Laboratory 4: Silicon Diodes and Their Applications

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***Abstract*—In this laboratory, we investigated various diode circuits and their characteristics, including the I-V characteristics of diodes, the effects of temperature on diode performance, Zener diodes, rectifiers, voltage regulation, and limiter circuits. A Myriad of configurations were constructed, and different input waveforms were ran to analyze the outputs of these circuits. The results highlight the behavior of diodes in different circuits and provide insights into their applications in signal processing, and voltage regulation. Further, it is noted that the Elvis II+ instrument, MATLAB and LTSpice were all used to process the tests, extract plots and to validate data respectively.**

***Index Terms*—1N4148, 1N5402, 1N5333A, Diode, I-V characteristic, Zener diode, rectifier, voltage regulation, limiter circuit, temperature effects**

I. Introduction

As seen in the ECSE 331 class, diodes are essential components in various electronic circuits, due to their useful characteristics. In this investigation, we aim to explore various diode circuits and their behavior under different conditions. This lab includes six main parts: examining the I-V characteristics of diodes, the impact of temperature on diode performance, Zener diodes, voltage regulation with Zener diodes, rectifiers, and limiter circuits. The lab provides insight and familiarization with diode applications and their performance in different electronic circuits.

II. Methodology and Analysis

A. I-V Characteristics Using a Curve Tracer

For the first part of this lab, we were asked to construct the circuit in figure 1. As observed from the figure, this circuit resembles a curve-trace setup with a difference amplifier for measuring the diode i-v characteristic. However, before we use it to examine the i-v characteristic for the 1N4148 diode, we wanted to verify the current sensing op-amp circuit operates as expected, delivering a gain of 10 V/V. So, to do this, we replaced the diode in the circuit of figure 1, with a 100 Ω resistor. Once this was done, we ran a triangular wave through the setup, as the saw-tooth waveform is not available on the ELVIS-II software. The output of this set up can be seen in figure 2, where we can see that the circuit indeed behaves as expected, essentially amplifying the input signal by a factor of 10. As seen from the figure, we achieve a slope of 0.01 A/V, giving us a resistance of 100 Ω, which matches our findings from LTSpice found in the appendix. Further, this value is valid as we replaced the diode in the circuit by a 100 Ω resistor.

We were then asked to place the diode to achieve a circuit that resembles that of figure 1. Then, we ran the same

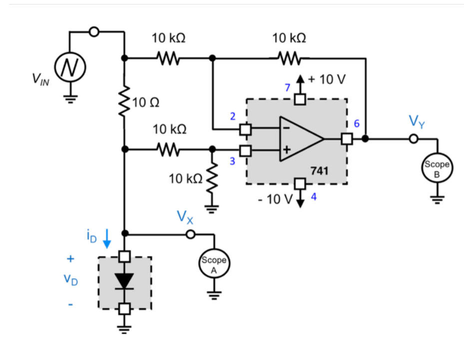

Fig. 1. Curve-Trace Set-Up for Measuring the Diode I-V Characteristic

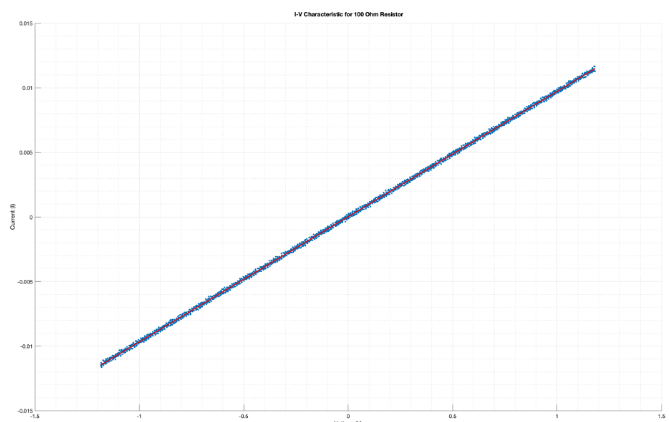

Fig. 2. I-V Characteristic of 100 Ω Resistor

triangular wave discussed earlier, and achieved the plot seen in figure 3. As seen from figure 3, we can examine, using a pointer, that the cut in voltage is roughly 0.639393 V; that is the minimum voltage that must be applied across the diode for it to start conducting current in the forward direction. We then performed piece-wise analysis on the plot to achieve the superimposed blue line seen in figure 3. The tangent line was taken from the point V = 0.7 V as specified, and the slope was calculated as 140.67 nA/V. Then, by way of MatLab, we examined the difference between the points on display to find the maximum difference in voltage. By interpolating our raw data, then finding the difference, we found that the maximum difference in voltage for the same two current points is around 0.149082 V. As seen, the piece-wise linear approximation is a useful and simple model for diodes, but its accuracy may be limited by specific diode characteristics and the operating conditions. More accurate models or simulation tools may be required for precise predictions that include micro measurements, and so the magnitude of the difference of this model may be too large. We found the same results from LTSpice, which can be found in appendix B. Further, the oscilloscope plot which the I-V characteristic was derived from can be found in appendix A.

