Laboratory No 3.

Silicon Diodes and Their Applications

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***Abstract*—This laboratory experiment investigates the i-v characteristics of silicon diodes under various conditions, examining the operational properties of signal, rectifier, and Zener diodes in forward, reverse, and breakdown regions. By employing the NI ELVIS-II+ test instrument, we capture diode responses across varying temperatures and voltages, allowing for a comprehensive analysis of diode applications in circuits as rectifiers, voltage regulators, and limiters. This report details experimental setups, procedures, data collection, and observations concerning diode performance.**

***Keywords*—Silicon diode, i-v characteristics, rectifier, Zener diode, NI ELVIS-II+, electronics, temperature dependence, voltage regulation**

I. INTRODUCTION

Diodes are fundamental components in electronics, frequently employed in applications requiring controlled current flow, such as rectification, voltage regulation, and signal limitation. Understanding the characteristics of silicon diodes, including their behavior in forward and reverse bias and their response to temperature variations, is essential for practical circuit design. This laboratory experiment focused on examining the i-v characteristics of several types of diodes—signal, rectifier, and Zener—using the NI ELVIS-II+ platform, a versatile test system that provides an integrated approach to circuit testing and analysis.

Through this experiment, diode operations across a range of voltage and temperature settings were explored, with key attributes such as forward voltage threshold, reverse breakdown voltage, and the impact of thermal conditions on diode performance being observed. The findings underscore the significance of diodes in circuit applications, demonstrating their roles in achieving desired voltage levels, limiting signal amplitude, and stabilizing outputs.

II. EXPERIMENT PROCEDURES AND ANALYSIS

This section presents a detailed analysis of six diode-based experiments: i-v characteristics using a curve tracer, diode temperature effects, Zener diodes, rectifiers, voltage regulation using Zener diode, and limiter circuit using diodes. Each experiment was designed to investigate specific diode behaviors and their practical applications in electronic circuits. The experiments were conducted using the NI ELVIS-II+ platform, enabling accurate measurement and analysis.

A. *Part 1: i-v Characteristics Using a Curve Tracer*

The voltage drop across the diode as well as the output voltage, V_X and V_Y, were measured using an oscilloscope as shown in the figure below. CH0 (channel A) was used throughout this section to measure the voltage across the diode, and CH1 (channel B) was used to measure the output voltage of the op-amp. Power was supplied to the 741 op-amp using a variable power supply. The function generator was set to generate a sawtooth waveform over a -2V to 2V signal range. Thus, the peak-to-peak of V_{in} would be 4V with a 0V offset.

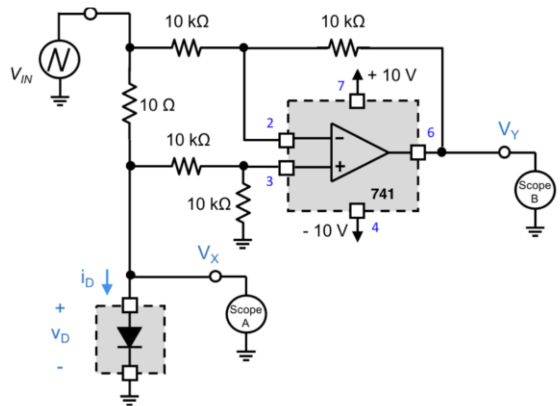

Figure 1.1: Curve tracer circuit

To verify that the current sensing op-amp circuit operates as expected without the diode present, the diode was replaced by a 100Ω resistor. By doing so, we want to verify that the voltage V_Y is 10 times greater than the diode current, i_D. The output responses of V_X and V_Y were captured using an oscilloscope as shown.

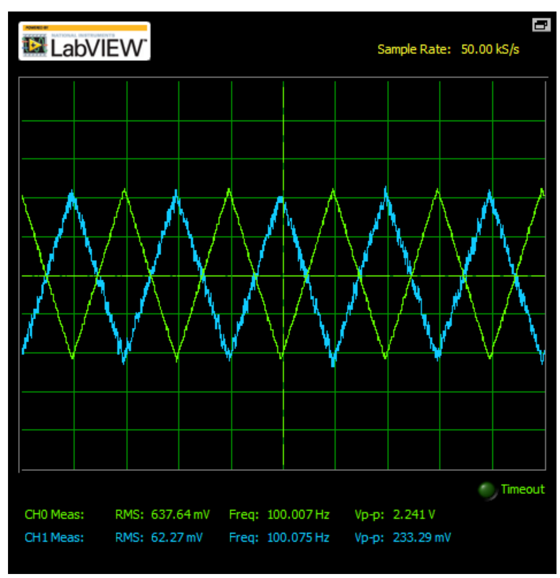

Figure 1.2: Curve tracer output response with 100Ω resistor where CH0 measures V_X and CH1 measures V_Y

Notice that V_X has an amplitude of $\frac{2.241V}{2} = 1.1205V$, and V_Y has an amplitude of $\frac{233.29mV}{2} = 116.645mV$. By circuit analysis and Ohm's law, the amplitude of the current i_D is 11.6645mV, which is approximately 10 times smaller than V_Y.

The results of the oscilloscope were also captured to confirm that the calculated i-v characteristics indeed correspond to a 10kΩ resistor, as seen in the figure below.

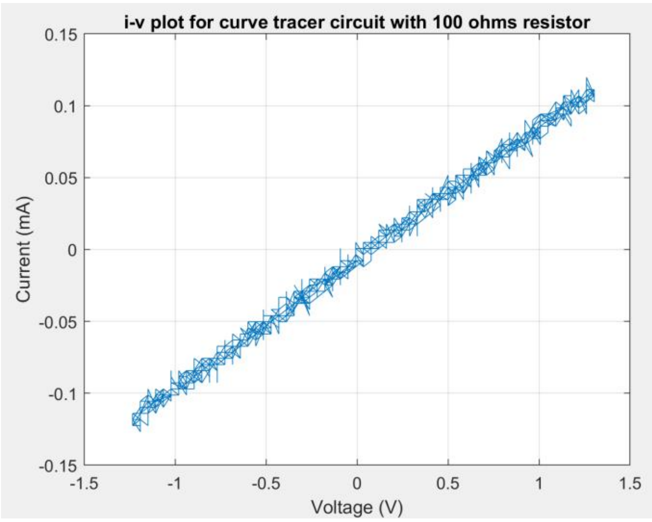

Figure 1.3: i-v plot of curve tracer circuit with 100Ω resistor

The slope of the i-v plot represents the conductance G, where the resistance R is the inverse of the conductance, $R = \frac{1}{G}$. Therefore, $R = \frac{1}{G} = \frac{V_2 - V_1}{I_2 - I_1} = \frac{(0.5-0)V}{(0.05-0)mA} = 10000\Omega$ which confirms that the calculated i-v characteristics indeed correspond to a 10kΩ resistor.

