ECSE331 Lab 4

Silicon Diode and Their Applications

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ECSE331

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ECSE331 Lab-4 Report

***Abstract* — This report mainly focuses on exploring applications of silicon diodes as rectifiers, voltage regulators, and limiters. In this lab, an investigation of i-v characteristics as a function of diode voltage will be applied to a signal, rectifier, and zener diode. Exploration and investigation of the forward, bias, and breakdown regions of the diode and temperature dependency will also be included in this lab.**

I. INTRODUCTION

The main purpose of this lab is to investigate the i-v characteristics of silicon diodes. In this lab, students are required to construct a curve tracer. With the curve-tracer, the i-v characteristics of silicon diodes and zener diodes will be measured, and the temperature effects of the diode will also be analyzed. Based on the curve-tracer, a limiter circuit will be built and investigated as well. To further explore applications of diodes, a half-wave rectifier will be constructed, and the behaviors of ripple will be analyzed. A voltage regulation using a zener diode will also be built, and behaviors of ripple will be investigated and compared with the measurement of the rectifier.

II. EXPERIMENT RESULTS

A. i-v Characteristics Using a Curve Tracer

a). i-v characteristic of a 100Ω resistor

We first built a curve tracer circuit, as shown in Fig. 2 (with a 100Ω resistor replacing the diode). We then plotted the i-v curve of a 100Ω resistor. In the tracer circuit, we measured the voltage V_x *and* V_y. Since $V_y = 10I_d$, the magnitude of the resistor should satisfy $R = \frac{V_x}{I_d} = \frac{10V_x}{V_y}$.We plotted the i-v curve of the resistor by plotting $-\frac{1}{10}V_y$ versus V_x. Theoretically, this curve should be a straight line with a slope equal to the reciprocal of the resistance (100Ω). $k = \frac{I_2-I_1}{V_2-V_1} = \frac{0.519mA-0.056mA}{0.050V-0.004V} = 10.065mA/V$

$$\frac{1}{k} = 0.0993V/mA = 99.3\Omega \approx R(100\Omega)$$

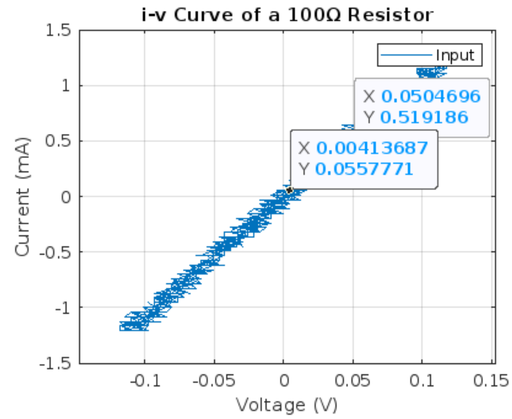

Fig. 1. i-v Curve of the 100Ω resistor

This result agrees with the theoretical value.

We can also confirm our i-v curve by calculating the resistance using $V_{Y,\,RMS,}$ and voltage across the resistor $V_{X,\,RMS}$ (Fig. 3):

$$R = \frac{V_{X,RMS}}{I} = \frac{V_{X,RMS}}{V_{Y,RMS}/10} = \frac{689.9mV}{(64.57/10)mA} = 106.85\Omega$$

we can thus verify that the current sensing op-amp circuit is also operating as expected.

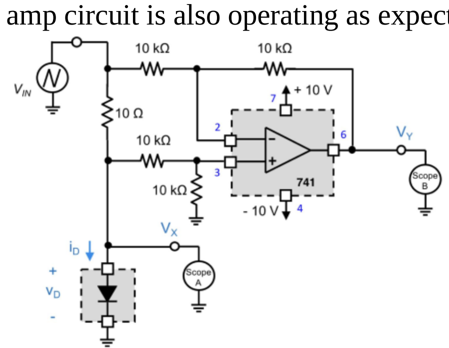

Fig. 2. Curve-trace set-up for measuring the diode i-v characteristic

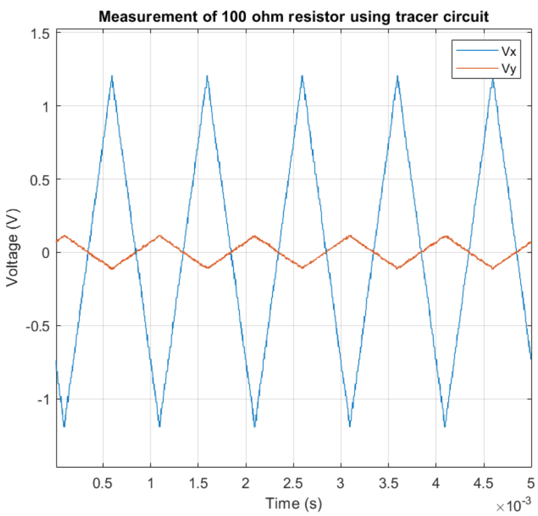

Fig. 3. Measured value of V_x and V_Y

b). i-v characteristic of a 1N4148 Diode

After verifying the circuit was operating as expected, we changed the 100Ω resistor to a 1N4148 diode. We plotted its i-v curve and observed its cut-in voltage is 0.5761V (Fig. 4).

