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Introduction to Microelectronic Circuits
Lab 2: Resistors and Diodes

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1 Introduction

In this lab, we examined the properties of a diode-connected npn bipolar transistor. Transistors are typically connected so that a small input current at the base terminal can control a larger current between the collector and emitter. In this lab, the base and collector terminals were connected together, which causes the transistor to behave like a pn junction diode where current can only flow in one direction.

2 Experiment 1: Diode-Connected Transistor Characteristics

2.1 Current-Voltage Characteristic

We studied the current-voltage characteristic and voltage-current characteristic of a diode by using an SMU to sweep a range of input currents and voltages. The voltage-current characteristic was found by inputting a logarithmic range of currents between 1nA and 10mA, and measuring the resulting voltage across the diode. The current-voltage characteristic was measured by inputting a voltage into the transistor and measuring the current across the same range of voltages. Both these sets of data are plotted on the same axis in Figure 1 on the following page. They do not show any differences between the two measurements, and follow the same theoretical fit.

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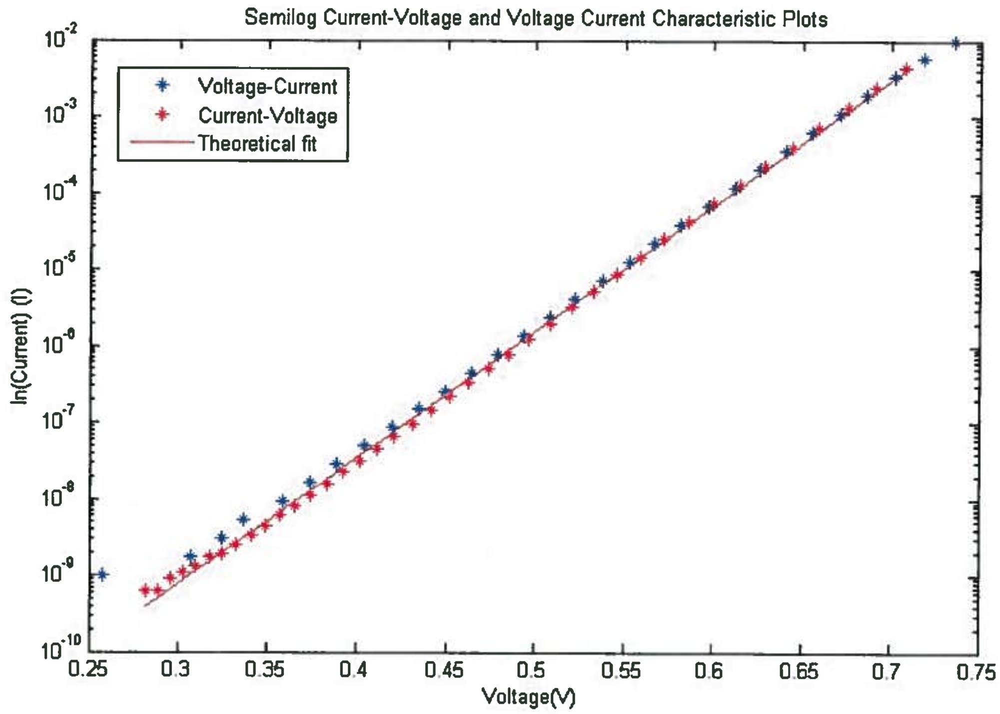

Figure 1: Current-voltage characteristic and voltage-current characteristic, with current plotted on a log scale. The line of best fit of the current voltage characteristic is given by y=ax+b, where $a = 37.94mV^{-1}$, and $b = -32.35$.

-1

From the current-voltage characteristic, we can determine a line of best fit using the ideal diode equation, where U_T is the thermal voltage and I_s is the saturation current.

$$I = I_s(e^{V/U_T} - 1) \tag{1}$$

Rearranging this equation gives us that:

$$ln(I) = ln(I_s) + \frac{1}{U_T}V \tag{2}$$

Therefore, the relationship between V and ln(I) can be described with a linear fit of the following form.

$$y = ax + b \tag{3}$$
$$a = \frac{1}{U_T} \tag{4}$$
$$b = ln(I_s) \tag{5}$$

Based on the calculated constants from MATLAB, the thermal voltage and saturation current can be calculated.