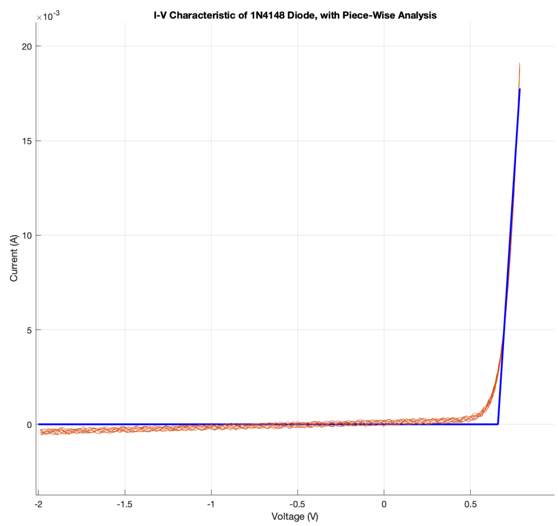

Fig. 3. I-V Characteristic of 1N4148 Diode, with Piece-Wise Analysis

We then replaced our diode with a 1N5402 power rectifier diode in figure 1 and ran the same input wave through the circuit. As seen in figure 4, we arrive at a similar plot to that of the 1N4148. The difference however is that the plot of the 1N5402 lies left of our plot in figure 3, implying that it has a lower forward voltage drop for the same forward current compared to the 1N4148. This can indicate that the device has lower resistance to current flow in the forward direction or has better conductivity properties. Further, this was validated using LTSpice in appendix B. The oscilloscope output for this instance of the lab can also be found in appendix A.

We then replaced the power rectifier diode with our original diode, but reversed the orientation on the board such that the positive end is grounded. As seen from figure 5, we arrived at a similar plot to that of figure 3 and 4, however, now, the current is very low or nearly zero for a wide range of negative voltages until the negative voltage reaches the breakdown voltage. Once the breakdown voltage is reached, the current will increase rapidly, in a similar fashion that it increased in figure 3. The oscilliscope output can be found in appendix A and the LTSpice validation can be found in appendix B.

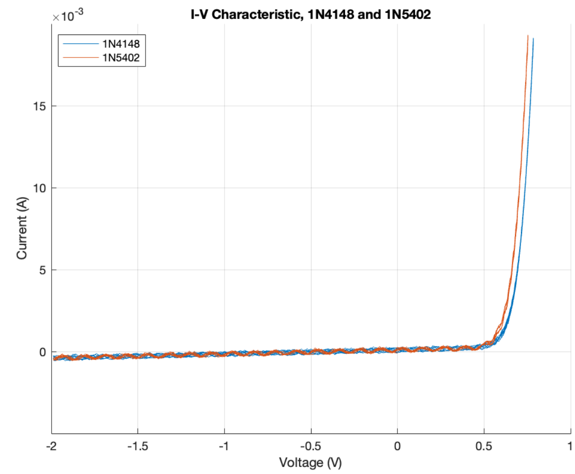

Fig. 4. I-V Characteristic of 1N4148 and 1N5402 Diode

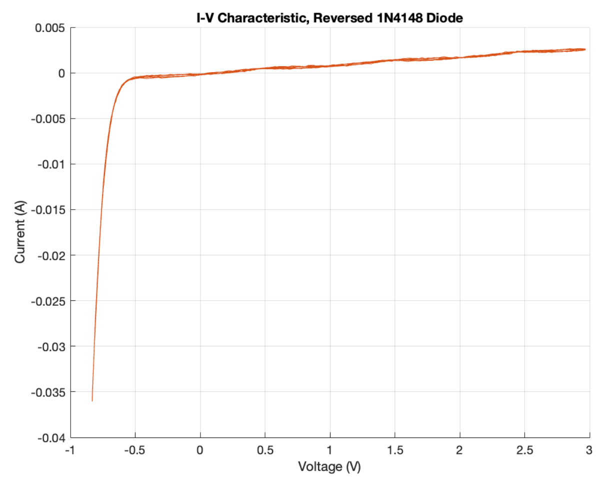

Fig. 5. I-V Characteristic of 1N4148 Diode, Reversed

B. Diode Temperature Effects

For this part, we are asked to repeat the circuit analysis we completed to arrive at figure 3, however at varying temperatures. That is, starting from room temperature, we gradually heated the diode, to examine how it performs at varying temperatures; 21, 38 and 47 degrees Celsius. As seen in figure 6, the 1N4148 diode performs differently under varying temperatures. More specifically, we can observe that as the temperature of performance increases, the forward voltage drop of the diode decreases, for the same forward current. This behaviour further follows from theory, as when the temperature of the semiconductor is increased, the overall kinetic energy of the electrons in the system increases, causing them to collide more frequently, resulting in more ionization and more conduction. In turn, this lowers the energy needed to make the semiconductor in the diode conduct, resulting in a lower forward voltage drop.

We then conducted the same setup on LTSpice and arrived at the same findings described above. The LTSpice plot can be found in appendix B, and the oscilloscope plot can be found in appendix A.