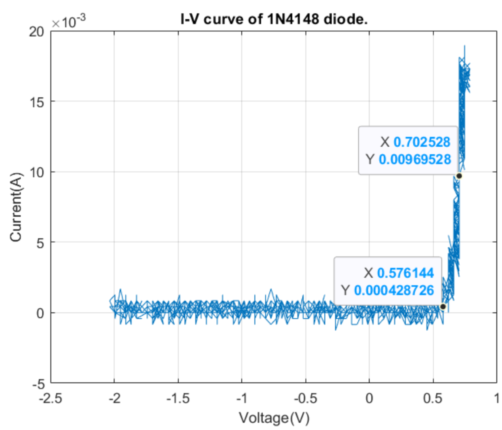

Fig. 4. i-v curve of the 1N4148 diode

At the diode voltage drop of 0.7V (Fig. 4), we calculated the reciprocal of the AC diode resistance as follows:

$$\frac{1}{R} = \frac{I}{V} = \frac{9.69mA - 0.429mA}{0.702 - 0.576V} = 73.5\ mA/V.$$

We built a piece-wise linear model to predict the diode behavior. To build this model, we will use cut-off voltage $V_{cut-off} = 0.5761V$ and one operating reference point. If we choose the point (0.7445,0.0173) as another reference point, we will get the piecewise linear model: $I = 0.1025 \times V - 0.0591$.

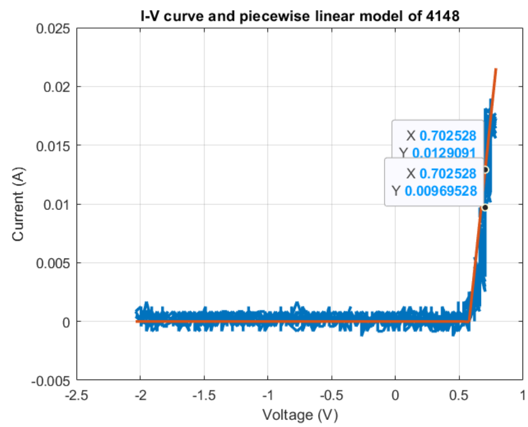

Fig. 5. Superimposed 1N4148 I-V behavior

We superimposed $I_{measured}$ and $I_{piecewise}$, and found out the maximum voltage difference over the range from -2V to +1V is 0.00321V. This difference is small, and hence the piece-wise linear approximation is a good model. However, the maximum difference may not be accurate since we measured multiple periods, and thus there is a lot of noise in the measured I-V curve. However, we can see the linear model is generally close to our measurement.

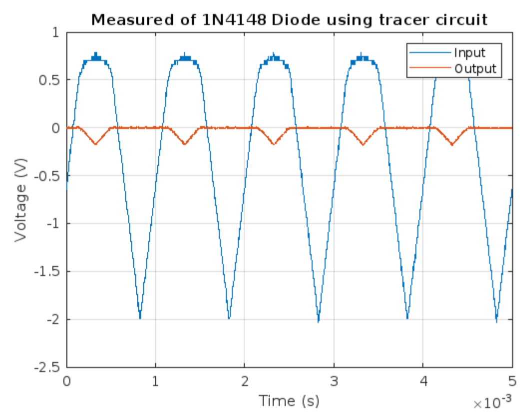

Fig. 6. Measured output and input of 1N4148 Diode

c). i-v characteristic of a 1N4005 Diode

We used the same circuit as in part (b), only with the 1N4148 diode being replaced with a 1N4005 diode.

We observed its cut-in voltage is around 0.6301V (Fig. 7).

At the diode voltage drop of 0.7V (Fig. 7), we calculated the reciprocal of the AC diode resistance as follows:

$$\frac{1}{R} = \frac{I}{V} = \frac{3.7mA}{0.71 - 0.63V} = 46.25mA/V$$

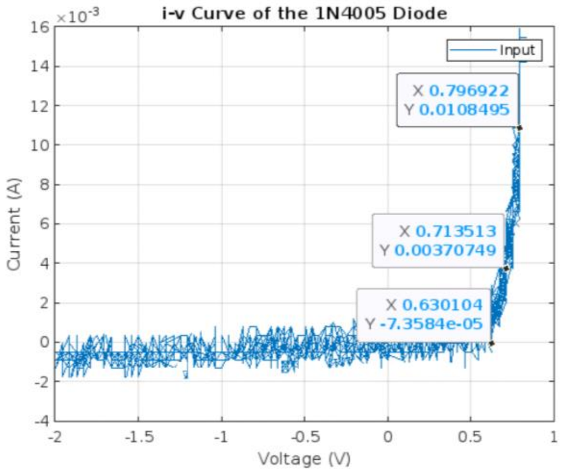

Fig. 7. i-v curve of the 1N4005 diode

We built its piece-wise model in the same way we did in part (b). If we choose the point (0.7969, 0.0108) and the point at cut-in voltage as references, then we can build the piecewise linear model (Fig. 8):

$$I = 0.0647 \times V - 0.0408$$

We superimposed $I_{measured}$ and $I_{piecewise}$ (Fig. 8) and observed that their maximum voltage difference, within the range of -2V to +1V, is 0.00411V. The difference is small, and hence this piece-wise linear approximation is a good model.

