Laboratory Experiment #2: Diode Characteristics and Circuits

Names:
Electric Circuits Laboratory I
The College of New Jersey
Department of Electrical and Computer Engineering (ECE)

Note that deliverables are highlighted in "yellow" and should be included in students' lab reports. "Green" boxes are used to block out certain parts of solutions. Students should use this document as a guide for their lab reports. However, they are expected to produce a separate document well thought-out introduction and conclusion as well as appropriate text linking schematics, photos, tables, graphs, and calculations. Students should discuss what steps they took between deliverables.

Do not try to recreate circuits from the pictures included in this lab. Use the schematics to generate a unique board layout.

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A. Introduction

- **Objective(s):** The students should identify the objective of this experiment, in their own words. If one objective does not exist, define a small set of objectives.
- **Why is this Important:** The students should describe why this experiment is important. Remember, that "because the teacher is making me for a grade" is not an acceptable answer. Perhaps the assignment will prepare students for future work in this or other courses.
- **Theory and Background:** The students should provide the reader with any background information relevant to understanding their report. Are there any schematics or equations that are relevant? Where are they?

B. Objectives

- Characterize the behavior of the Zener Diode.
- Design, construct, and test a dc power supply composed of voltage rectifier, low-pass filter, and voltage regulator.
- Examine the response of this supply to changes in load.

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C. Background and Theory

Diodes

In electronics, a diode is a type of two-terminal electronic component with a nonlinear current–voltage characteristic. A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material connected to two electrical terminals. A vacuum tube diode (now rarely used except in some high-power technologies) is a vacuum tube with two electrodes: a plate and a cathode. The most common function of a diode is to allow an electric current to pass in one direction (called the diode's forward direction), while blocking current in the opposite direction (the reverse direction). Thus, the diode can be thought of as an electronic version of a check valve. This unidirectional behavior is called rectification, and is used to convert alternating current to direct current, and to extract modulation from radio signals in radio receivers.

However, diodes can have more complicated behavior than this simple on–off action. Semiconductor diodes do not begin conducting electricity until a certain threshold voltage is present in the forward direction (a state in which the diode is said to be forward biased). The voltage drop across a forward biased diode varies only a little with the current, and is a function of temperature; this effect can be used as a temperature sensor or voltage reference.

Semiconductor diodes have nonlinear electrical characteristics, which can be tailored by varying the construction of their P–N junction. These are exploited in special purpose diodes that perform many different functions. For example, diodes are used to regulate voltage (Zener diodes), to protect circuits from high voltage surges (Avalanche diodes), to electronically tune radio and TV receivers (varactor diodes), to generate radio frequency oscillations (tunnel diodes, Gunn diodes, IMPATT diodes), and to produce light (light emitting diodes). Tunnel diodes exhibit negative resistance, which makes them useful in some types of circuits.

Figure 1: Ideal Diode Schematic and Current / Voltage Characteristics

Rectifier

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC) which flows in only one direction. The process is known as rectification. Physically, rectifiers take a number of forms, including vacuum tube diodes, mercury arc valves, solid state diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches. Historically, even synchronous electromechanical switches and motors have been used. Early radio receivers, called crystal radios, used a "cat's whisker" of fine wire pressing on a crystal of galena (lead sulfide) to serve as a point-contact rectifier or "crystal detector".

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Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. As noted, detectors of radio signals serve as rectifiers. In gas heating systems flame rectification is used to detect presence of flame.

The simple process of rectification produces a type of DC characterized by pulsating voltages and currents (although still unidirectional). Depending upon the type of end-use, this type of DC current may then be further modified into the type of relatively constant voltage DC characteristically produced by such sources as batteries and solar cells. A device which performs the opposite function (converting DC to AC) is known as an inverter.

Figure 2: Full-Wave Diode Rectifier

Low-Pass Filter

A low-pass filter is a filter that passes low-frequency signals but attenuates (reduces the amplitude of) signals with frequencies higher than the cutoff frequency. The actual amount of attenuation for each frequency varies from filter to filter. It is sometimes called a high-cut filter, or treble cut filter when used in audio applications. A low-pass filter is the opposite of a high-pass filter. A band-pass filter is a combination of a low-pass and a high-pass.