Then, the 100Ω resistor was replaced by a 1N4148 diode. The output responses of V_X and V_Y are captured by the oscilloscope as shown below, with CH0 representing V_X and CH1 representing V_Y.

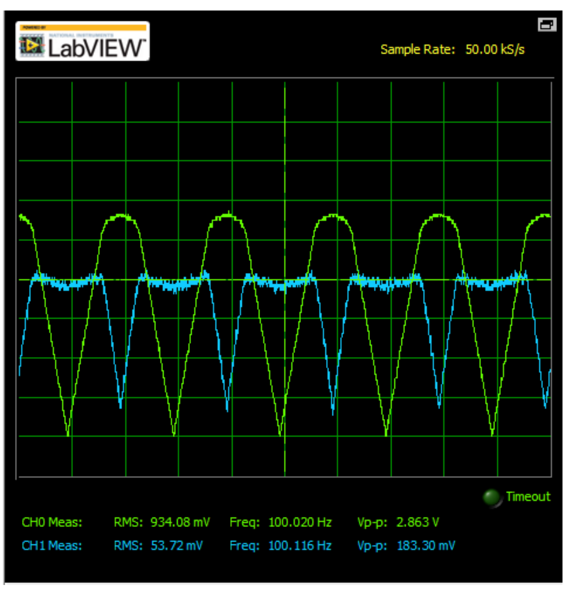

Figure 1.4: Curve tracer output response with 1N4148 diode where CH0 measures V_X and CH1 measures V_Y

The logged data obtained from the oscilloscope was saved to generate an i-v plot. The process was then repeated by replacing the 1N4148 diode by a 1N4005 diode. The generated plots are found below.

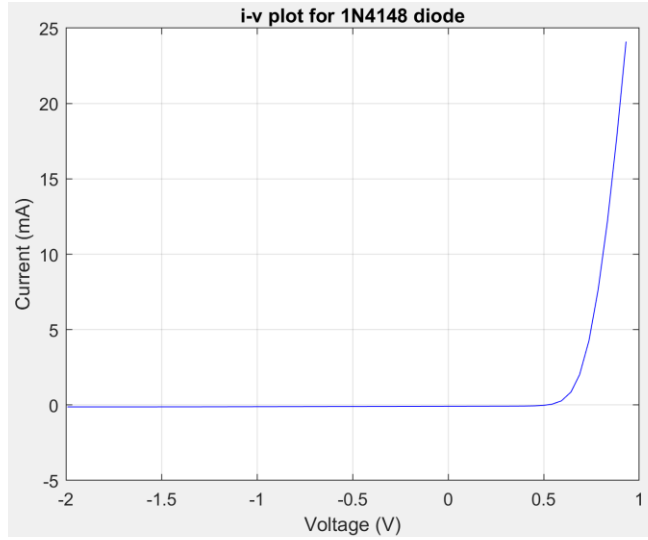

Figure 1.5: i-v plot of 1N4148 diode using MATLAB

Let cut-in voltage be defined as the forward voltage at which the diode starts conducting. By this definition, the cut-in voltage of the 1N4148 diode would be around 0.5V, because this is where the current first appears, and becomes nonzero.

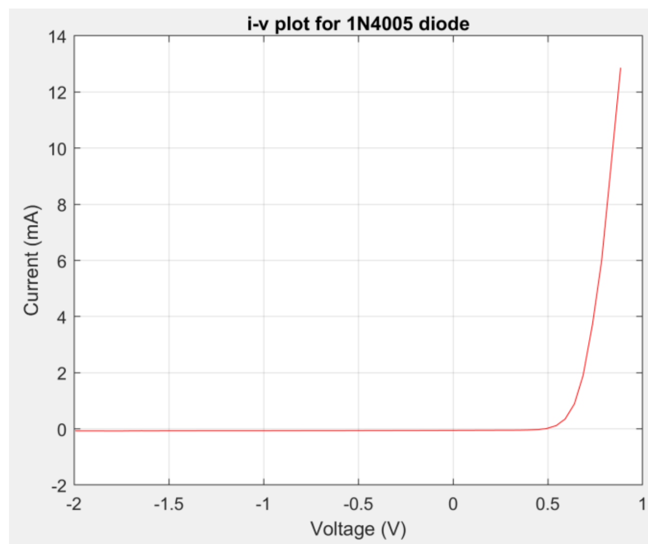

Figure 1.6: i-v plot of 1N4005 diode using MATLAB

Again, by using the same definition for the cut-in voltage, it is possible to obtain a cut-in voltage of around 0.5V for the 1N4005 diode.

To find the slope of the i-v characteristic at 0.7 V (which represents the reciprocal of the diode's AC resistance r_d), we can calculate the slope, i.e. the derivative $\frac{dI}{dV}$ around the 0.7 V point for both diodes using the data points below.

Table 1: Collected i-v points around 0.7V for 1N4148 and 1N4005 diodes

1N4148 diode (V, mA)	1N4005 diode (V, mA)

0.643	0.863	0.640	0.888
0.688	2.012	0.686	1.901
0.737	4.264	0.736	3.741
0.785	7.657	0.784	5.996

For the 1N4005 diode, the slope at 0.7 V is approximately 36.8 mA/V, whereas for the 1N4148 diode, the slope at 0.7 V is approximately 45.96 mA/V. These slopes correspond to the reciprocal of the AC resistance of each diode at that point.