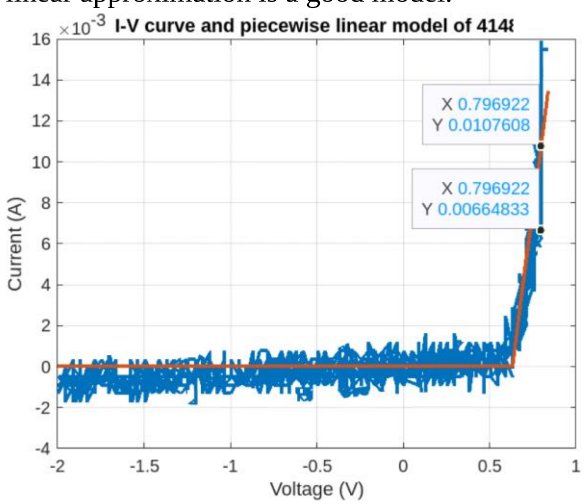

Fig. 8. Superimposed piecewise linear model of 1N4005

In order to have better illustrate the difference between the I-V plots that we measured before and remove the noises, we approximate the I-V plots by selecting a continuous set of data points within one period and plot the superimposed curve as shown in figure 9. From the plot, we noticed there's no obvious difference between the trend of the i-v curves of the two diodes. 1N4005 Diode may have a slightly higher current at a given voltage.

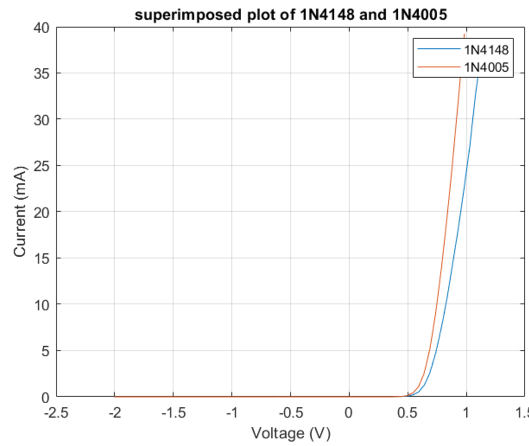

Fig. 9. Superimposed i-v curve of 1N4005 diode and 1N4148 Diode

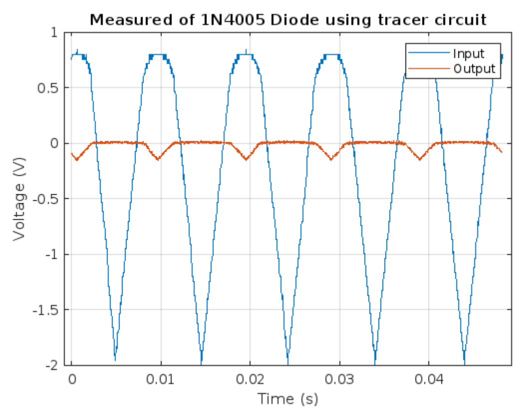

Fig. 10. Measured output and input of 1N4005 Diode

Then we reserved the direction of the 1N4148 diode. Comparing the graph we got (Fig. 11) with the previous one (Fig. 6), we noticed that the graph is inverted.

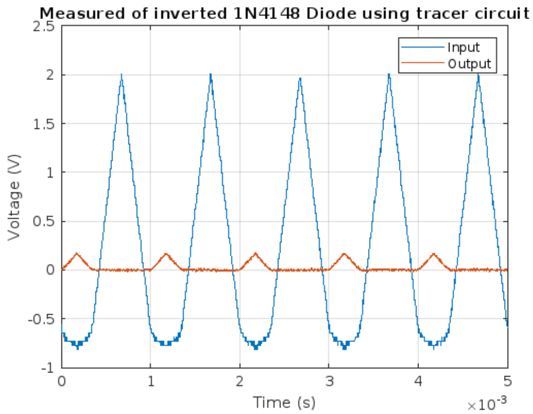

Fig. 11. Measured output and input of inverted 1N4148 Diode

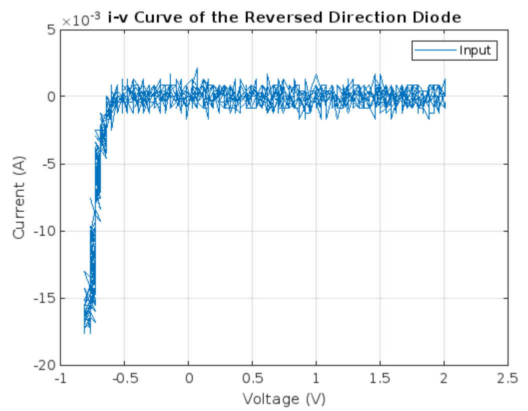

Fig. 12. i-v curve of the inversed diode

B. Diode Temperature Effects

In this part, we measured the temperature effects of the diode. We built our circuit as shown in Fig. 2

To investigate how temperature can affect behaviors of the diode, we need to use formula (2) and formula (3):

$$I = I_S \times (e^{V/\eta V_T} - 1)\ (2)$$

$$V_T = \frac{KT}{q}\ (3)$$

I_S and V_T are temperature dependent, and hence we should focus on analyzing changes of the two values as the temperature changing. K is the Boltzmann's constant (1.38×10^{-23} J/K), T is temperature (in Kelvin), q is the magnitude of the electronic charge (1.6×10^{-19}C), and we assign $\eta = 1$

According to formula (2), we expected the current to decrease as the temperature decreases.

a). 1N4148 Diode at 65°C

From the i-v curve of the diode at 65°C (Fig. 13), we can obtain I_s as follows.