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units? -1

$$a = 37.94 \, V^{-1} \tag{6}$$
$$b = -32.35 \tag{7}$$
$$U_T = 26.3mV \tag{8}$$
$$I_s = 8.92 \times 10^{-15} A \tag{9}$$

This theoretical line of best fit for the current-voltage characteristic is also plotted on the graph in Figure 1 on the previous page.

2.2 Incremental Resistance

The incremental resistance of the diode is a relationship between the voltage and current through the diode. The incremental resistance is given by the following formula:

$$r_d = \frac{\partial V}{\partial I} \tag{10}$$

This relationship can be approximated by the diff command in MATLAB, where the incremental resistance is approximately equal to the diff(V)/diff(I). The resulting incremental resistance as a function of current is plotted in Figure 2.

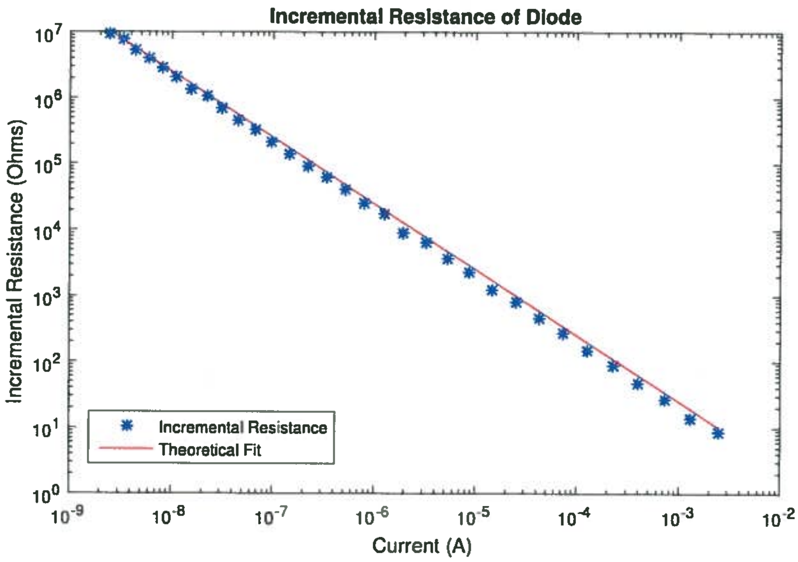

Figure 2: Log-Log Plot showing incremental resistance of diode-connected transistor as a function of the current flowing through it. The graph contains the MATLAB approximation of R_d using the diff command, and a theoretical fit from the derivative of voltage with respect to current ($\frac{\partial V}{\partial I} = U_T \frac{1}{I}$).

We can take the derivative of the voltage through the diode to get a calculated value for the incremental resistance by rearranging the equation for the current through a diode.

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$$I = I_s(e^{V/U_T} - 1) \tag{11}$$
$$V = U_T ln(I/I_s) \tag{12}$$
$$\frac{\partial V}{\partial I} = U_T \frac{1}{I} \tag{13}$$

This theoretical fit is included in Figure 2 on the previous page.

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

not 10x apart! -1

We selected 470Ω, 4.7kΩ, and 10kΩ resistors. We put each in series with our diode-connected 2N3904 transistor from experiment 1, and used the SMU to measure the current flowing into the series combination and measure the voltage across the diode connected transistor as we swept the input voltage over a few volts from zero, as shown in Figure 3 and Figure 4 below.

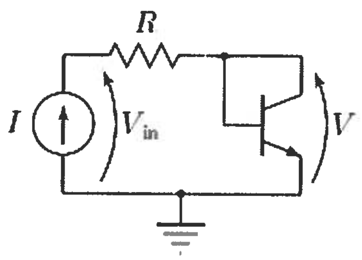

Figure 3: Test setup for measuring voltage across the diode-connected transistor while supplying current

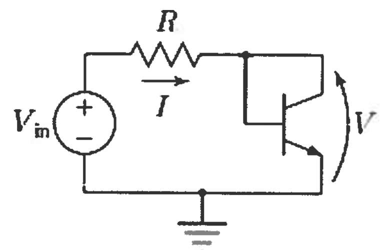

Figure 4: Test setup for measuring current through the diode-connected transistor and supplying voltage

As expected, two different regimes of operation can be seen in our measured data. When the applied input voltage is less than approximately 0.6V, the voltage across the diode-connected transistor as a function of the applied voltage is linear, and afterwards it is constant at 0.6V across the diode, regardless of input voltage. This means that the 0.6V is the diode's approximate turn on voltage, and once that voltage level is surpassed, the diode allows all forward current while maintaining a certain voltage drop.