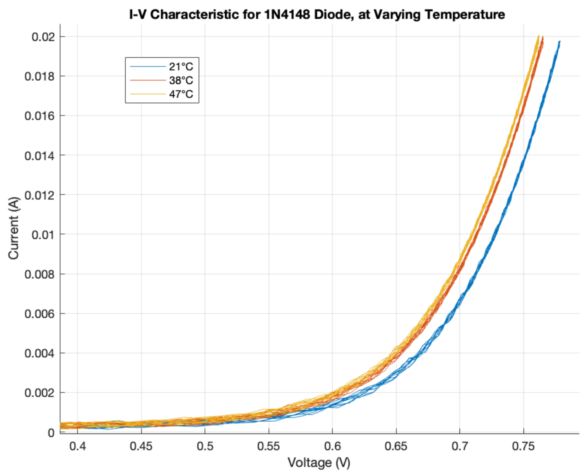

Fig. 6. I-V Characteristic of 1N4148 Diode, Under Varying Temperature

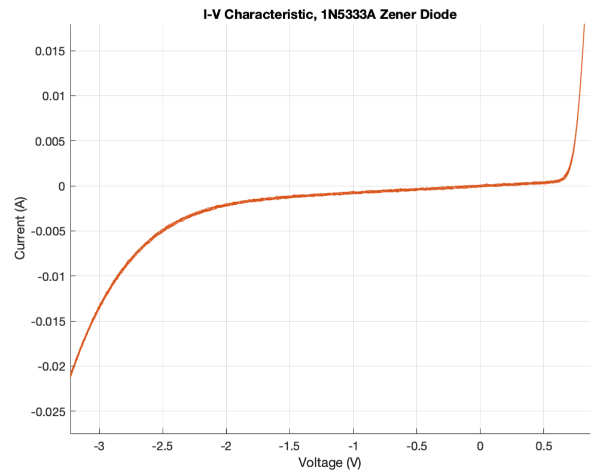

Fig. 8. I-V Characteristic of a 3.3 V Zener Diode

C. Zener Diodes

We were then asked to replace the working diode with a 1N5333A Zener diode in our circuit configuration seen in figure 1, to arrive at the circuit in figure 7. We then ran the same triangular pulse through the circuit to arrive at the i-v characteristic in figure 8. As we can observe from the figure, the diode is indeed operating in the breakdown region. The diode's breakdown region starts at near the knee current. And as seen from the figure this point corresponds to around -3.37437 V, when the diode starts conducting high amounts of current. As mentioned in ECSE 331 class, the ac resistance of the Zener diode, can be arrived at by performing 1/slope, where the slope is the slope of the tangent line to the Zener voltage point. As mentioned previously, plot analysis was completed using MATLAB to arrive at a slope of 0.050429 A/V, and so it follows that the AC resistance inside it's breakdown region is 19.83 Ω.

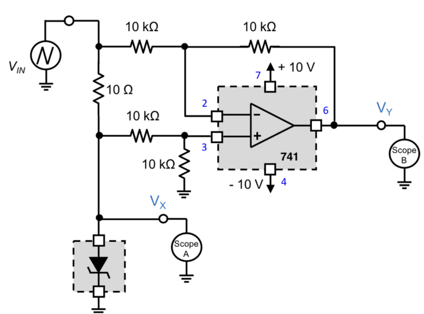

Fig. 7. Capturing the I-V characteristic of a 3.3 V Zener Diode

We then conducted the same setup on LTSpice and arrived at the same findings described above. The LTSpice plot can be found in appendix B, and the oscilloscope plot can be found in appendix A.

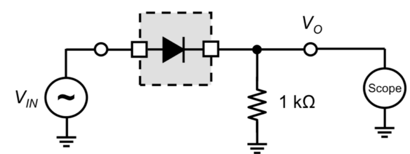

Fig. 9. Half-Wave Rectifier Circuit

D. Rectifiers

We then constructed the half-wave rectifier circuit seen in figure 9, using the 1N5402 power rectifier diode. Then, commenced to run a 60 Hz, 5 V amplitude sinewave as input to arrive at the oscilloscope plot seen in figure 10. As seen in figure 10, when the input sine wave is positive, the diode is forward-biased, and current flows through it, allowing the positive half-cycle to appear at the output. When the input sine wave is negative, the diode is reverse-biased, and no current flows through it, effectively blocking the negative half-cycle from the output. Hence why our figure looks like a cut off sine wave.

We were then asked to place a 1 uF capacitor across the load resistor of the rectifier circuit to arrive at the circuit seen in figure 11. We ran the same sine wave as before to arrive at the input output plot in figure 12. As seen from figure 12 the circuit creates a simple passive filter, also known as a capacitor filter. The purpose of this filter is to reduce the ripple voltage and smooth out the pulsating DC output waveform from the half-wave rectifier circuit we observed earlier. As seen, the output is simply a ripple voltage representing the 'smoothed out' version of the positive-only sine wave we saw earlier. The ripple seen at the output has a frequency of 59.978 Hz, which is the same as the input sine wave. As for the amplitude, we see that the RMS value of the ripple sits at a voltage of 4.453 V, close to the 5V amplitude of our input signal. The peak to peak value of the ripple however is reduced to 212.77 mV,

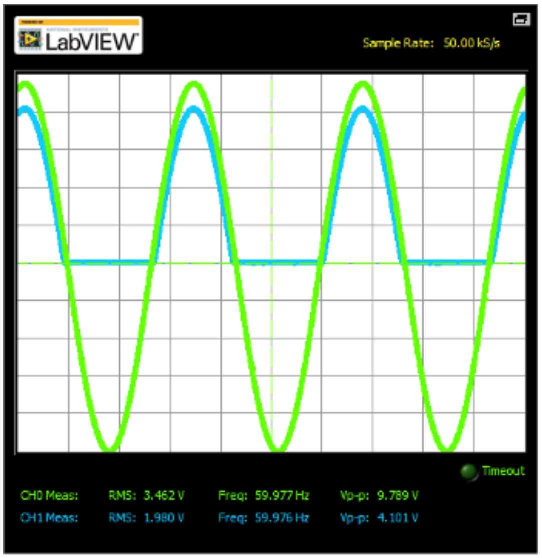

Fig. 10. Half-Wave Rectifier Circuit, Oscilloscope Output

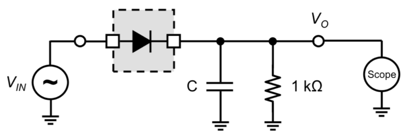

Fig. 11. Half-Wave Rectifier Circuit with Peak-Detector

which makes sense as our input gets flattened to a DC value of 4.453 V.