Low-pass filters exist in many different forms, including electronic circuits (such as a hiss filter used in audio), anti-aliasing filters for conditioning signals prior to analog-to-digital conversion, digital filters for smoothing sets of data, acoustic barriers, blurring of images, and so on. The moving average operation used in fields such as finance is a particular kind of low-pass filter, and can be analyzed with the same signal processing techniques as are used for other low-pass filters. Low-pass filters provide a smoother form of a signal, removing the short-term fluctuations, and leaving the longer-term trend.

Figure 3: First-Order Low-Pass Filter

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Voltage Regulator

A voltage regulator is an electrical regulator designed to automatically maintain a constant voltage level. A voltage regulator may be a simple "feed-forward" design or may include negative feedback control loops. It may use an electromechanical mechanism, or electronic components. Depending on the design, it may be used to regulate one or more AC or DC voltages.

Electronic voltage regulators are found in devices such as computer power supplies where they stabilize the DC voltages used by the processor and other elements. In automobile alternators and central power station generator plants, voltage regulators control the output of the plant. In an electric power distribution system, voltage regulators may be installed at a substation or along distribution lines so that all customers receive steady voltage independent of how much power is drawn from the line.

Figure 4: Zener Diode Voltage Regulator

D. Materials

- 1N4733 Zener Diode
- Various Resistors and Capacitors
- Basic Laboratory Equipment (e.g. DMM)

E. Procedure and Analysis

Part #1: Diode Characterization

Step #1: Acquire 1N4733 Zener Diode from the stock room. Download this device's datasheet with the table partially shown below. Note the information provided in Figure 5.

Electrical Characteristics @ T_A = 25°C unless otherwise specified

Type Number	Nominal Zener Voltage (Note 2)	Test Current	Maximum Zener Impedance (Note 3)			Maximum Reverse Leakage Current		Max Surge Current 8.3ms	Temperature Coefficient @ I_{ZT}
	V_Z @ I_{ZT}	I_{ZT}	Z_{ZT} @ I_{ZT}	Z_{ZK} @ I_{ZK}	I_{ZK}	I_R	@ V_R	I_{ZS}	
	(V)	(mA)	(Ω)	(Ω)	(mA)	(μA)	(V)	(mA)	%/°C
1N4728A	3.3	76	10	400	1.0	100	1.0	1380	-0.08 to -0.05
1N4729A	3.6	69	10	400	1.0	100	1.0	1260	-0.08 to -0.05
1N4730A	3.9	64	9.0	400	1.0	50	1.0	1190	-0.07 to -0.02
1N4731A	4.3	58	9.0	400	1.0	10	1.0	1070	-0.07 to -0.01
1N4732A	4.7	53	8.0	500	1.0	10	1.0	970	-0.03 to +0.04
1N4733A	5.1	49	7.0	550	1.0	10	1.0	890	-0.01 to +0.04
1N4734A	5.6	45	5.0	600	1.0	10	2.0	810	0 to +0.045
1N4735A	6.2	41	2.0	700	1.0	10	3.0	730	+0.01 to +0.055
1N4736A	6.8	37	3.5	700	1.0	10	4.0	660	+0.015 to +0.06
1N4737A	7.5	34	4.0	700	0.5	10	5.0	605	+0.02 to +0.065
1N4738A	8.2	31	4.5	700	0.5	10	6.0	550	0.03 to 0.07
1N4739A	9.1	28	5.0	700	0.5	10	7.0	500	0.035 to 0.075
1N4740A	10	25	7.0	700	0.25	10	7.6	454	0.04 to 0.08
1N4741A	11	23	8.0	700	0.25	5.0	8.4	414	0.045 to 0.08
1N4742A	12	21	9.0	700	0.25	5.0	9.1	380	0.045 to 0.085

Figure 5: 1N4733 Zener Diode (with Anode and Cathode Highlighted) and Data Sheet

Step #2: Measure the resistance of the diode in both forward and reverse directions using the digital multi-meter (DMM).