First, we calculated V_T using formula (2):

$$V_T = \frac{1.38 \times 10^{-23} \times (65 + 273.15)}{1.6 \times 10^{-19}} = 0.0292V$$

Then we have I = 6.32mA at V = 0.7V, and we plug these values into formula (1) to get:

$$I_S = \frac{I}{(e^{V/\eta V_T} - 1)} = \frac{6.32 \times 10^{-3} A}{(e^{0.7V/0.0292V} - 1)}$$

$$= 2.452 \times 10^{-13} A$$

Hence, at 65°C, we have theoretical current:

$$I = 2.452 \times 10^{-13} \times (e^{V/0.0292} - 1)$$

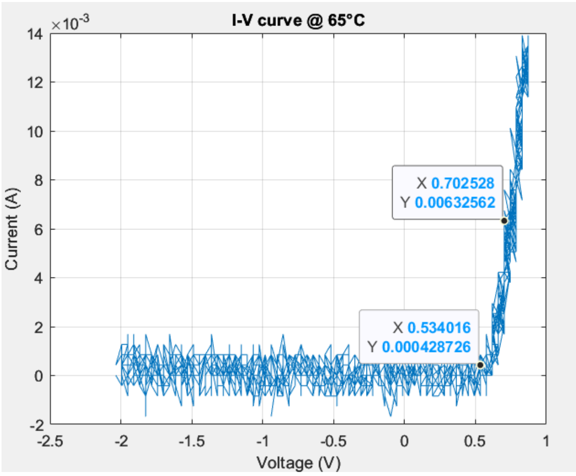

Fig. 13. i-v curve of 1N4148 diode at 65°C

b). 1N4148 Diode at room temperature (26°C)

From the i-v curve of the diode at room temperature (Fig. 14), we can obtain I_s as follows.

First, we calculated V_T using formula (2):

$$V_T = \frac{1.38 \times 10^{-23} \times (26 + 273.15)}{1.6 \times 10^{-19}} = 0.0258V$$

Then we have I = 8.43mA at V = 0.7V, and we plug these values into formula (1) to get:

$$I_S = \frac{I}{(e^{V/\eta V_T} - 1)} = \frac{4.22 \times 10^{-3} A}{(e^{0.7V/0.0258V} - 1)}$$

$$= 6.95 \times 10^{-15} A$$

Hence, at 26°C, we have theoretical current:

$$I = 6.95 \times 10^{-15} \times (e^{V/0.0258} - 1)$$

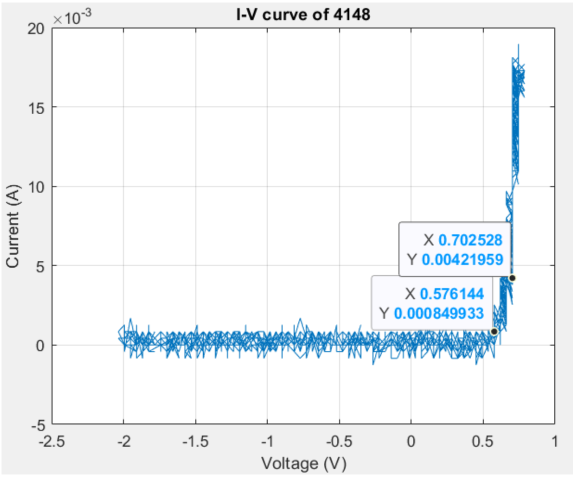

Fig. 14. I-v curve of 1N4148 diode at room temperature (26°C)

c). 1N4148 Diode at 2°C

From the i-v curve of the diode at 2°C (Fig. 15), we can obtain I_s as follows.

First, we calculated V_T using formula (2):

$$V_T = \frac{1.38 \times 10^{-23} \times (2 + 273.15)}{1.6 \times 10^{-19}} = 0.0237V$$

Then we have I = 5.90mA at V = 0.7V, and we plug these values into formula (1) to get:

$$I_S = \frac{I}{(e^{V/\eta V_T} - 1)} = \frac{6.74 \times 10^{-3} A}{(e^{0.7V/0.0237V} - 1)}$$
$$= 1.002 \times 10^{-15} A$$