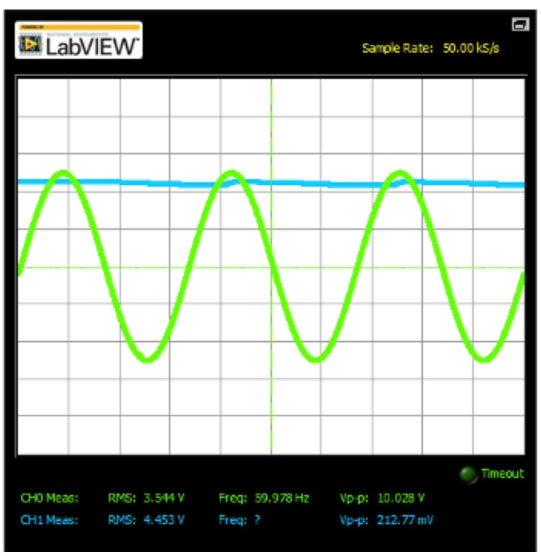

Fig. 12. Half-Wave Rectifier Circuit with Peak-Detector, Oscilloscope Output, 1uF

We then replace the 1uF capacitor with a 100uF capacitor in the circuit of figure 11 to arrive at the plot in figure 13. As seen from the plot, the circuit flattens the input to a near DC ripple with the same frequency as the input, roughly 60 Hz. The amplitude of the output is also decreased in terms of peak-to-peak voltage to 25.76 mV. This implies that the higher capacitance resulted in more ‘flattening’, while it maintained an RMS voltage value of 4.396 V. It follows now, that since the ripple has nearly become a straight line, we can describe it in an equation as ripple_voltage = 4.396, as it is a straight horizontal line at 4.396 V.

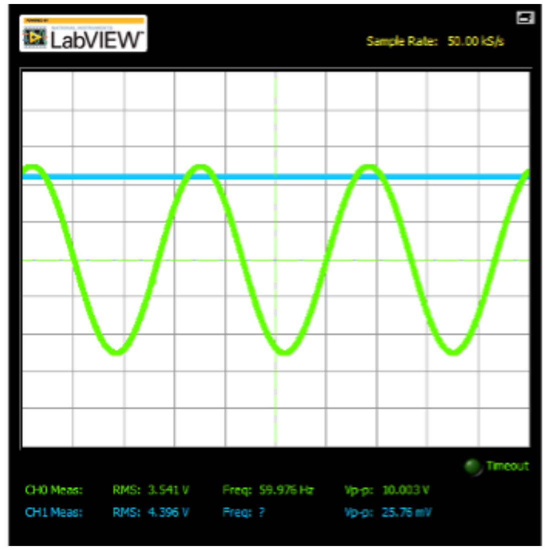

Fig. 13. Half-Wave Rectifier Circuit with Peak-Detector, Oscilloscope Output, 100uF

We then conducted the same three setups on LTSpice and arrived at the same findings described above. The LTSpice plots can be found in appendix B.

E. Voltage Regulation Using Zener Diode

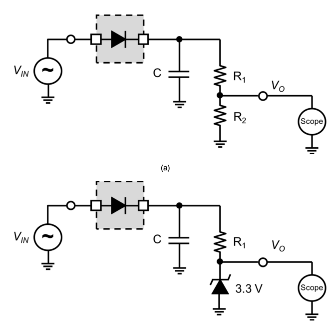

Fig. 14. Voltage Reference Using: (a) Resistor Divider, (b) Zener Diode

Within this part of the laboratory, we were asked to compare two different ways to reduce a DC level from a fixed AC supply. And so, for the first way; we used the same circuit as in the previous part, but using the 100uF capacitor, and replacing the 1 kΩ load with a voltage divider circuit to arrive at the circuit in figure 14a. We then ran the same sine wave from the preceding part to arrive at the plot in figure 15. As seen from the figure, the output is a ‘flattened’ ripple with the same frequency as the input signal, with an RMS average value of 3.357V, which matches the goal of this circuit to produce a DC voltage of 3.3V. The amount of ripple at the output is actually however, higher than all of the ripples observed before, as the output signal has a peak to peak voltage value of 407.51 mV.

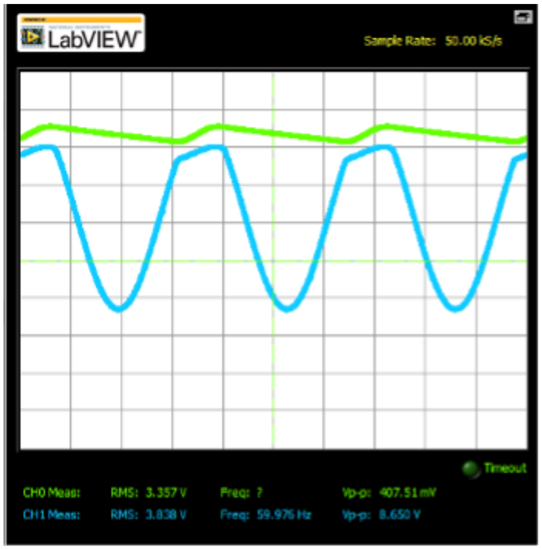

Fig. 15. Voltage Reference Using Resistor Divider, Oscilloscope Output

We then replaced the voltage divider with the 1N5333 Zener diode and a series resistor of approximately 1 kΩ to arrive at the circuit in figure 14b. Then, by running the same sine wave discussed arrived at the plot seen in figure 16. We find from this plot that the output voltage has an average RMS value of 2.496 V and that the ripples have decreased substantially. Further, we can see that the output signal now has a peak to peak voltage value of 41.52 mV, leading us to believe that this configuration provides the smallest AC ripple compared to the resistor-divider network created earlier.

We then conducted the same two setups on LTSpice and arrived at the same findings described above. The LTSpice plots can be found in appendix B.

