure 6, we have plotted the voltage across the diode-connected transistor as a function of the applied input voltage for all of the three resistor values that we used - 200 Ω, 2 $k\Omega$, and 20 $k\Omega$.

We cut off the points up to 0.6 [V], since the equation only models the current in region where $V > V_{on}$. In doing this, we isolate the theoretical fit that matches the experimental region that we are operating in.

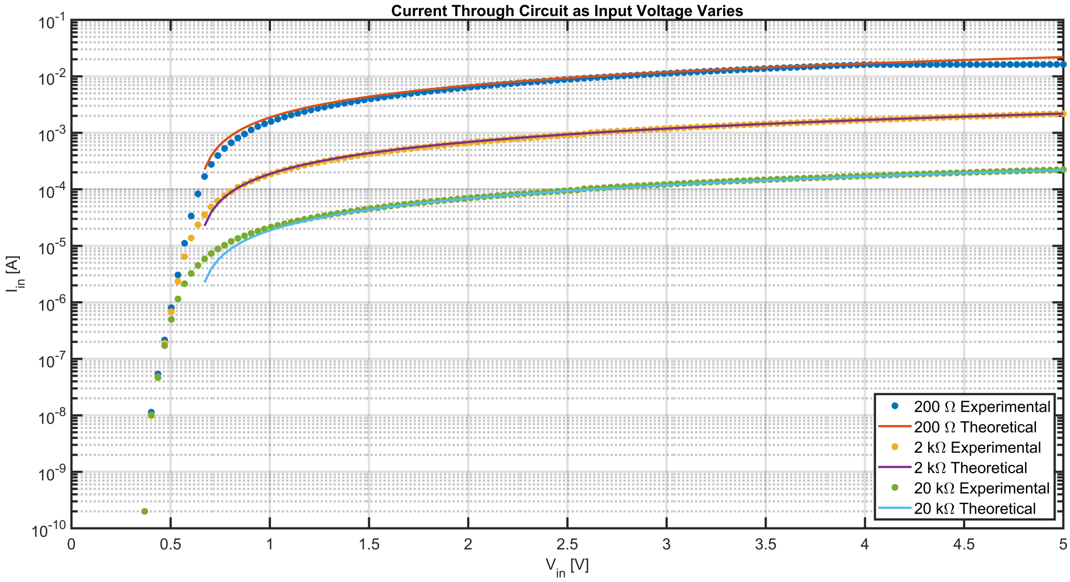


Figure 7: Current through circuit as input voltage varies

In Figure 7, we plotted on a semilog [y] axis showing the measured current flowing into the circuit as a function of the applied input voltage. The equation (Equation 5) that we have models the current in the region where $V > V_{on}$. Due to this reason we offset the fit by 0.6 [V] to the right, in order to account for the approximate V_{on} value.