Note that the DMM must be properly configured to perform resistance measurements. The red lead must be connected to red terminal in upper-right corner of the DMM. The black lead must be connected to the black terminal directly below it. Refer to Figure 6. Also note that the diode is forward-biased when the black end of the diode with a shorter lead (cathode) is connected to black lead of DMM. The longer lead (anode) will be connected to the red lead of the DMM.

Figure 6: Configure DMM to Perform Resistance Measurement for Forward-Biased 1N4733 Diode

Step #3: Complete table below.

Table 1: Diode Resistance vs. Current Direction

direction	**resistance** (ohms)
forward-bias	
reverse-bias	

Step #4: Measure the current conducted by diode while both forward and reverse biased using the digital multi-meter (DMM). The schematic shown in Figure 7 demonstrates how this may be done.

Figure 7: Test Circuit Required to Measure Current Flow Through 1N4733 Diode (Left is Schematic, Right is Practical)

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Note that the DMM must be configured "differently" to perform current measurements, as compared to voltage: 1) leads must be connected to terminals in lower-right corner of the DMM, 2) the user must hit Shift + DC I to activate appropriate mode, and 3) leads must be placed "in series" with circuit components (not parallel). Refer to Figure 8.

Note that if the DMM does not take current measurements properly, a fuse in back of the unit may be "blown."

Figure 8: Configure DMM to Perform Current Measurements

Note that pictures of this setup are shown below.

Figure 9: Lab Setup for Step #4

Step #5: Complete table below.

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Table 2: Voltage-Current Characteristic for 1N4733 Diode

Bias	V_{diode} (V)	I_{diode} (A)
Reverse	-5.750	
Reverse	-5.500	
Reverse	-5.250	
Reverse	-5.000	
Reverse	-4.500	
Reverse	-4.000	
Reverse	-3.000	
Reverse	-2.000	
Reverse	-1.000	
Forward	0.000	
Forward	0.250	
Forward	0.500	
Forward	0.750	
Forward	1.000	
Forward	1.250	
Forward	1.500	

Note that the behavior of this diode, excluding breakdown region where $v_D < -5.5V$, may be described by the equation below.

$$i_D = 0.00001\,\mathbf{exp}\left(\frac{v_D}{V_T}\right) in\ uA \qquad (1)$$

Step #6: Calculate the value of V_T such that (1) describes the data presented in Table 2. Show work.

Step #7: Graph the results from Table 2 along with the trendline defined above. An example is shown in Figure 10.

Note the format and title used for the graph below. It is important to include appropriate axis labels with units, legend, and title. One good title format is "Dependent Variables vs. Independent Variables for Circuit X with Components Y1, Y2, Y3 and Parameters Z1, Z2, Z3".

Figure 10: Current Through Diode (iD) vs. Voltage Across Diode (vD) for 1N4733 Zener Diode with Zener Voltage of 5.5V, Trendline is Included (Dotted-Blue Line)

Step #8: What is the "nominal" forward-bias voltage across the 1N4733 diode? In other words, at what positive voltage does the graph above present a vertical asymptote?

Step #9: What is the Zener Voltage associated with the 1N4733 diode? What does this value mean?

A Look Ahead… In this next section of the lab, students will design a $2.8Vdc$ power supply. This circuit will accept a sine-wave input with amplitude of $5V$ and frequency of $60Hz$. The objective is to supply a $50k\Omega$ resistor with less than 10% ripple in dc supply voltage. Refer to Figure 11 and Figure 12.

Figure 11: Sample dc Power Supply Composed of Full-Wave Diode Rectifier, Low-Pass Filter, Diode-Based Voltage Regulator, and Load

Figure 12: Desired Input and Output Voltage vs. Time for DC Power Supply

Part #2: Diode Voltage Rectifier

Step #10: Design a full-wave diode rectifier in PSpice using 1N4149 Zener Diode. An example is provided below.