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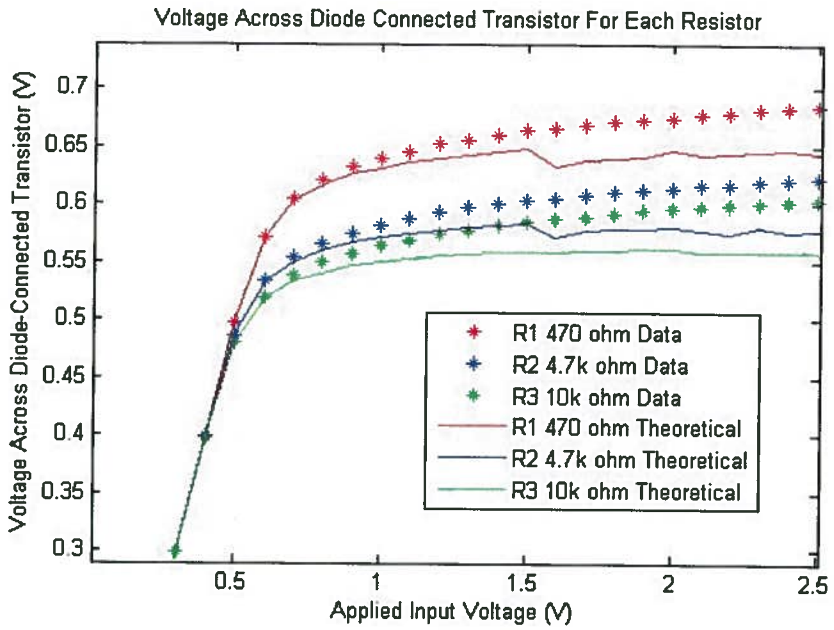

Figure 5: Single plot of voltage across the diode-connected transistor as a function of applied input voltage for all resistors used. Some of the theoretical lines are not perfectly smooth. They were found using the equation V = Vin - IR for each resistor. The reason they are not perfectly smooth is because some measured data was used to find the current through the resistor for an applied voltage on the same timescale. Discrepancies seen come from error in these measurements, but the lines still show the expected behavior.

The fit line found using Kirchoff's Voltage Law:

$$V_d = V_{in} - I * R \tag{14}$$

The voltage drop across the diode should always be ≤ 0.7 V, even if the input voltage increases. The voltage drop across the resistor will increase and compensate for the constant voltage drop across the diode. For instance, if the voltage were at 1V, the diode will drop 0.7V and the resistor will only drop 0.3V, and when the voltage were at 2.5V, the diode will drop 0.7V still and the resistor will need to drop 1.8V across it.

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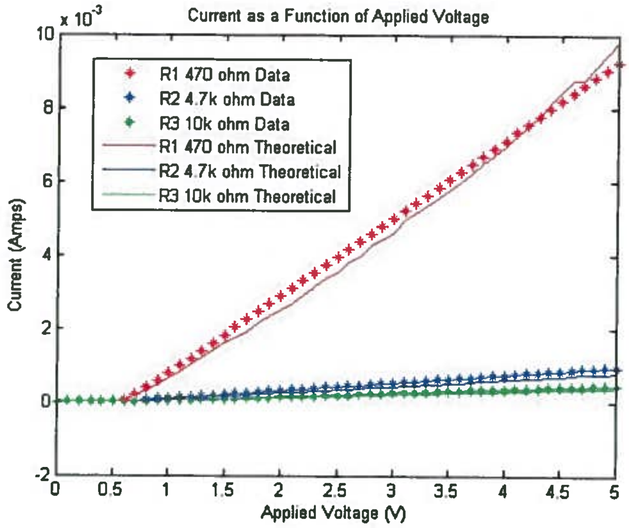
Fit eqn? parameters? -3



should be on three separate plots, can't see the green curve at all... -4

Figure 6: Linear plot showing the input current as a function of the applied input voltage for each of the three resistors. Our initial theoretical fits were off by a factor of 2. We are not certain where this went wrong, but have accounted for it by multiplying the currents by 2 for the expected values. This is seen here as well as in Figure 7.

Figures 6 and 7 use the theoretical fit line:

$$I = I_s(e^{V_d/U_t} - 1) \tag{15}$$

This theoretical relationship was found previously in the pre-lab to be the ideal current across a diode.