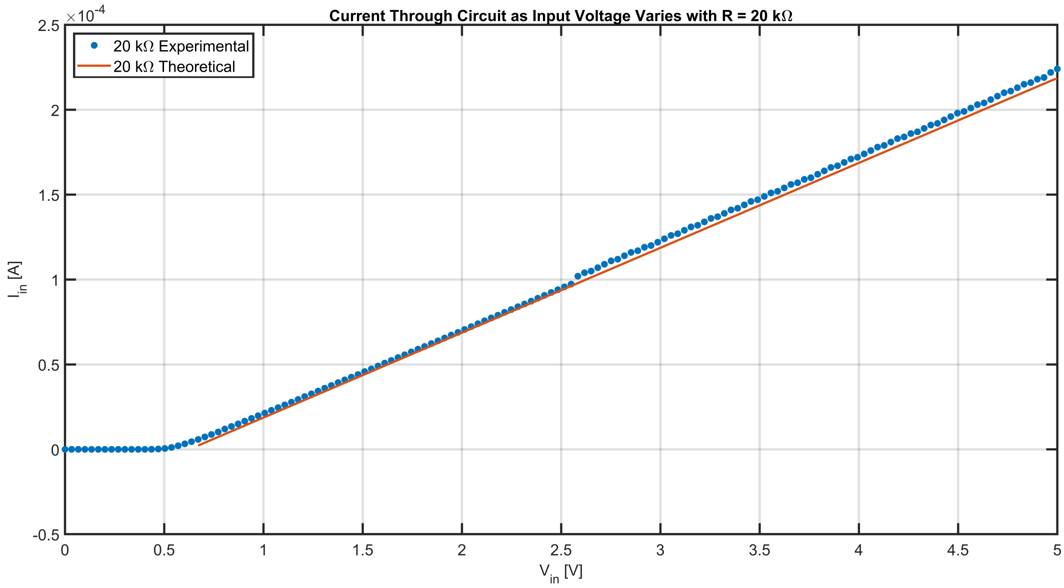


Figure 8: Current through circuit as input voltage varies with $R = 200\Omega$

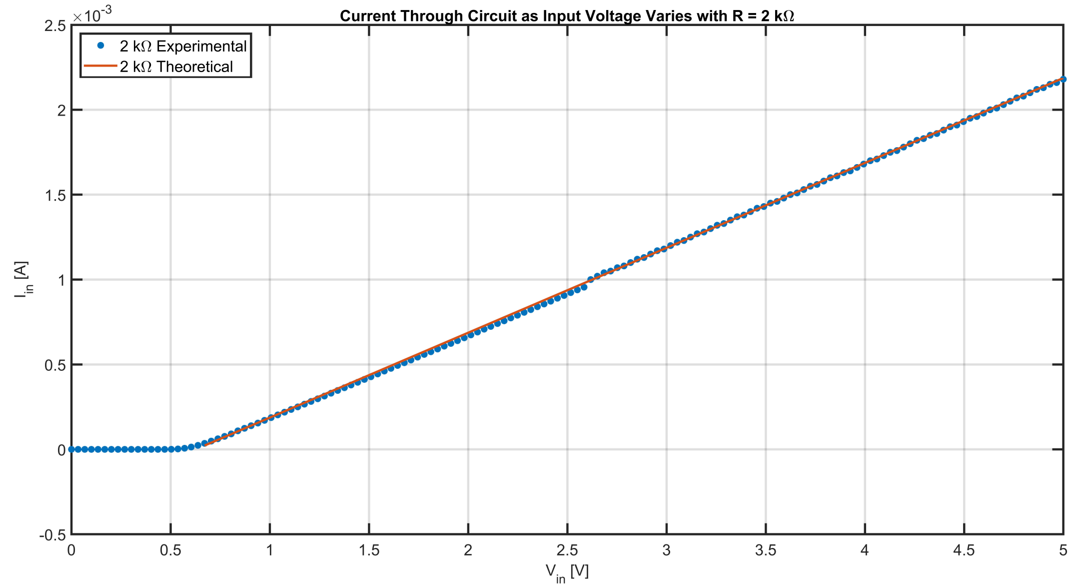


Figure 9: Current through circuit as input voltage varies with $R = 2k\Omega$

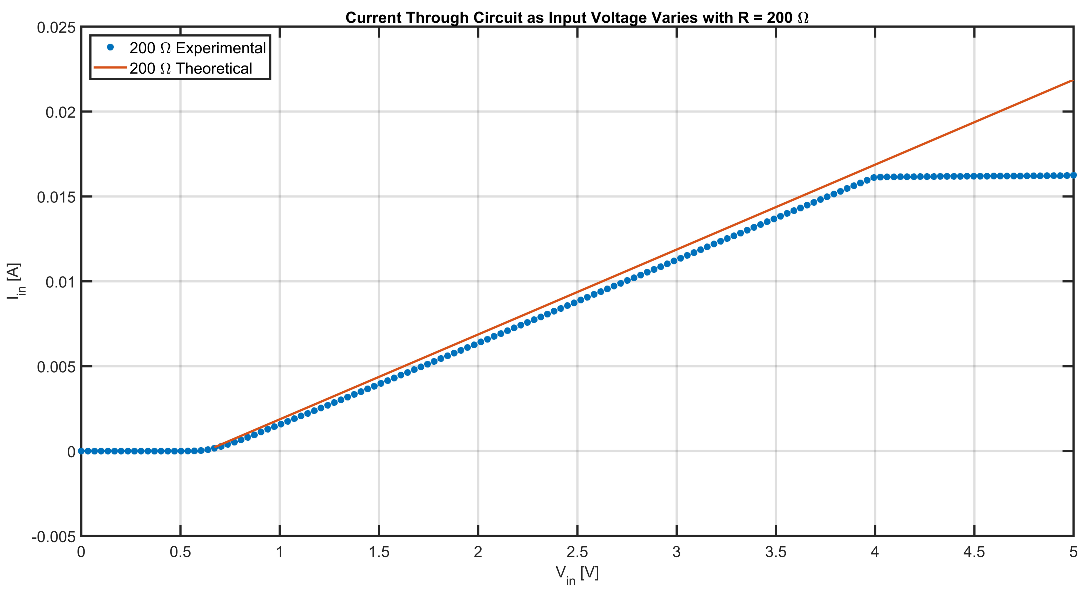


Figure 10: Current through circuit as input voltage varies with $R = 20k\Omega$

Finally, we have plotted (on a linear axes) graphs showing the input current as a function of the applied input voltage for each of the three resistors. Additionally, we have included the theoretical plots wherever they were applicable. For the theoretical lines, we used Equation 5.