Hence, at 2°C, we have theoretical current:

$$I = 1.002 \times 10^{-15} \times (e^{V/0.0237} - 1)$$

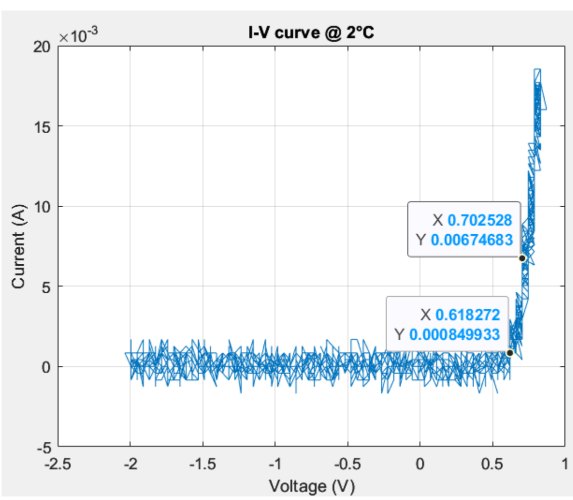

Fig. 15. i-v curve of 1N4148 diode at 2°C

From three i-v curve graphs shown above and the theoretical expression of the current that we calculated before, as the temperature is decreasing, the value of I at the same voltage is decreasing; the decrease in I_s overcomes the increase in $e^{V/\eta V_T}$. We can also notice that as temperature decreases, the cut-in voltage increases since there's a positive shift. This agrees with our prediction.

C. Zener Diode

In this part, we investigated the i-v characteristic of the zener diode. We built our circuit as shown in Fig. 16.

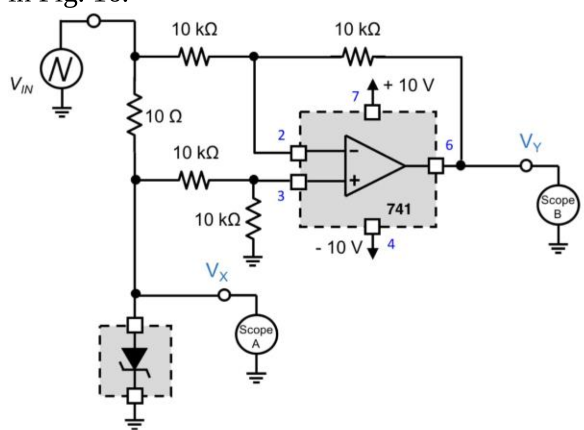

Fig. 16. Capturing the i-v characteristic of a 3.3V zener diode

We can obtain its breakdown region from its i-v curve (Fig. 17). From the graph, we can observe that the breakdown region occurs for voltage values less than -2.71V.

We can also obtain the AC resistance of the zener diode, which is the reciprocal of the slope of the breakdown region:

$$slope = \frac{I_2 - I_1}{V_2 - V_1} = \frac{-0.0042 - (0.0135)}{-2.71 - (-3.13)}$$
$$= 0.022$$

$$R = \frac{1}{slope} = \frac{1}{0.022} = 45.45\Omega$$

Hence, the AC resistance is 45.45Ω .

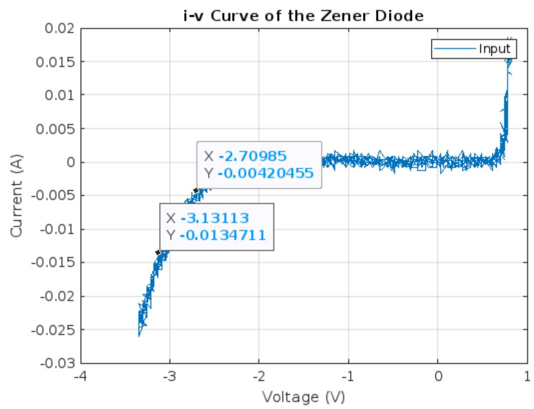

Fig. 17. i-v characteristic of a 3.3V zener diode

D. Rectifiers

We constructed our half-wave rectifier circuit as shown in Fig. 18.

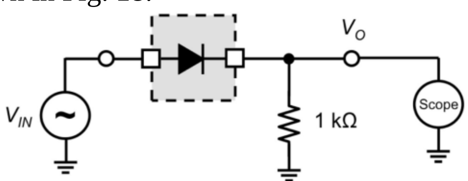

Fig. 18. Half-wave rectifier circuit

We displayed both the output and input signal on the same plot to compare them (Fig. 19). We observed that when the input voltage is negative, the output voltage will be zero; when the input voltage if greater than or equal to zero, the output voltage is almost the same as the input voltage, but its magnitude is slightly smaller than the input voltage.

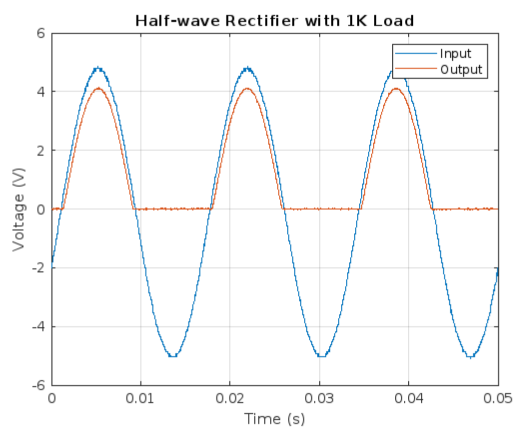

Fig. 19. Comparison between the input and output voltage of a half-wave rectifier

We then inserted a 1μF capacitor across the load resistor (Fig. 20).

