Circuits Lab 2

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1 Experiment 1: Diode-Connected Transistor Characteristics

1.1 voltage-current and current-voltage characteristic

We first measured the voltage-current and current-voltage characteristic of our circuit. We then fitted an exponential to the current-voltage characteristic and plotted that as well. This plot is shown in Figure 1 on the following page. There are some distinct differences between the voltage-current characteristic and current-voltage characteristic. The current-voltage characteristic shows a distinctly higher current flow in the first (lower voltage) regime and tails off in the third (higher voltage) regime. This is because the SMU that we used to collect the data has certain hardware limitations. In the middle regime, the correlation between the two is very good.
The equation for the exponential fit to our current-voltage characteristic is $I = 5E - 14 * e^{35.465v}$. From this we can extract $I_s = 5E - 14$ and $U_T = 1/35.465 = 0.0282$. This exponential fit matched our data with an R^2 values of .99165, meaning over 99 percent of the variance in our data was explained by the exponential fit. This means our theoretical exponential was a very good fit to our data.

1.2 Incremental Resistance

We took our measured voltage-current relation and computed the incremental resistance of the diode: $r_d = \frac{\partial V}{\partial I}$. We also did a theoretical fit of the data, using U_T and our current. The fit of the two is very good. The plot is show in Figure 2 on page 3.

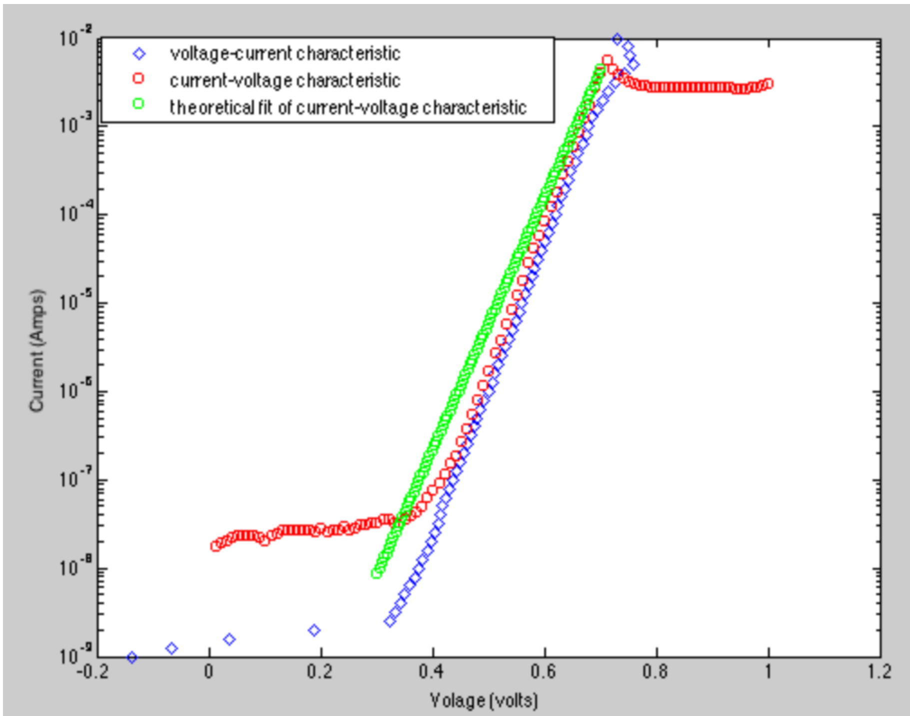

Figure 1: Voltage-current characteristic, current-voltage characteristic, and theoretical fit of current-voltage characteristic of a resistor in serious with a diode connected transistor

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

2.1 Resistors

Here are the values of the resistors we used, as measured by the Keithley 2400 SourceMeter:

R1	$.108k\Omega$
R2	$1.005k\Omega$
R3	$9.90k\Omega$
R4	$99.39k\Omega$

We chose them as to span three orders of magnitude while keeping the current output of the SMU reasonable with respect to both extremes.