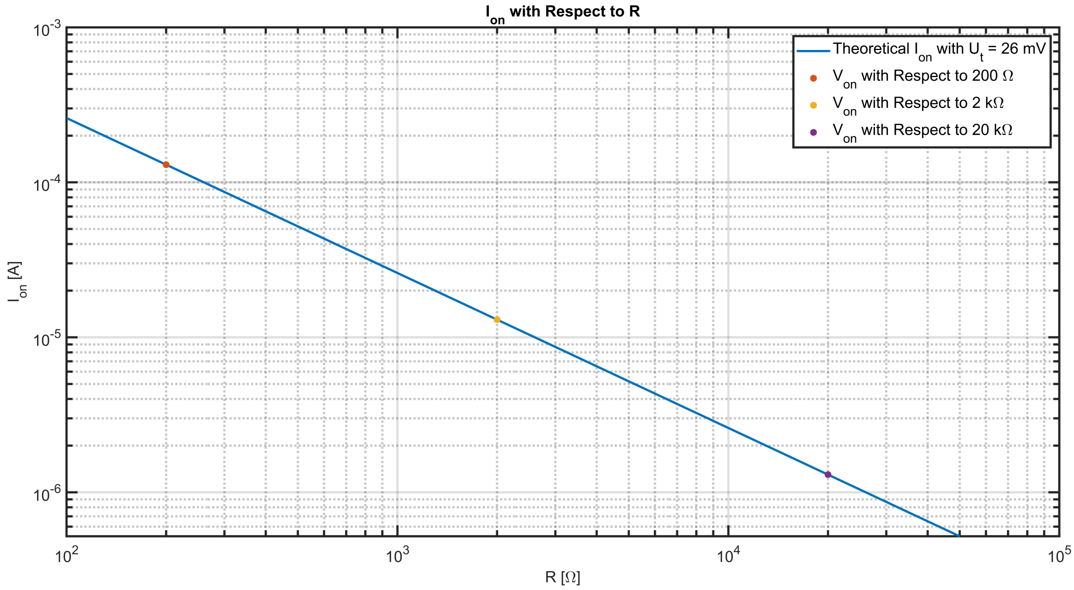


Figure 11: I_{on} with respect to R

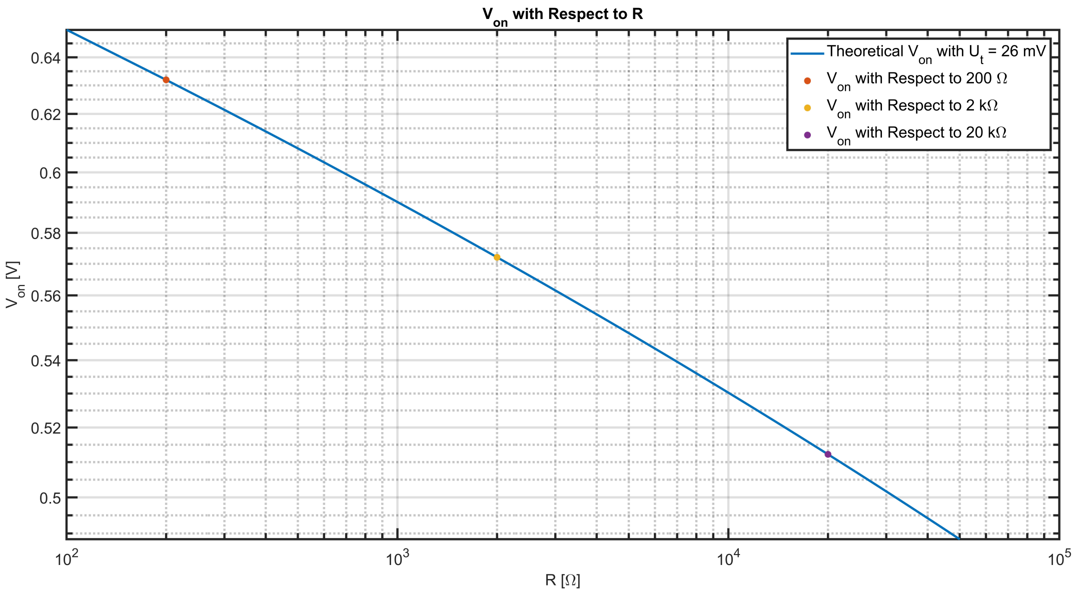


Figure 12: V_{on} with respect to R

2.4 Discussion

Qualitatively, the circuit behaves as we expected it to. This is because, until $V < V_{on}$, the voltage across the transistor increases linearly since the diode-connected transistor is in that region. Beyond this voltage threshold, the voltage across the transistor has a logarithmic relationship with the input voltage. This response is modeled by Equation 4.

We found (using Equation 3) that the absolute percent difference for the 200 Ω current in plot (Figure 8) to be 5.2%. In doing this, we only considered the region of $\sim 0.6V$ to $4V$.

For the $2,000$ Ω resistor, we found an absolute percent difference of 0.5% between the theoretical characteristics and experimental data. We only considered the region of 0.6 V and over.

For the $20,000\ \Omega$ resistor, we found an absolute percent difference of 2.5 % between the theoretical characteristics and experimental data. For this data, we also only considered the region above 0.6 V.

When looking at the values for I_{on} and V_{on}, they match our predictions from the prelab analysis. The reason this qualitatively makes sense is because I_{on} is proportional to R (through Equation 6). This is shown in a linear fit on Figure 11. Similarly, the V_{on} characteristics make sense qualitatively. This is because Equation 7 shows that V_{on} will be proportional to $\log\left(\frac{I_{on}}{I_s}\right)$. Thus, the fit should be linear with a semilog-x plot. This relationship is demonstrated in Figure 12 as the line is fairly linear over the region we are considering.