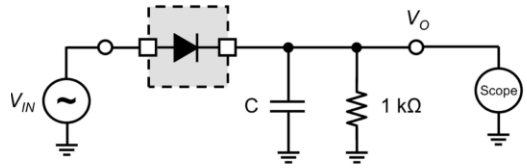

Fig. 20. Half-wave rectifier with peak-detector

The $V_{in} = 5sin(2\pi \times 60t)$, the ripple appears when V_{in} is greater than zero. The ripple has the same frequency as the input voltage, which is 60Hz, and its peak-to-peak voltage is 4.027V(Fig. 21). Since the capacitance is very small, it discharges quickly. Since here the premise $RC >> T$ isn't satisfied, the ripple is relatively big and very close to the input signal.

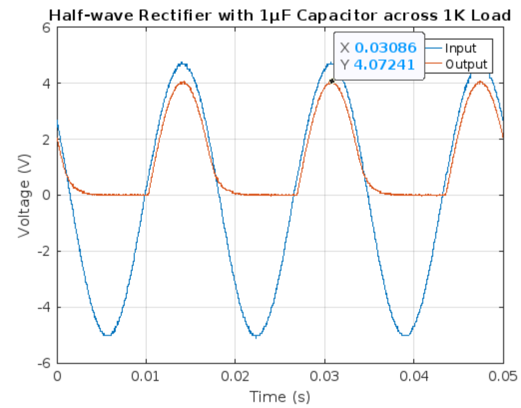

Fig. 21. Comparison between the input and output signals (1μF)

We then increased the capacitance to 100μF. We can observe from the graph (Fig. 22), it discharges much slower. The peak-to-peak voltage of this ripple equals $\cdot 3.30869V - 2.8844V = 424.29mV$. Its frequency remains almost the same, but its amplitude decreases.

By analyzing these results, we can give an equation to describe the ripple:

$$V_{r,pp} = \frac{1}{f \times R \times C}$$

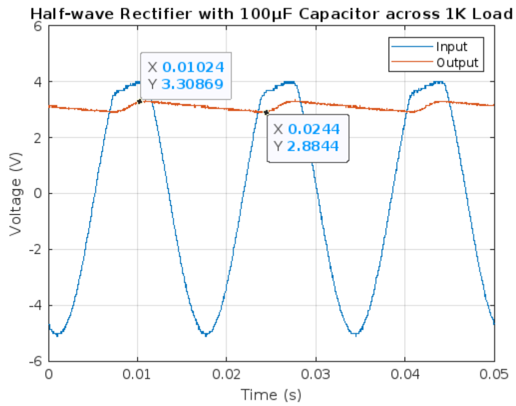

Fig. 22. Comparison between the input and output signals (100µF)

E. Voltage Regulation Using Zener Diode

In this section, we investigated the two different ways to reduce a DC level from a fixed DC supply.

a). Regulation with resistors

The half-wave rectifier circuit's 1k ohm resistor was divided into two resistors as shown in figure 23. In order to have a higher RMS value for the output voltage, R_2 should be much higher than the R_1. In this case, we selected 1k ohm for R_2 and 10 ohm for R_1. As we observed in figure 24, output has average value of 3.081V and the ripple is 424.3mV. Compared to what we get in previous part, the ripple is slightly reduced and average values remain almost the same.

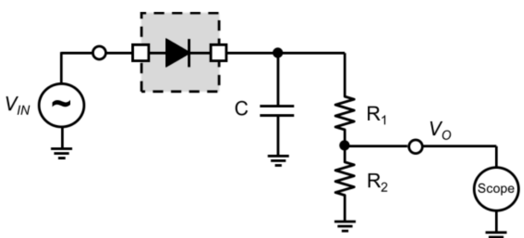

Fig. 23. Half-wave rectifier with resistor divider

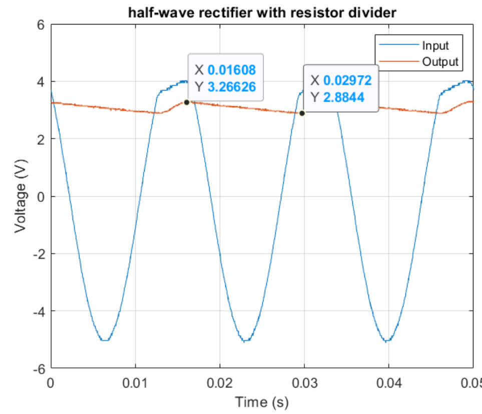

Fig. 24. Voltage across R_2 (Orange) and input (blue) in a half-wave rectifier with resistor divider.

b). Voltage Regulation with a Zener Diode

We then changed R_2 to 1N5333 Zener diode.The output voltage measured by oscilloscope is shown in figure 26. The output has average value of 2.248V and the ripple has only *84.86mV* peak-to-peak value.The ripple is apparently much smaller than previous two. We can conclude that voltage regulation with a Zener diode will provide smallest AC ripple.

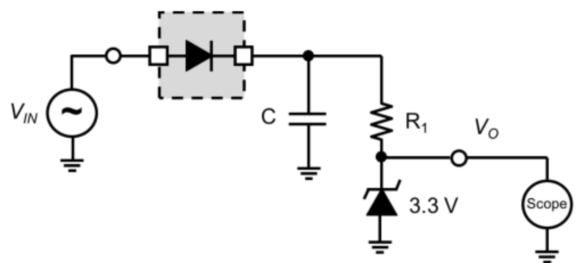

Fig. 25. Half-wave rectifier with Zener diode circuit.