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Figure 13: Full-Bridge Diode Rectifier in PSpice Using 1N4149 Zener Diode

Note that the load is "floating" and, as such, one will need a differential voltage probe to observe its potential. A single ended voltage probe may be used for the input. Use VSIN (not VAC) for v_{GS} source.

Step #11a: In the lab report, include a screenshot of this PSpice schematic.

Step #11b: Open a new simulation profile using the button in the top-left corner of screen. Provide an appropriate simulation name.

Figure 14: Open and Name the New Simulation Profile

Step #12a: Simulate the transient response of this circuit to 0.05s (approximately 3 cycles). Use a maximum step-size of 0.1*ms*.

Figure 15: Transient Response Profile

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Step #12b: Copy this data to Microsoft Excel. This is done by: 1) clicking the name of the desired trace in the bottom-left corner of simulation result screen, 2) hitting Control+C, then 3) using Control+V to paste in Excel.

Figure 16: Use Control+C and Control+V to Copy Simulation Data from PSpice to Microsoft Excel

Step #13: In the lab report, include a graph (like that shown in Figure 17) that compares the simulated input and output of this full-wave diode rectifier. Please graph all simulation data in Microsoft Excel.

Figure 17: Simulated Input and Output Voltages vs. Time for Full-Wave Diode Rectifier Utilizing 1N4149 Diode

Step #14: Build the circuit shown in Figure 13 using 1N4733 Zener Diodes, $1k\Omega$ load resistor, and waveform generator. Refer to Figure 18 and Figure 19.

Figure 18: Schematic for Hardware Implementation of Full-Wave Diode Rectifier with Differential Measurement

Figure 19: Full-Wave Diode Rectifier in Hardware

Note waveform generator setup presented below. Remember to hit "Output" button to activate the output.

Figure 20: Configure Waveform Generator to Supply Input Voltage

Note that the oscilloscope probes are grounded and, therefore, cannot be used to take differential measurements as in PSpice. One must use channels #1 and #2 of the oscilloscope to measure voltage potential at both ends of the load. The oscilloscope has a "MATH" function that allows users to subtract the channel #2 waveform from channel #1. This is illustrated below.

Figure 21: Configure Oscilloscope to Take Differential Measurements

Step #15: In the lab report, include a picture of this hardware.

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Step #16: Supply the circuit an appropriate input $v_S = 5\mathbf{sin}(2\pi 60t)$. Measure both the input and output waveforms using the oscilloscope. Use the Agilent IntuiLink Data Capture Application to copy and paste these waveforms into the lab report. An example is provided below.

Remember to include measurements for 1) amplitude, 2) RMS magnitude, and 3) frequency of the input and output waveforms.

Figure 22: Input (Left) and Output (right) Voltage vs. Time for Full-Wave Diode Rectifier Shown in Figure 19 with Δt of 5.0ms/division and ΔV of 2.0V/division

Note that, if one cannot locate the Data Capture Application, a shortcut to the software may be placed on desktop using the procedure shown in Figure 23. The application is located C://Program Files/Agilent/Intuilink/Data Capture.

Figure 23: How To Bring "Agilent IntuiLink Data Capture Program" to Desktop

Part #3: Low-Pass Filter

Step #17: Design an RC low-pass filter with corner frequency of $60Hz$ using (3) where $R = 1k\Omega$. In the lab report, include a schematic for this circuit. Show calculation of C.

$$f_0 = \frac{1}{2\pi RC} \; in\ Hz = \qquad (3)$$

Step #18a: Implement this circuit in PSpice. The $1k\Omega$ load resistor shown in Figure 13 should be removed. It will be replaced with the low-pass filter described above.

Figure 24: Full-Bridge Diode Rectifier in Series with f0 = 6000Hz Low-Pass Filter

Step #18b: In the lab report, include a screenshot of this PSpice schematic.