F. Limiter Circuit Using Diodes

For the last part of this investigation, we were asked to construct the circuit in figure 17, with a 1.5V battery cell as seen, with the 1N4148 signal diode. We than ran a triangular wave form that varies between -2V to 3V to arrive at the oscilloscope and the i-v plot seen in figure 18 and 19. As seen from this plot, the diode-battery arrangement turns on near the cut in voltage at around 2.133 V, where after the current running through the arrangement substantially increases at a very high rate.

We then replaced the diode battery arrangement with two opposite facing diodes of 1N4148 to arrive at the circuit in figure 20. We then ran a triangular signal varying from -2V to 2V through the circuit to arrive at the oscilloscope and i-v characteristic found in figures 21 and 22. As seen

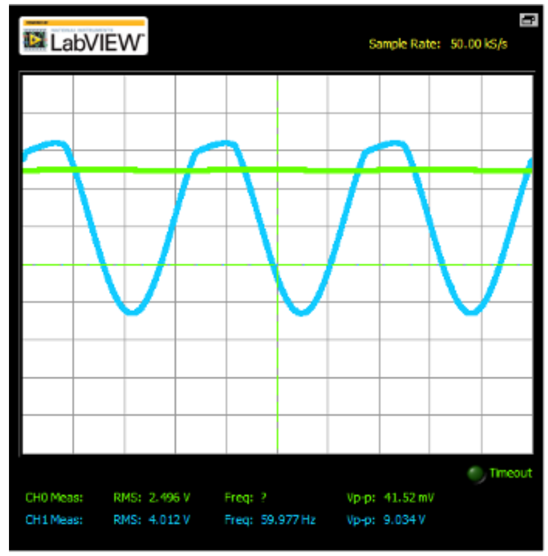

Fig. 16. Voltage Reference Using Zener Diode, Oscilloscope Output

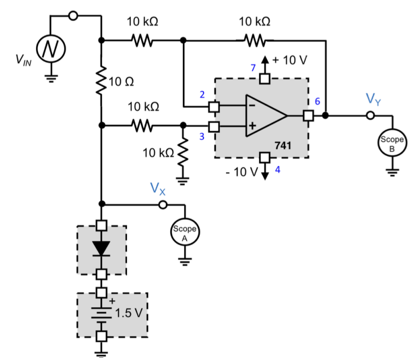

Fig. 17. Capturing the I-V Characteristic of a Diode and a 1.5 V Voltage Source, Limiter Circuit

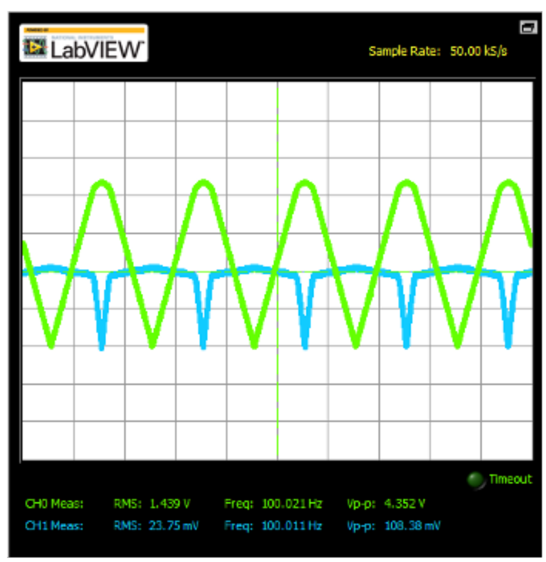

Fig. 18. Limiter Circuit with Voltage Source, Oscilloscope Output

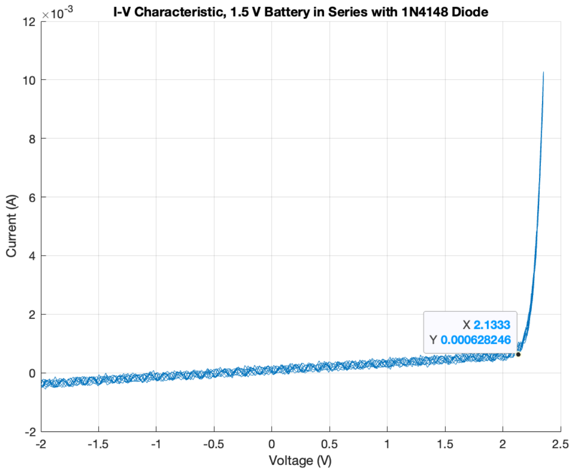

Fig. 19. Limiter Circuit with Voltage Source, I-V Characteristic

from the plots, the output signal is limited to the voltage range between the forward voltage drops of the diodes and the reverse breakdown drops. This circuit can be used in various applications to protect components or circuits from voltage spikes or to shape wave forms for specific purposes. Further, it can be used to reduce noise using the flipped arrangement, specifying a specific range. The circuit can be useful in smaller signals within the range described by the breakdown region and the forward voltage but is less effective with larger signals outside the range.

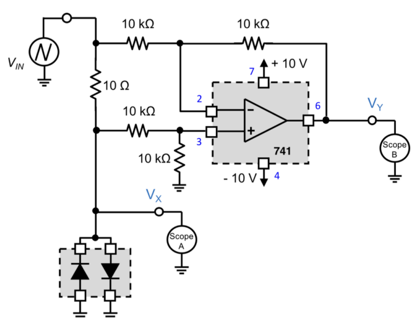

Fig. 20. Capturing the I-V Characteristic of Two Back-to-Back Diodes

We then conducted the same two setups on LTSpice and arrived at the same findings described above. The LTSpice plots can be found in appendix B.