Once the i-v plots for the 1N4148 and the 1N4005 diodes are superimposed as showed in the figure below, it is possible to deduct that the experimentation results for both diodes are quite similar.

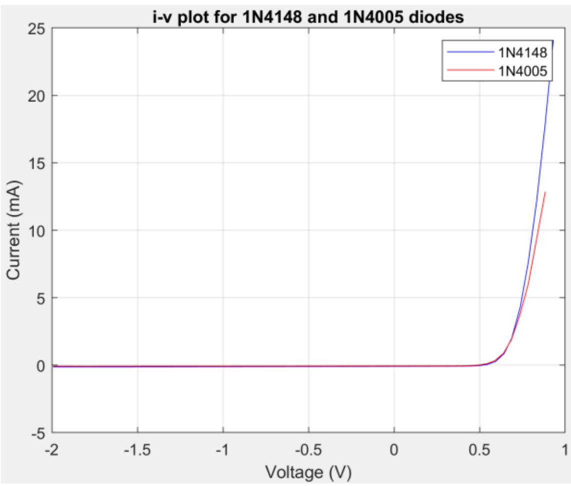

Figure 1.7: i-v plot of 1N4148 and 1N4005 diodes using MATLAB, superimposed

The piecewise linear model for a diode consists of a threshold voltage V_{th} (typically around 0.7 V for silicon diodes) and a linear segment with the previously calculated r_d slope beyond this threshold, approximating the diode's resistance in the "on" state. Using this model, the idealized linear behavior is plotted and overlayed on the actual i-v curves as seen below.

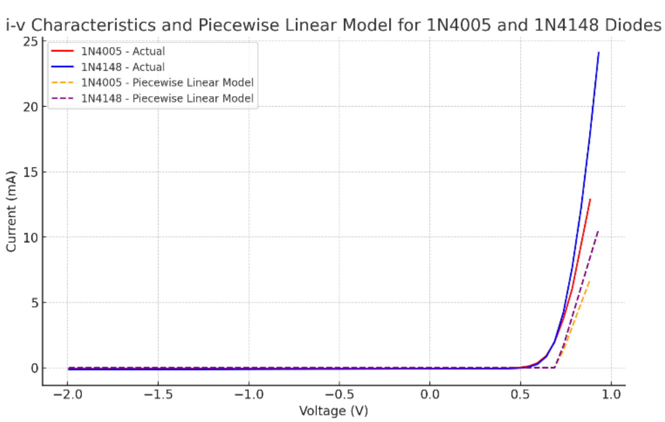

Figure 1.8: i-v characteristics and piecewise linear model of 1N4148 and 1N4005 diodes, superimposed

For the 1N4005 diode, the maximum difference between the actual i-v curve and the piecewise linear model over the voltage range -2 V to +2 V is approximately 6.09 mA. For the 1N4148 diode, the maximum difference is approximately 13.48 mA. These values are obtained from running a simple Python script.

The piecewise linear model provides a basic approximation but shows noticeable deviations, particularly at higher current levels. For practical applications where high precision is not required, the piecewise linear model can be acceptable; however, it lacks accuracy at higher currents and voltage levels, as shown by the maximum deviations.

Finally, after reversing the 1N4148 diode, we examine the outputs recorded by the oscilloscope. The logged data is then used to create an i-v plot in MATLAB, as shown below.

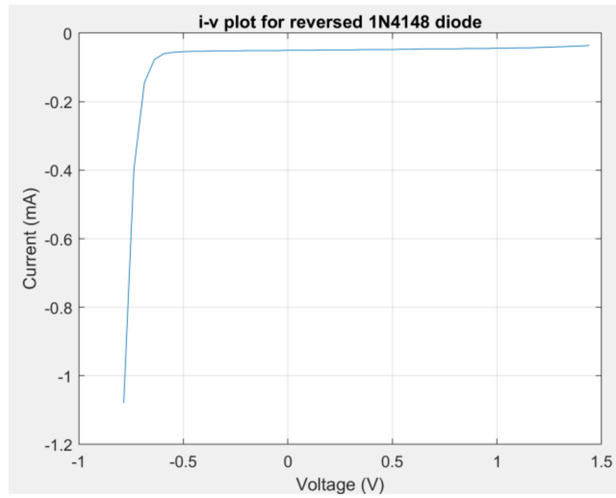

Figure 1.8: i-v plot of reversed 1N4148 diode using MATLAB

This plot indicates that the diode's behavior is also reversed. For instance, the cut-in voltage shifts from 0.5V in the non-reversed 1N4148 diode to -0.5V in the reversed configuration, as negative current begins to flow before reaching -0.5V.

B. Part 2: Diode Temperature Effects

In part 2 of the lab, the same curve tracer circuit as part 1 is analyzed. However, the diode will be under different temperature conditions to analyze how different diode temperatures affect the output responses. Again, the function generator will be set to generate a sawtooth waveform with peak-to-peak voltage of 4V with an offset of 0V so that V_{in} varies from -2V to 2V.

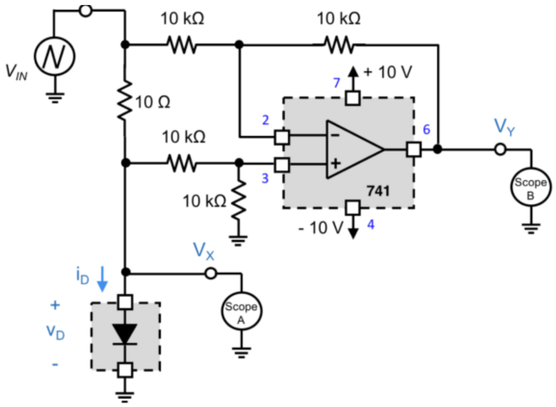

Figure 2.1: Curve tracer circuit

The measurements were first taken at room temperature, then at cold and hot temperatures using a freeze spray and a hot-air blowgun. The temperature of the diode was recorded using a hand-held thermal imager. The i-v plots are shown in the figure below, obtained using MATLAB.