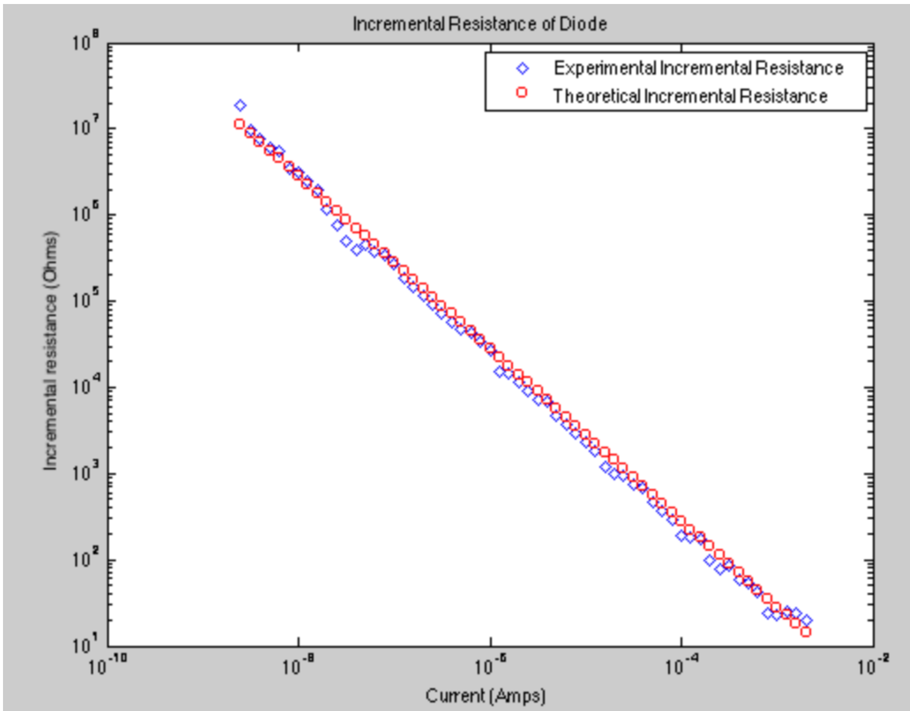

Figure 2: Incremental resistance of a diode as a function of current

2.2 Testing and Initial Observations

We deadbugged the R1 resistor in series with the diode-connected 2N3904 transistor and channel 1 of the SMU and we connected channel 2 across the transistor. We connected the negative terminal of the power supply channel to the emitter.

We then used a python script to supply 101 distinct voltages spaced evenly from 0V to 5V on channel 1 of the SMU. At each voltage, the script recorded the current through channel 1 and the voltage across channel 2. The script ran 4 times, pausing in between to allow us to replace the resistor with the R2, R3 and R4 resistors. The data was saved to a .csv file.

The data demonstrated two distinct qualitative regions across the board, and each had a significant number of data points. This corresponds to our initial calculations in the prelab. The only substantial inaccuracy was a plateau in the current measured from 2.75V through 5V in the R1 trial (Figure 5 on page 6). The measured current did not exceed 20.4 mA, which we take to be a limitation of the SMU.

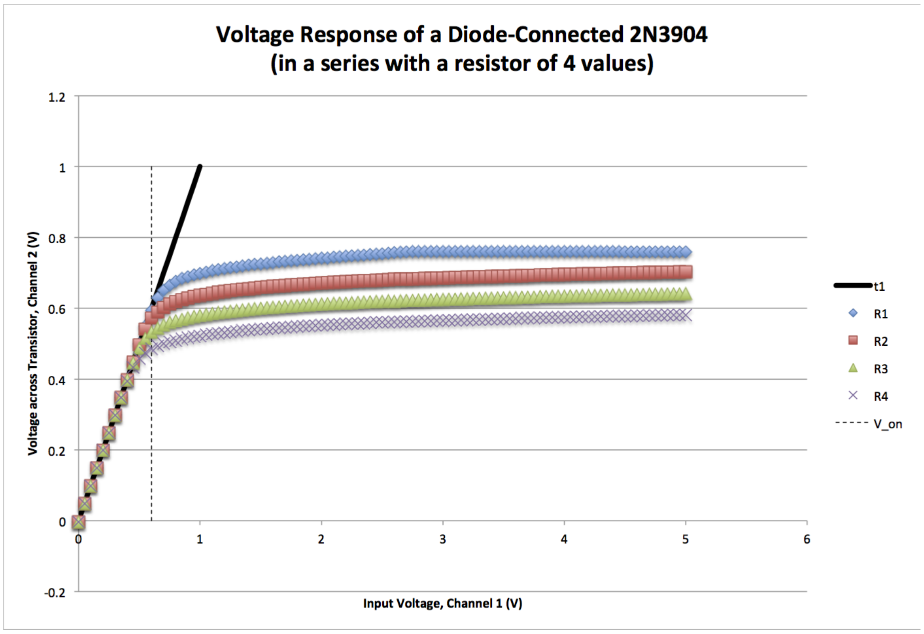

Figure 3: Voltage across diode-connected transistor in series with one of the above resistors over a 5V sweep of input voltages

2.3 Transistor voltage analysis

Figure 3 shows the voltage across the transistor for a range of input voltages for each of the four resistor values. Note that the plateau is visible here, too (which also serves to highlight the logarithmic shape of the rest of the graph). The graph clearly shows both qualitative regions and suggests the following V_{on} values:

R1	.60V
R2	.55V
R3	.50V
R4	.45V

This linearity makes sense given that the turn-on voltage is determined logarithmically, and our choice of resistors is exponential.