III. Conclusion

Throughout this investigation, we have explored diode circuits, analyzed their characteristics, and identified potential applications. We have observed how the I-V characteristics of diodes change under different configurations and the effects of temperature on their performance. Zener diodes were studied in voltage regulation applications, and rectifiers were analyzed for their ability to convert AC signals into DC. The results obtained in this study contribute to our understanding of diode

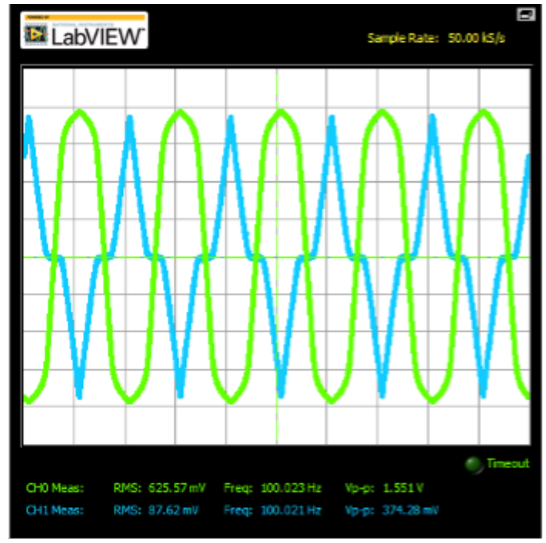

Fig. 21. Limiter Circuit with Back-to-Back Diodes, Oscilloscope Output

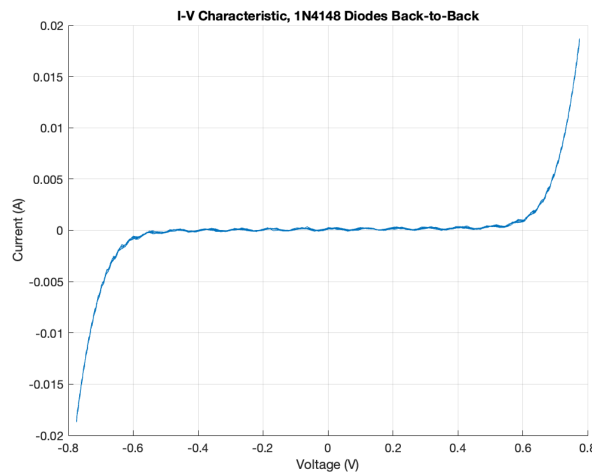

Fig. 22. Limiter Circuit with Back-to-Back Diodes, I-V Characteristic

behavior in different electronic circuits. Further, all findings were validated by way of LTSpice, and data was analyzed by way of MATLAB.

IV. References

[1] A. S. Sedra and K. C. Smith, Microelectronic Circuits, 8th ed. Oxford University Press, 2019.