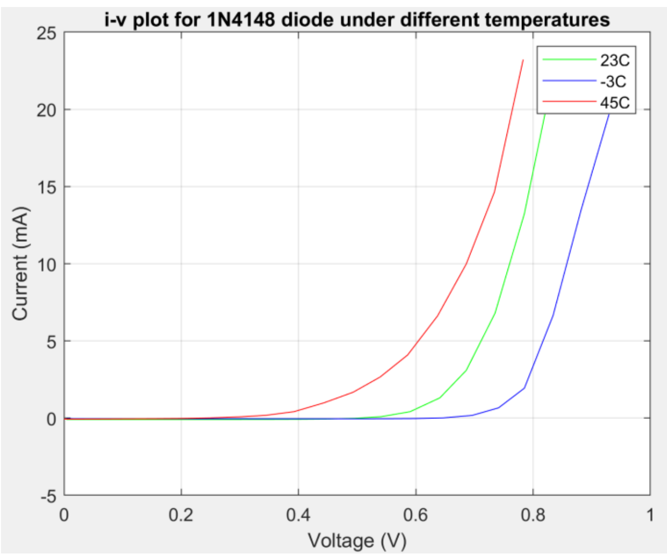

Figure 2.2: i-v plot for 1N4148 diode under different temperatures

As seen in the i-v plot for the 1N4148 diode under different temperatures, the cut-in voltages differ when the temperature of the diode is varied. The cut-in voltage is defined to be the forward voltage where the diode starts conducting, which would correspond to the voltage as soon as the current becomes nonzero. In the experiment, the cut-in voltages are observed to be 0.3V for 45 degrees Celsius, 0.5V for 23 degrees Celsius, and 0.7V for -3 degrees Celsius. Thus, the hotter the temperature, the lower the cut-in voltage and vice versa.

As temperature increases, the i-v characteristics of the diode exhibit a lower cut-in voltage, reflecting the reduced barrier for current conduction. This behavior is due to the intrinsic properties of the diode's semiconductor material, where the thermal energy at higher temperatures facilitates electron movement, effectively lowering the required forward voltage for conduction. For instance, in our experiment, the 1N4148 diode's cut-in voltage was approximately 0.3 V at 45°C, 0.5 V at room temperature (23°C), and increased to 0.7 V at -3°C. This shift can be attributed to the increase in the diode's saturation current I_s with temperature, which follows an exponential relationship. Consequently, the diode conducts more current at a given forward voltage as temperature rises, resulting in a steeper i-v curve. This thermal sensitivity of diodes is critical in applications where temperature stability is essential, as varying ambient conditions can significantly affect diode performance.

C. Part 3: Zener Diodes

In part 3 of the lab, the following curve tracer circuit was built to capture the i-v characteristic of a 3.3V 1N5226B Zener diode. The function generator was set to generate a sawtooth waveform over a -5V to 2V signal range. Thus, the peak-to-peak of V_{in} would be 7V with a -1.5V offset.

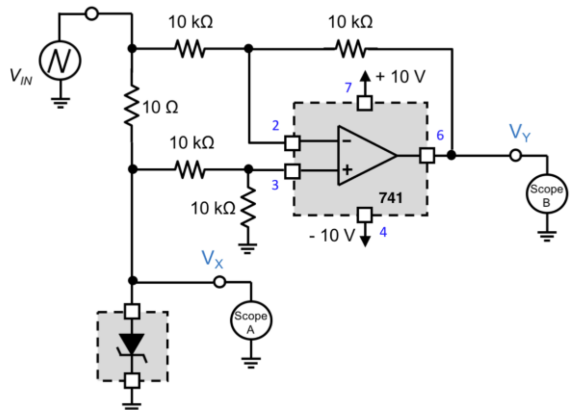

Figure 3.1: Curve tracer circuit with 3.3V 1N5226B Zener diode

The results were captured using an oscilloscope. CH0 captures V_x and CH1 captures V_Y.

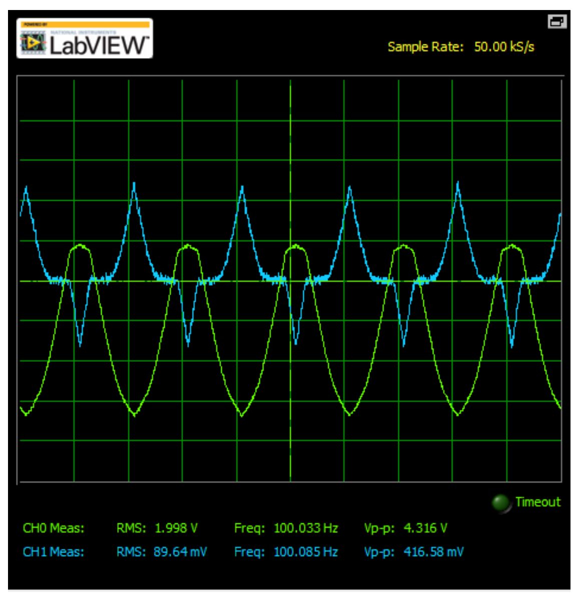

Figure 3.2: Curve tracer output response with 3.3V 1N5226B Zener diode where CH0 measures V_X and CH1 measures V_Y

Then, the logged output response was saved to generate an i-v plot using MATLAB. The visualization generated will help in identifying the voltage in which the Zener diode breakdown occurs. The i-v plot is as follows:

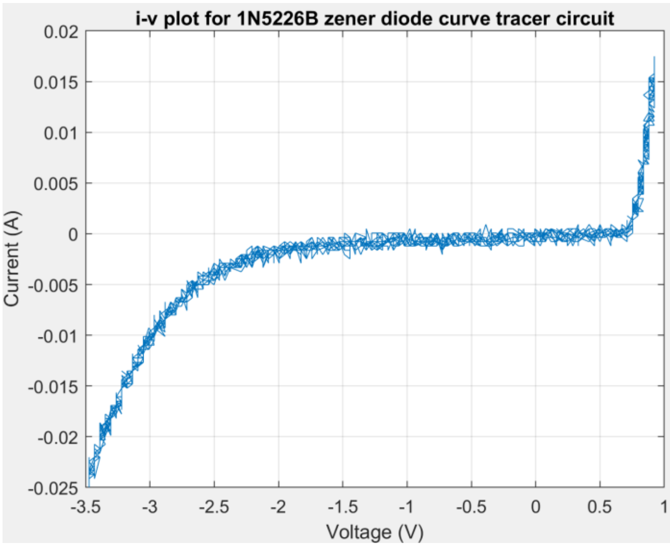

Figure 3.3: i-v plot for 3.3V 1N5226B Zener diode

Zener diodes allow current to flow in reverse bias when the voltage reaches the Zener voltage. Before reaching the Zener voltage (i.e., for voltages smaller than the Zener voltage), the current flows "backwards". The zone in which the current flows in the "backwards" direction is defined as the Zener breakdown region. Here, by observing the i-v plot, it is possible to obtain the breakdown voltage of around -2.5V.