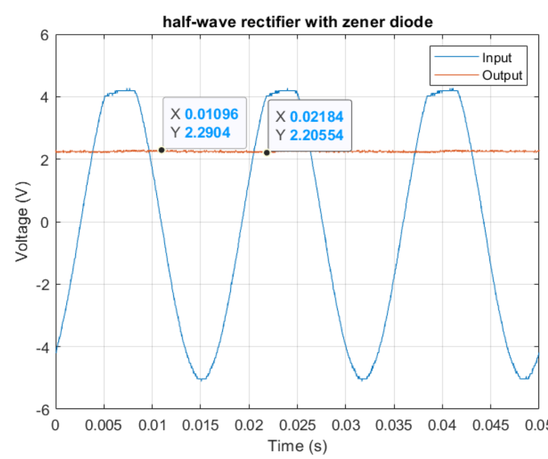

Fig. 26. Voltage across *Zener diode*(Orange) and input (blue) in a half-wave rectifier with Zener diode.

F. Limiter Circuit Using Diodes

In this part, we built our circuit as shown in Fig. 27

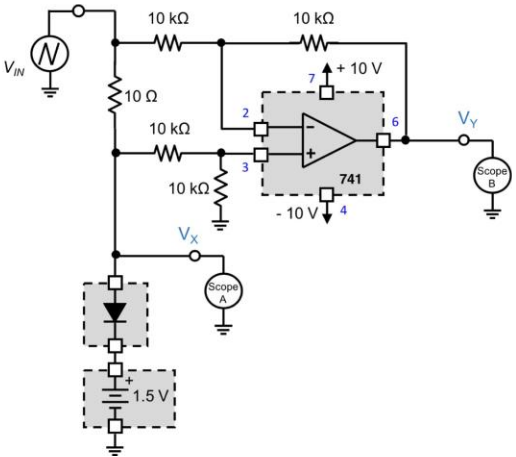

Fig. 27. Limiter circuit (with 1.5V battery)

From Fig. 28, we noticed after the input voltage passing 2.177V, the diode-battery will have a non-zero value, which means it turns on. Hence, at around 2V, the diode-battery arrangement will turn on. This can also be observed from the i-v curve of this limiter circuit (Fig. 29).

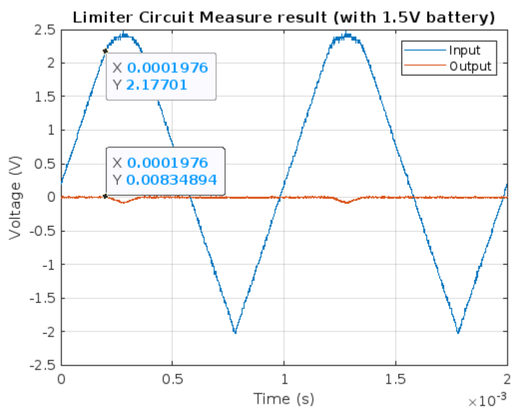

Fig. 28. Limiter circuit measured results (with 1.5V battery)

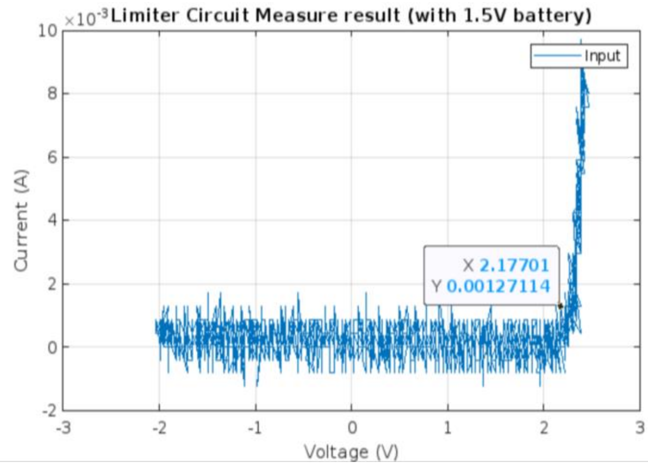

Fig. 29. i-v curve of the limiter circuit (with 1.5V battery)

We then changed the circuit to using two 1N4148 diodes connected in reversed directions (Fig. 30).

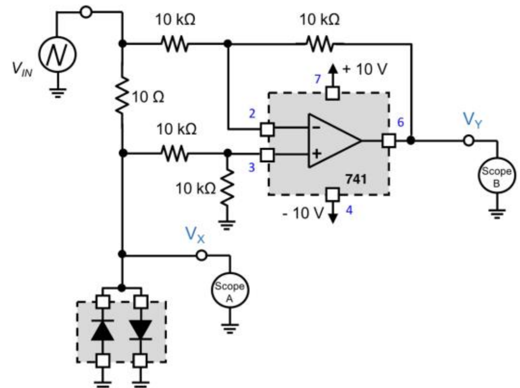

Fig. 30. Limiter circuit (with two 1N4148 diodes)

Due to the nature of the diode, two back-to-back diodes connected together can limit signals with too high or too low voltages. Hence, this circuit arrangement can be used in noise cancellation or small signal applications; it cannot be used in large signal applications because of the nature of diodes.