Appendix A: Oscilloscope Plots

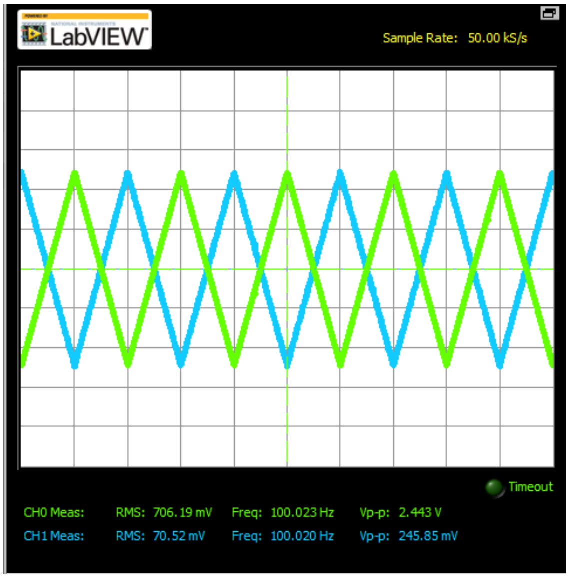

Figure 1 - Oscilloscope for 100 Ohm Resistor, Part A

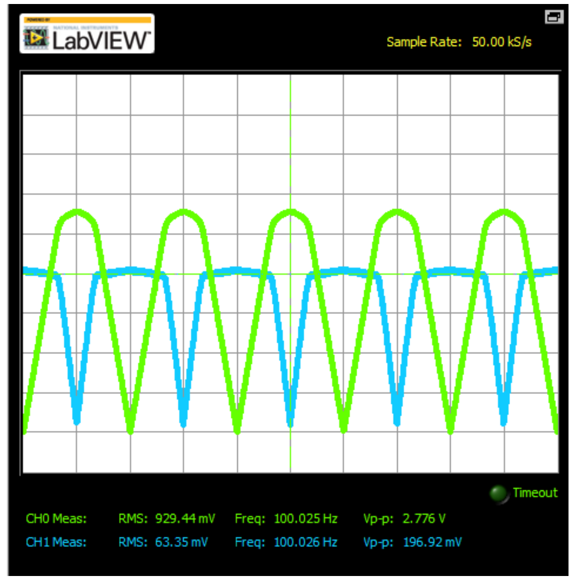

Figure 2 - Oscilloscope for 1N4148 Diode, Part A

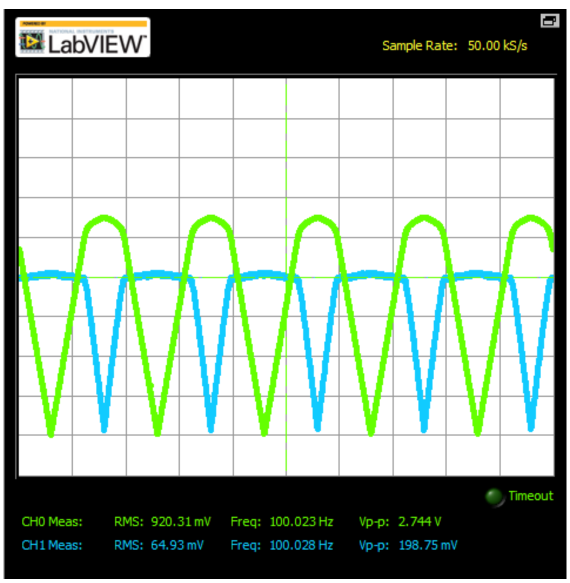

Figure 4 - Oscilloscope for 1N5402 Diode, Part A

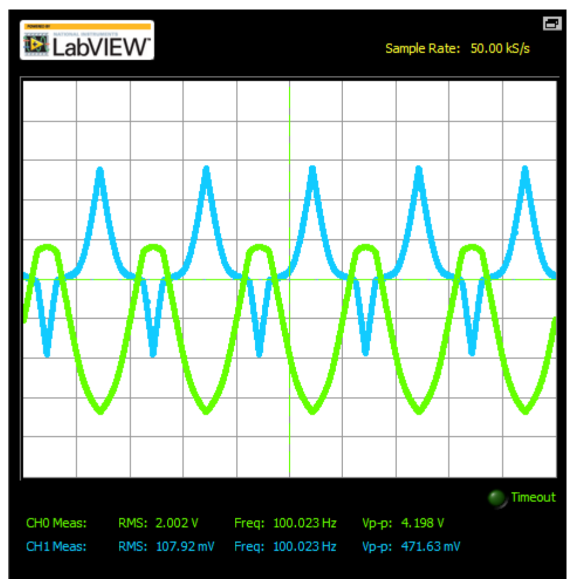

Figure 3 - Oscilloscope for Zener Diode, Part C

Appendix B: LTSpice Plots

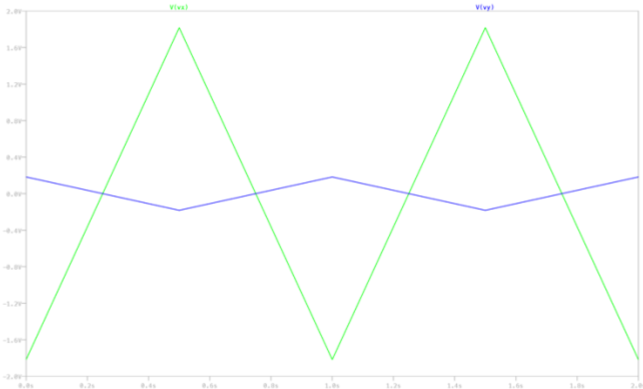

Figure 1 – Plot for 100Ohm Resistor, Part A

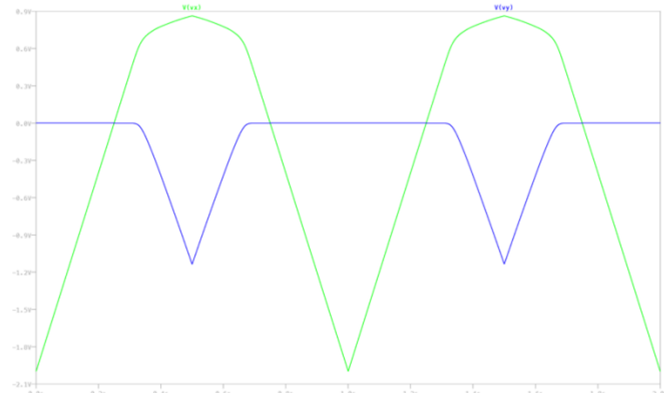

Figure 2 – Plot for IN4148 Diode, Part A

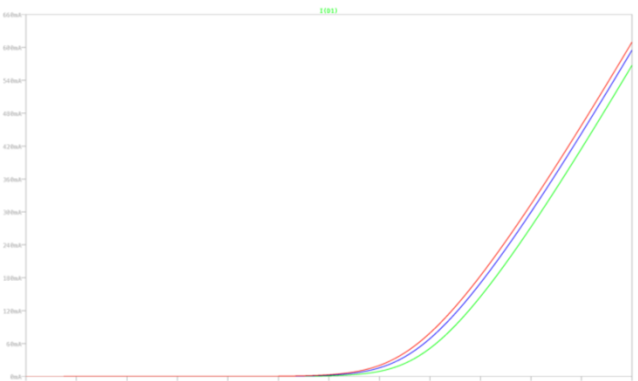

Figure 3 – Plot for Part B, Varying Temperature

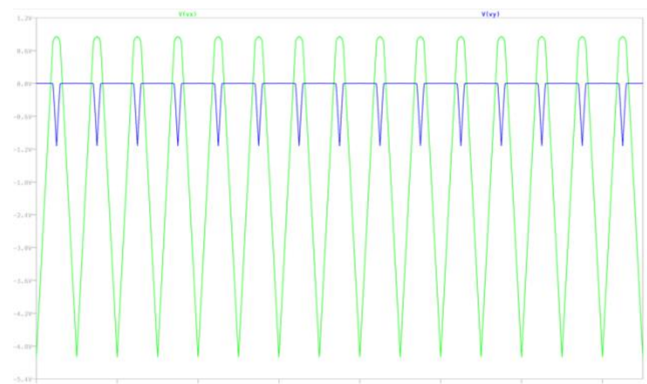