In the breakdown region, the slope $\frac{dI}{dV}$ can be calculated by taking the change in current over the change in voltage within the region around -2.5 V where the i-v curve is linear. The AC resistance r_d in the breakdown region is the reciprocal of this slope. Taking datapoints (V, I) = (-3, -0.01) and (V, I) = (-3.5, -0.025), the AC resistance can be calculated as such:

$$r_d = \frac{1}{\frac{dI}{dV}} = \frac{dV}{dI} = \frac{-3 + 3.5}{-0.01 + 0.025} = 33.33\Omega$$

D. Part 4: Rectifiers

In part 4 of the lab, a half-wave rectifier circuit was built as shown in the circuit diagram below using a 1N4005 power rectifier diode and a 100kΩ load. A 60Hz sine wave with an amplitude of 5V (peak-to-peak voltage of 10V with 0V offset) was generated using a function generator.

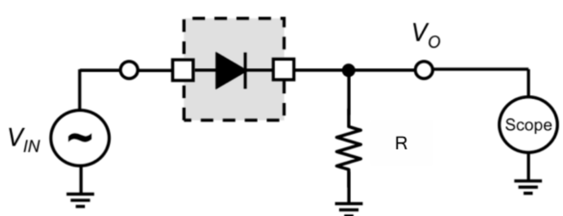

Figure 4.1: Half-wave rectifier circuit

The output voltage response across the load resistor was read using an oscilloscope as shown below. Note that CH0 captures V_o and CH1 captures V_{in}.

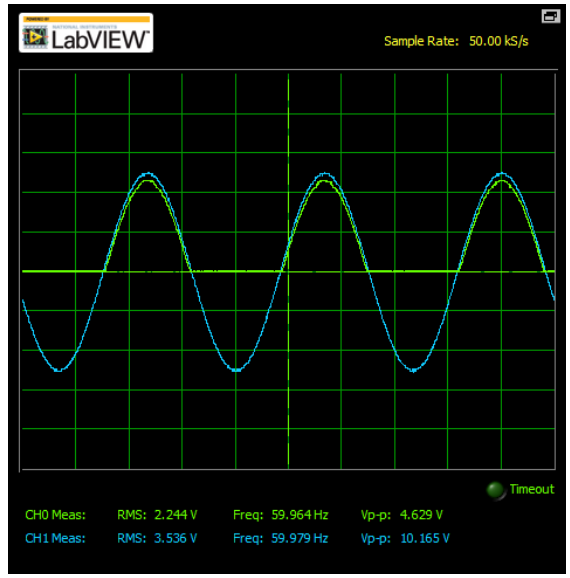

Figure 4.2: Half-wave rectifier circuit output response

Notice that the peak-to-peak voltage of V_o, captured by CH0 is 4.629V and the peak-to-peak voltage of V_{in}, captured by CH1 is 10.165V. $\frac{V_{in}}{V_o} = \frac{10.165V}{4.629V} = 2.2 \approx 2$, and thus V_o approximately got halved from V_{in}. It seems like this was achieved by the rectifier circuit successfully converting alternating current (AC) into direct current (DC), where the negative part of the AC waveform got blocked off.

Then, the half-wave rectifier circuit was modified by adding a capacitor in parallel to the load resistor. Then the same sane wave input signal of 60Hz was maintained.

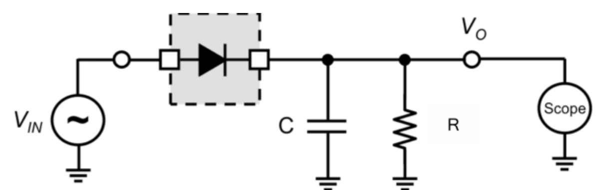

Figure 4.3: Half-wave rectifier circuit with peak-detector

The following two graphs show the output responses of an oscilloscope when C=1µF, and when C=100µF. Again, CH0 captures V_o and CH1 captures V_{in}.