Figure 7 uses the same data as figure 6, but just shows another view including log scale.

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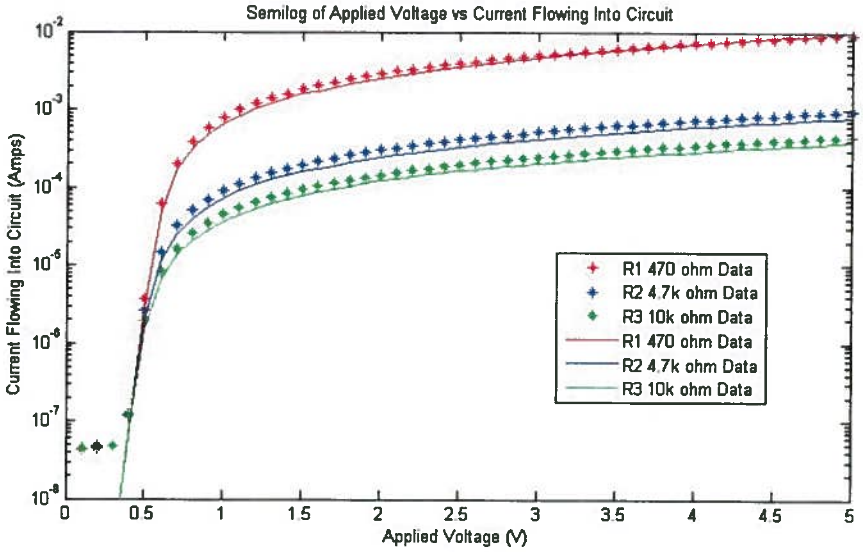

Fit eqn? Params? -1

Figure 7: Single semilog plot showing the measured current flowing into the circuit as a function of the applied input voltage for each of the three resistors. Our initial theoretical fits were off by a factor of 2. We are not certain where this went wrong, but have accounted for it by multiplying the currents by 2 for the expected values. This is seen here as well as in Figure 6

In figure 6, the graph corresponds the input voltage and measured current. As the input voltage rises to 0.7V, the voltage across the diode is similar and begins to conduct forward current.

We can extract the values of I_{on}, U_t by looking at figure 7. Qualitatively, we can see that the diode allows current at around 0.6 V, and at that point in time, the current (as the diode turns "on"), measures around $10e^{-5}$ if the diode is in series with a $10K\Omega$ resistor. To calculate I_{on}, we have:

$$I_{on} = \frac{U_t}{R} \tag{16}$$

$$I_{on} = \frac{0.026V}{10,000} \tag{17}$$

$$I_{on} = 2.6e^{-6} \tag{18}$$

units? -1

The calculated value for I_{on} does not quite match the qualitative value seen in figure 7 as it is one order of magnitude off consistently. However, this calculation includes a measured value for U_t (the thermal voltage), an ideal value for the resistor and a lack of high sampling on the graph.

I_{on} is used to find the theoretical turn-on voltage of the diode, V_{on}.

$$V_{on} = U_t * log(I_{on}/I_s) \tag{19}$$

$$V_{on} = 0.026V * log(2.6e^{-6}/8.92e^{-15}A) \tag{20}$$

$$V_{on} = 0.583V \tag{21}$$

The extracted value for V_{on} is very close to both the qualitative value seen in figure 5 (0.6V), and the expected theoretical of 0.7V. The theoretical value comes from the material, silicon, and the expected turn-on time of an ideal diode.

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Resistor value	Qualitative value for I_{on} (A)	Theoretical value for I_{on} (A)
470 Ω	10^{-4}	5×10^{-5}
4.7 kΩ	10^{5}	5×10^{-6}
10 kΩ	10^{-5}	2.5×10^{-6}

Table 1: Comparisons of the qualitative and calculated values of the turn-on current

Values of V_{on}? Plot of V_{on} vs (I_{on} vs

4 Conclusion

By examining the IV characteristics of a diode-connected transistor, it is possible to understand how the diode behave differently in different regimes. When the current through the circuit is less than the turn-on current of the diode, the current increases linearly with voltage, and the voltage through the diode is mostly constant. When the current through the circuit is greater than the turn-on current of the diode, the voltage changes logarithmically with current and the voltage through the diode approaches the turn-on voltage.