Figure 4 – Plot for Part C

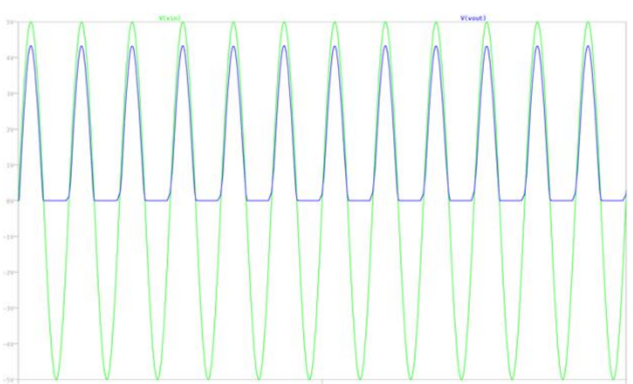

Figure 5 - Half-Wave Rectifier Circuit, Oscilloscope Output

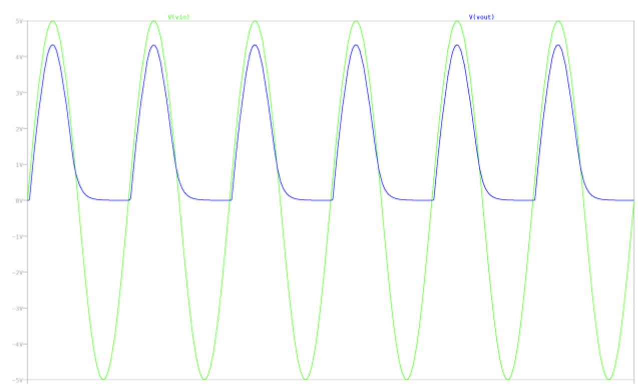

Figure 6 - Half-Wave Rectifier Circuit with Peak-Detector, Oscilloscope Output, 1uF

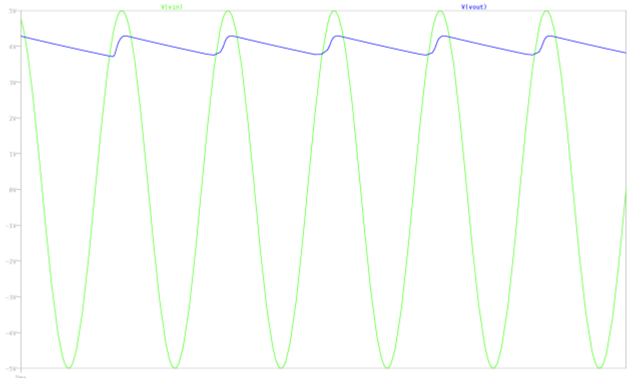

Figure 7 - Half-Wave Rectifier Circuit with Peak-Detector, Oscilloscope Output, 100uF

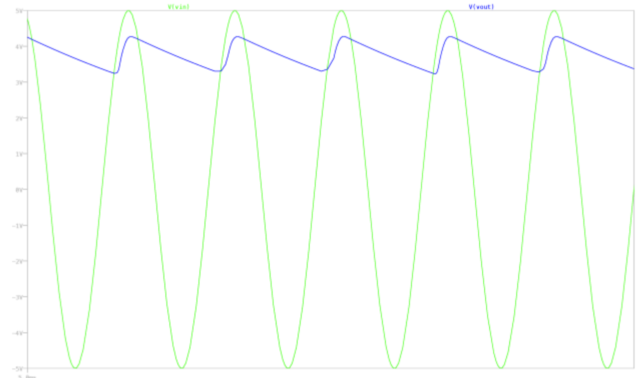

Figure 8 – Plot for Part E, Voltage Divider

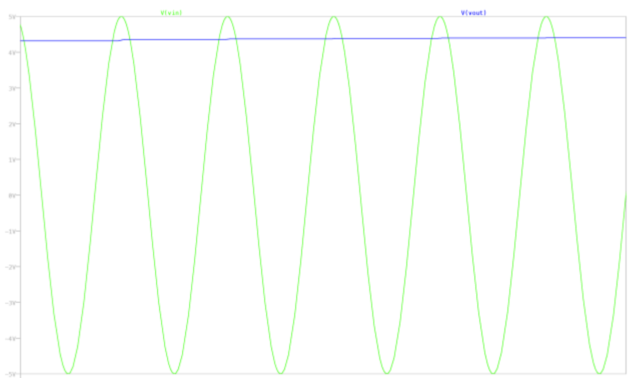

Figure 9 – Plot for Part E, Zener Diode

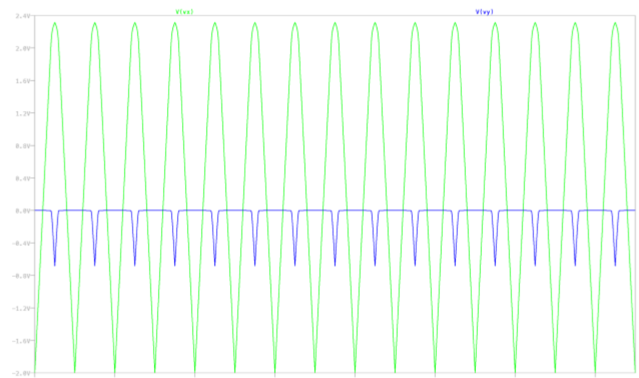

Figure 10 – Plot for Part F, Battery

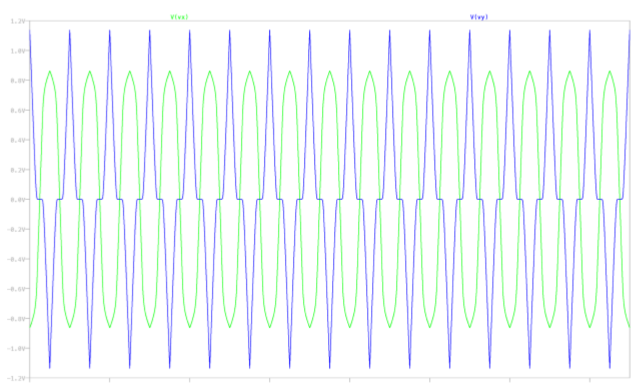

Figure 11 – Plot for Part F, Back-to-Back