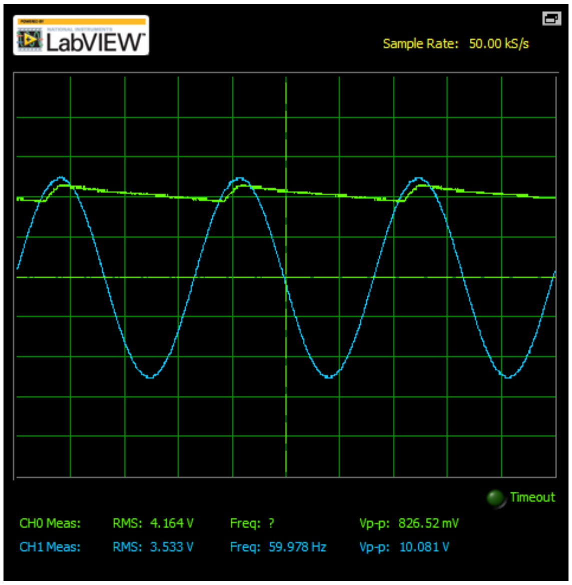

Figure 4.4: Half-wave rectifier circuit response output with 1μF capacitor

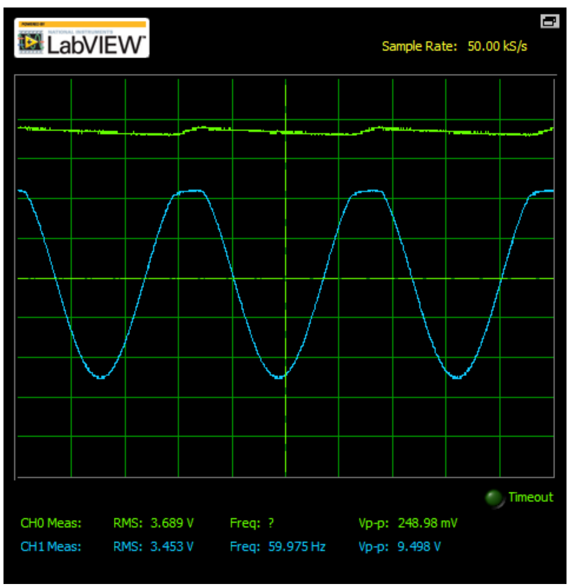

Figure 4.5: Half-wave rectifier circuit response output with 100μF capacitor

The ripple observed is the small oscillation in the output signal due to the discharge of the capacitor between peaks. When using a 1 μF capacitor, the output exhibited a significant ripple of 826.52mV due to the faster discharge rate of the smaller capacitor. In contrast, increasing the capacitance to 100 μF resulted in improved smoothing, with a lower ripple amplitude of 248.98mV, as the larger capacitor discharged more slowly. The frequency of the ripple in both cases remained consistent at approximately 60 Hz, matching the input frequency as the negative part of the input AC signal is simply blocked off, making the output signal a DC-like signal. The ripple voltage amplitude decreased with the increase in capacitance, confirming that a larger capacitor reduces ripple by maintaining a higher average voltage between cycles. This behavior aligns with the theoretical equation for ripple voltage in a half-wave rectifier, shown as the following:

$$V_r = \frac{I}{f \times C}$$

where V_r represents the ripple voltage, C represents the capacitance and f represents the frequency. This equation and the experimental results illustrate how adjusting capacitance can effectively control ripple in a rectified output.

E. *Part 5: Voltage Regulation Using Zener Diode*

In this part of the lab, two different ways of reducing a DC level from a fixed DC supply was compared. First, the rectifier circuit from the previous section of the lab was slightly modified as seen below to achieve a voltage divider circuit. In order to obtain a V_o of 2.5V, the circuit had to be analyzed. Assuming a voltage drop of 0.7V across the 1N4005 diode and a sine wave V_{in} of 5V at 60Hz, we can deduce that $V_x = 5 - 0.7 = 4.3V$.

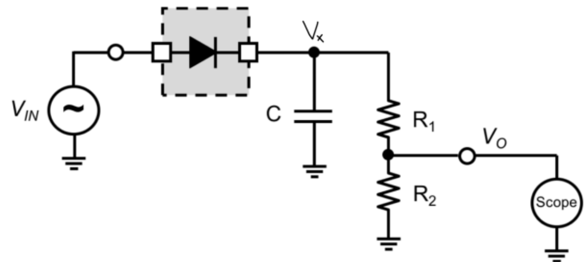

Figure 5.1: Voltage regulation circuit using resistor divider (a)

The following system of equations was solved to obtain the R_1 and R_2 values necessary for a V_o of 2.5V.

$$\begin{cases} R_1 + R_2 = 100k\Omega \\ V_o = V_x \times \dfrac{R_2}{R_1 + R_2} \end{cases}$$

where V_o = 2.5V and V_x = 4.3V. Then, R_1 was found to be approximately 40kΩ and R_2 was found to be approximately 60kΩ. With the calculated resistor values, the output response of the circuit was observed using an oscilloscope.

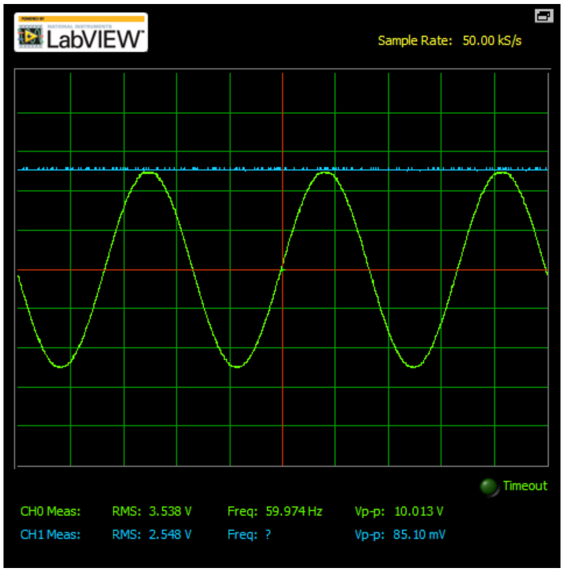

Figure 5.2: Voltage regulation circuit using voltage divider output response

Notice that V_o, represented by CH1, is indeed 2.548V (see RMS, i.e. average value), which is approximately 2.5V. This therefore confirms that our calculated resistor values are correct. The ripple of the output voltage, which corresponds to the peak-to-peak voltage on the oscilloscope, is 85.10mV. The ripple obtained from the voltage divider circuit is therefore much smaller compared to the amount of ripple present in our previous measurement of the rectifier of part IV.

Then, the resistor divider was replaced with the 3.3V 1N5226B diode, as shown in the circuit diagram below.

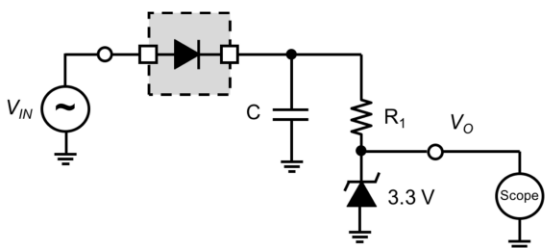

Figure 5.3 Voltage regulation using Zener diode (b)

The output voltage across the Zener diode was observed using the oscilloscope. Again, the output voltage was captured by CH1.