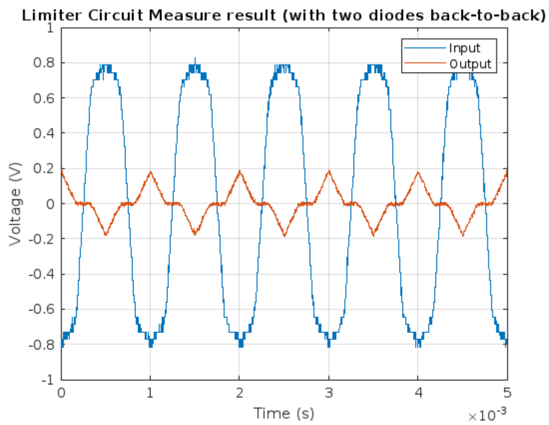

Fig. 31. Limiter circuit measured results (with two diodes connected in opposite directions)

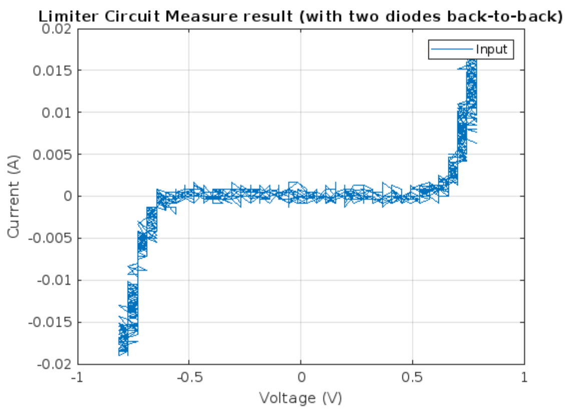

Fig. 32 . i-v curve of limiter circuit (with two diodes connected in opposite directions)

III. CONCLUSION

In this lab, we analyzed and explored the behaviors and applications of diodes.

We mainly investigated the i-v characteristics of different diodes (1N4148, 1N4005, and zener diode) and identified their forward bias, reverse bias, and breakdown regions.

By analyzing the behaviors of diodes under different temperatures, we concluded that a higher temperature would lead to a lower cut-in voltage.

Furthermore, we gained hands-on experience in implementing useful circuits with diodes. By building the circuit and analyzing the results, we now have a better understanding of diodes and regulation circuits.

APPENDIX

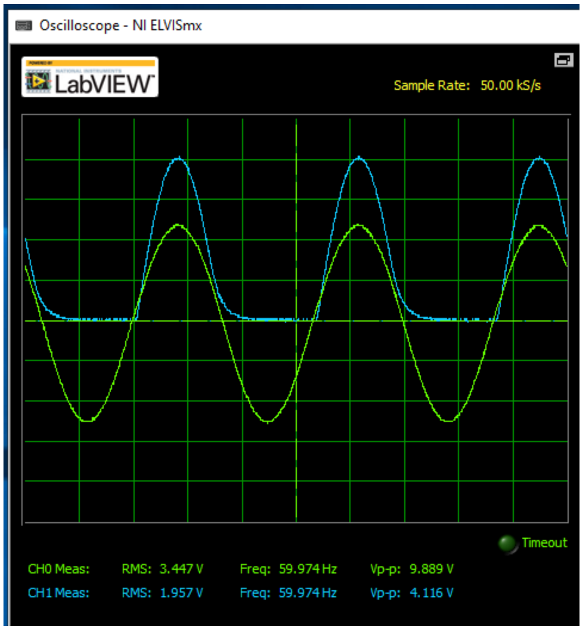

Fig. 33. Half-wave rectifier with 1µF capacitor (with frequency shown)

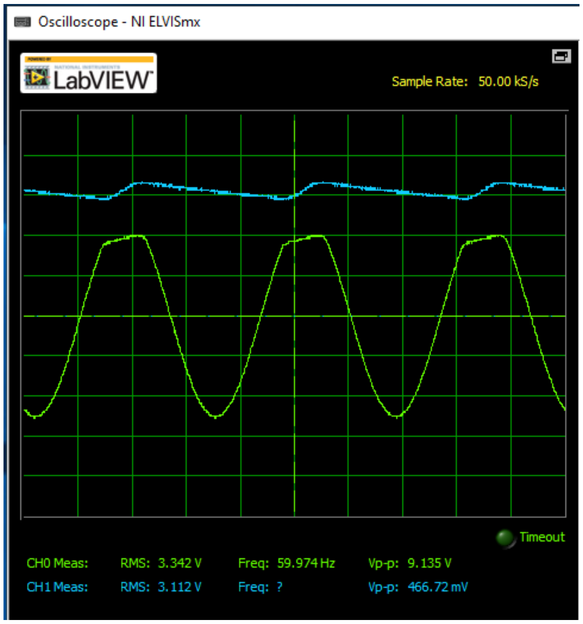

Fig. 34. Half-wave rectifier with 100µF capacitor (with frequency shown)