In the first qualitative region, almost all of the voltage change is reflected across the transistor. This means that the approximate theoretical curve is $V = V_{in}$. The graph fits this theoretical line very well and all discrepancy reflects the limitations of our assumption (some small amount of voltage is dropped across the resistor as well).

In the second qualitative region, almost none of the voltage change is reflected across the transistor and therefore the voltage lines become near horizontal. More precisely, the approximate theoretical curve is logarithmic with very small coefficients (U_T) both in front and inside the function. The graph mimics this behavior very, very well.

2.4 Circuit current analysis

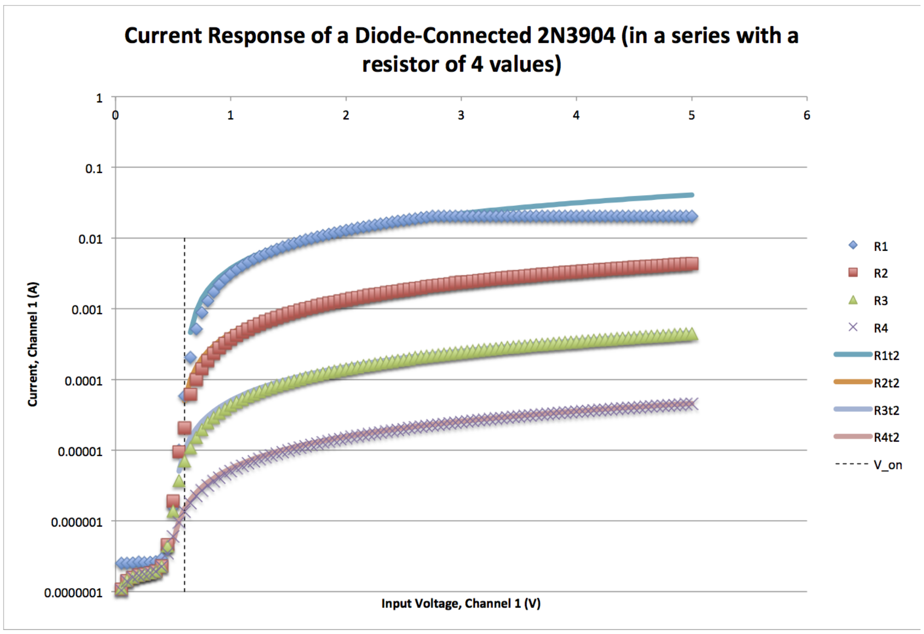

Figure 4: Current through diode-connected transistor in series with one of the above resistors over a 5V sweep of input voltages (logarithmic)

Figure 4 and Figure 5 on the next page show the current through the resistor and transistor for the same 101-point spread of voltages and the same four resistors. In the semilog plot, we added 191nA to all values to make sure that the minimum value was non-negative (the readings for the region with negligible current were negative and thus a very important qualitative characteristic of the circuit went unrepresented in this logarithmic form). The graphs agree with previously estimated turn-on voltages (this is best seen in the linear graph) and suggest the following I_{on} values:

R1	$205.3\mu A$
R2	$20.5\mu A$
R3	$3.54\mu A$
R4	$.413\mu A$

These values make sense in that they are separated by factors of around 10, and they should be inversely proportional to the resistance (which is also separated by factors of 10).