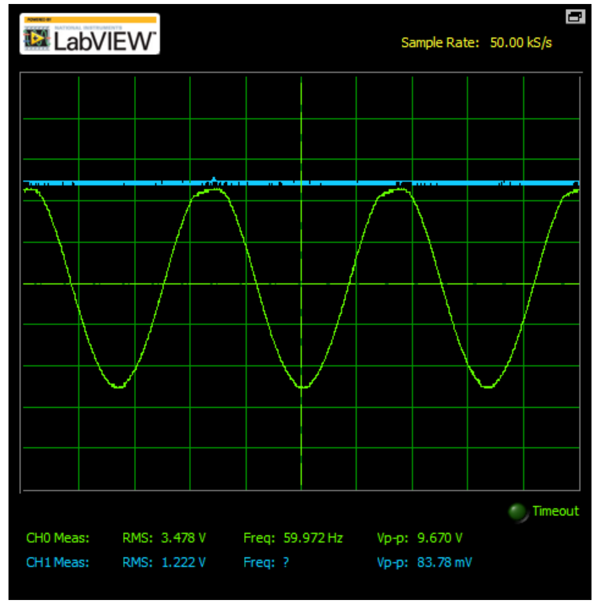

Figure 5.4: Voltage regulation circuit using 3.3V 1N5226B Zener diode output response

The average value of V_o is observed to be 1.222V (see RMS), and the ripple is 83.78mV. The ripple had a slight decrease from the previous resistor divider circuit, which aligns with the theoretical expectation. However, one issue is that with circuit (a), the ripple was 85.10mV, which is almost the same as the ripple in circuit (b).

Theoretically, the ripple in circuit (b) should be smaller due to the presence of the 3.3V Zener diode, which acts as a voltage regulator. The Zener diode is designed to maintain a stable output by clamping the voltage across V_o at approximately 3.3V whenever the input voltage exceeds this threshold. During the charging phase, when the input voltage goes above 3.3V, the Zener diode conducts, keeping the output at a constant level. When the input voltage drops below this threshold, the capacitor C supplies current to the load, helping to maintain the voltage across V_o and reducing fluctuations. This action should ideally reduce the ripple voltage at V_o by clamping the peaks and relying on the capacitor during dips, thus smoothing the output more effectively than the resistor divider circuit in (a), where no such regulation is present.

In practice, the small difference in ripple between the two circuits may result from limitations in the Zener diode's regulation ability or insufficient capacitor value to fully stabilize the output. Additional factors such as component tolerances, diode response time, and load fluctuations can also impact the ripple, leading to results that do not entirely match theoretical predictions.

F. Part 6: Limiter Circuit Using Diodes

A 1.5V battery cell was placed in series with the 1N4148 signal diode in a curve tracer circuit as shown in the circuit diagram below. The input voltage signal was set to be in a sawtooth waveform with a peak-to-peak amplitude of 5V with an offset of 0.5V so that it varies between 2V and -3V.

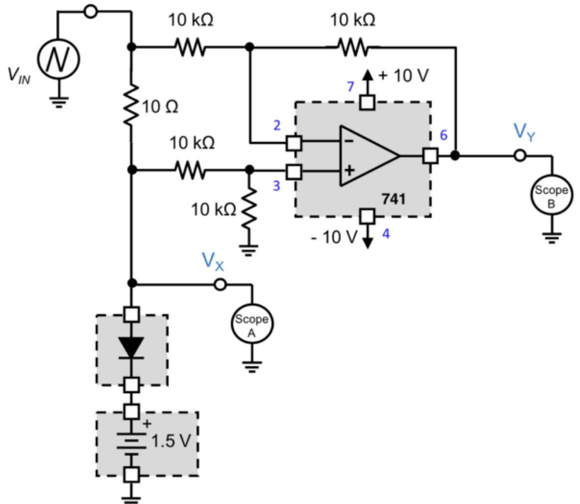

Figure 6.1: Limiter circuit diagram with 1.5V battery cell

An oscilloscope was used to capture the behaviour of V_X and V_Y as shown in the figure below. CH0 represents scope A and CH1 represents scope B.

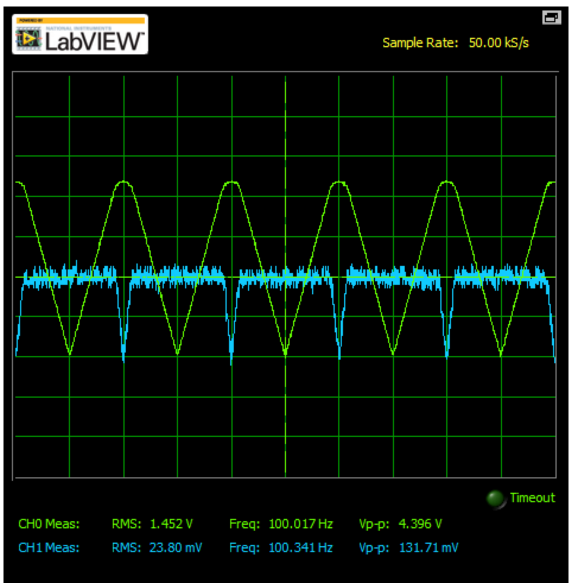

Figure 6.2: Limiter Circuit Output Response with 1.5V battery cell

Using data collected from the oscilloscope, it was possible to obtain the i-v plot using MATLAB, as shown in the figure below.

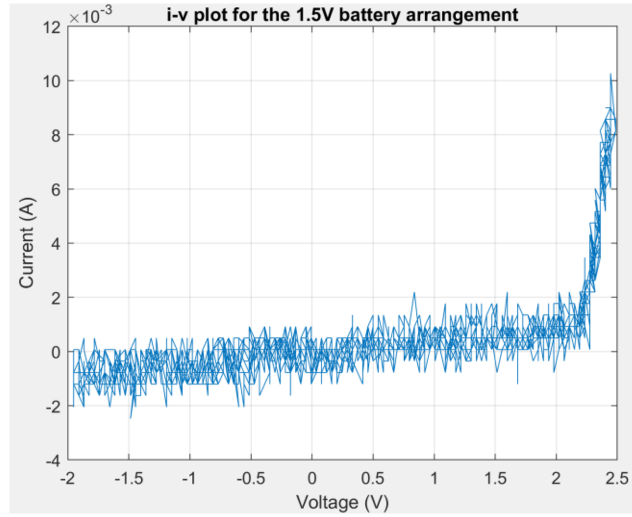

Figure 6.3: i-v plot for limiter circuit with 1.5V battery cell using MATLAB with data obtained from the oscilloscope

It is safe to assume that the diode-battery arrangement turns on at approximately 2.2V, because that is when we see the current appear in the i-v plot above.

Next, the circuit was modified to have two parallel 1N4148 signal diodes in reverse directions, instead of having one diode with a 1.5V battery cell. The new circuit diagram is found in the image below.

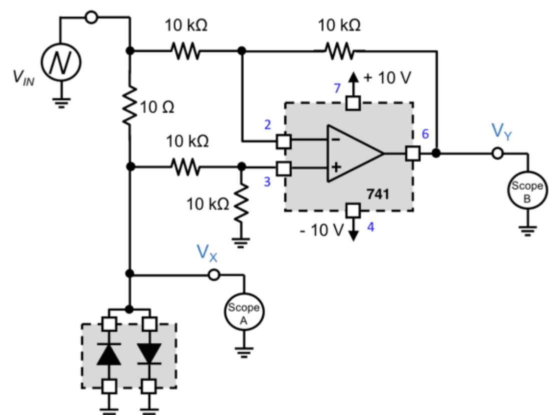

Figure 6.4: Limiter circuit diagram with two 1N4148 signal diodes in reverse directions

The input voltage signal was set to be in a sawtooth waveform with a peak-to-peak amplitude of 4V with an offset of 0V so that it varies between 2V and -2V. As shown in the figure below, an oscilloscope was used to capture V_X and V_Y, where CH0 represents V_X and CH1 represents V_Y.

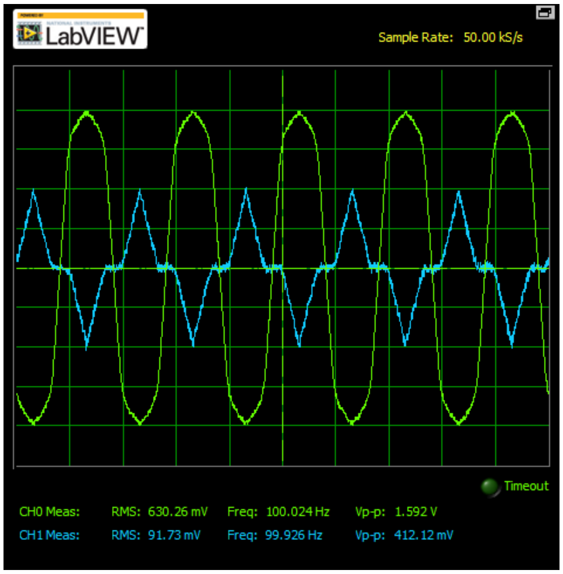

Figure 6.5: Limiter Circuit Output Response with 2 1N4148 signal diodes in reverse directions

Note that the waveform of CH1, representing V_Y, is visibly clipped at both the positive and negative ends. This is due to the two 1N4148 diodes arranged back-to-back. As the voltage exceeds the forward threshold (around ±0.7V), the diodes begin conducting and limit the signal, as shown in CH1. Using data collected from the oscilloscope, it was possible to obtain the i-v plot using MATLAB, as shown in the figure below.

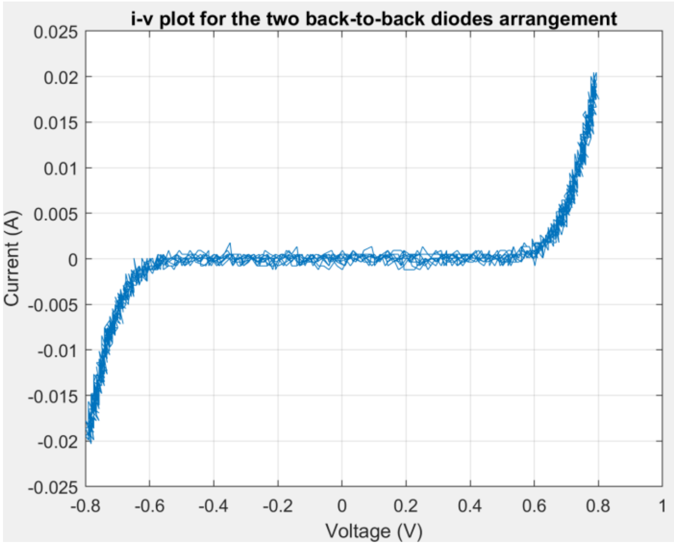

Figure 6.6: i-v plot for two 1N4148 diodes in reverse directions using MATLAB with data obtained from the oscilloscope

This type of circuit is used to prevent signals from exceeding certain voltage limits, as we can tell by the name of the circuit (limiter circuit). It could be used in signal processing where the protection of sensitive components from over-voltage is required. The diodes will begin conducting when the input voltage exceeds their forward of reverse threshold, effectively clamping the output signal to a safe range.

This circuit is generally more effective for large signals because the diodes only start conducting once the voltage exceeds the forward threshold (around 0.7V in this case). Smaller signals below the diode threshold voltage, will pass through unaffected, while larger signals will be clipped, limiting the output to a specific range.

III. Conclusion

In this lab, various op-amp and diode circuits were constructed and analyzed to observe their behaviors in practical scenarios. It was demonstrated that op-amps, unlike ideal models, exhibit offset voltage and allow small currents to flow into their inputs. This experiment confirmed that real op-amps have biased input currents and offset voltages.

Additionally, the lab provided practical insights into the characteristics and applications of various diodes, including signal, rectifier, and Zener diodes. Through these experiments, the versatility of diodes in rectification, voltage regulation, and signal limitation was observed. Furthermore, the lab highlighted how the gain of amplifiers depends on frequency, with noticeable distortion occurring at higher input frequencies. This observation underscores the limitations of op-amps in high-frequency applications, where output stability may be compromised.