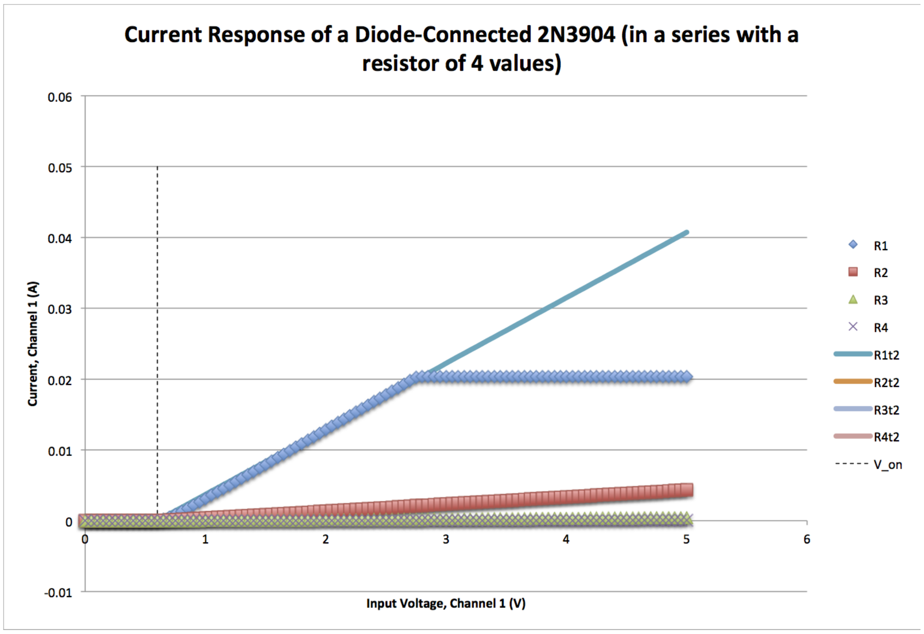

Figure 5: Current through diode-connected transistor in series with one of the above resistors over a 5V sweep of input voltages (linear)

In the first qualitative region, current in the circuit should not be rising much at all. We see this demonstrated in both graphs. In fact, the value was so low, that some of the measured results were negative.

In the second qualitative region, all the voltage change should be across the resistor and the current should be rising proportionally to $1/R$. This is well demonstrated in both graphs. We started the theoretical curve from V_{on} (i.e. $V = (V_{in} - V_{on})/R$).

Once again we note that the plateau demonstrated in both graphs is a limitation of the testing equipment.

2.5 Conclusion

Both voltage and current analysis shows a clear qualitative change at a resistance-dependant turn-on voltage and the curves on either side behave much as expected given our assumptions:

$$
\begin{array}{ll}
V = V_{in} & \text{for } V_{in} < V_{on} \\
V = U_T * \ln(V_{in}/RI_s) \approx V_{on} & \text{for } V_{in} > V_{on} \\
I = 0 & \text{for } V_{in} < V_{on} \\
I = (V_{in} - V_{on})/R & \text{for } V_{in} > V_{on}
\end{array}
$$

The relationships between turn-on voltage and current with resistance value

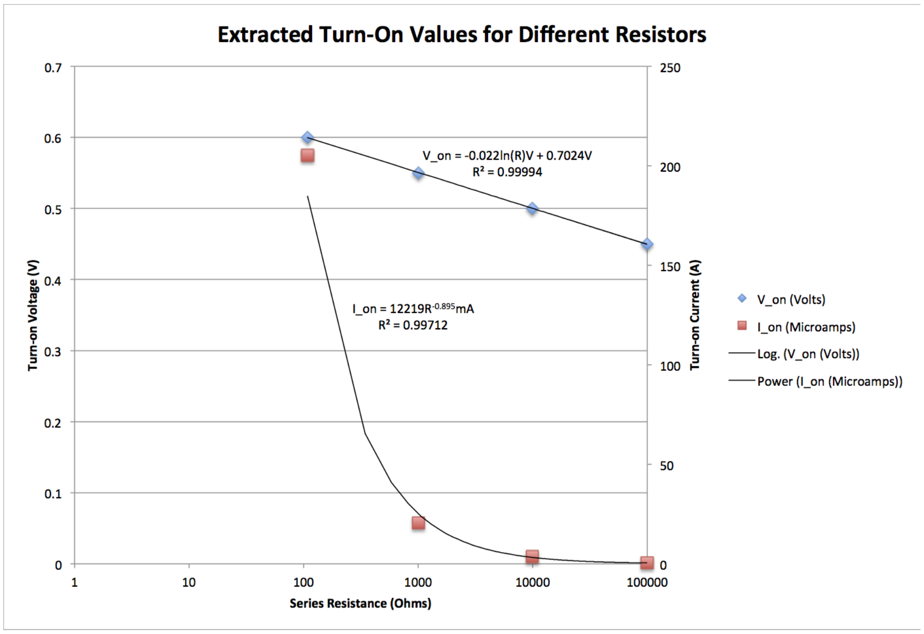

Figure 6: Estimated turn-on voltage and current for 4 resistors

are plotted in Figure 6. These are the theoretical behaviors:

$I_{on} = U_T/R$
$V_{on} = U_T * \ln(U_T/RI_s)$

Both behave close to expected and, given the crude approximation of the data points, the values they give for U_T are close to accurate: 22mV and 12mV respectively.