Step #19: Simulate the transient response of this circuit to 0.5s (approximately 30 cycles). Use a maximum step-size of 0.1ms. In the lab report, include a graph (like that shown in Figure 25) that compares the simulated input and output of this full-wave diode rectifier. Please graph all simulation data in Microsoft Excel.

Figure 25: Series Low-Pass Filter and Full-Wave Diode Rectifier Input and Output Waveforms vs. Time with 1N4733 Zener Diode, RF = 1000Ohms, and CF =

Step #20: Explain what is happening during the first $200ms$ of this simulation.

Step #21: Build the circuit shown in Figure 24. Refer to Figure 18 and Figure 19.

Figure 26: Schematic for Hardware Implementation of Low-Pass Filter in Series with Full-Wave Diode Rectifier with Differential Measurement

Figure 27: Series Connection of Full-Wave Diode Rectifier and Low-Pass Filter in Hardware

Step #22: In the lab report, include a picture of this hardware.

Step #23: Supply the circuit an appropriate input $v_S = 5\mathbf{sin}(2\pi 60t)$. Measure both the input and output waveforms using the oscilloscope. Use the Agilent IntuiLink Data Capture Application to copy and paste these waveforms into the lab report. An example is shown below.

Remember to include oscilloscope measurements for 1) average and 2) amplitude of the output voltage. This allows quantification of voltage ripple.

Figure 28: Output Voltage vs. Time for Low-Pass Filter in Series with Full-Wave Diode Rectifier as shown in Figure 24 with 1N4733 Zener Diode, RF = 1kOhm, CF = [redacted] Δt of 5.0ms/division and ΔV of 2.0V/division

Step #24: What is the average output voltage of this circuit in hardware? How does it compare to the desired value of 2.8V?

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Part #4: Diode Voltage Regulator

Step #25: Design a voltage regulator to regulate output at 2.8V. How many diodes (in series) are required? Remember that each diode exhibits a forward-bias voltage of approximately $0.7V$. In the lab report, include this drawing (hand-drawn is ok).

Step #26: Implement this circuit in PSpice. The diodes should be placed in parallel with the low-pass filter previously implemented. In the lab report, include a screenshot of this PSpice schematic.

Step #27: Simulate the transient response of this circuit to 0.5s (approximately 30 cycles). Use a maximum step-size of 0.1ms. In the lab report, include a graph that compares diode voltage regulator output to input. Please graph all simulation data in Microsoft Excel.

Step #28: Complete the DC power supply by placing diode-based voltage regulator at output of the low-pass filter (aka. in parallel with the capacitor). Refer to Figure 29and Figure 30.

Figure 29: Schematic for Hardware Implementation of dc Power Supply with Differential Measurement

Figure 30: DC Power Supply in Hardware

Step #29: In the lab report, include a picture of this hardware.

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Step #30: Supply the circuit an appropriate input $v_S = 5\mathbf{sin}(2\pi 60t)$. Measure both the input and output waveforms using the oscilloscope. Use the Agilent IntuiLink Data Capture Application include these waveforms in the lab report. An example is shown below.

Remember to include oscilloscope measurements for 1) average and 2) amplitude of the output voltage. This allows quantification of voltage ripple.

Figure 31: Output Voltage vs. Time for DC Power Supply Composed of Full-Wave Diode Rectifier, Low-Pass Filter, and Diode-Based Voltage Regulator with 1N4733 Zener Diode, RFilter = 1kOhm, CF = [redacted] Δt of 5.0ms/division and ΔV of 2.0V/division

Step #31: How does the average output of the DC power supply in PSpice compare to hardware?

Part #5: Load Testing

Step #32: Place a $50k\Omega$ load resistor in parallel with the multi-diode voltage regulator (across V_{Out}). Copy and paste the resulting output waveform into the lab report with oscilloscope measurements for: 1) average and 2) amplitude. Repeat this process for $R_L = 10k\Omega$, $5k\Omega$, and $1k\Omega$. An example is shown below.

Figure 32: Voltage Ripple for 50k, 10k, 5k, 1k Load Resistors (with values of 168mV, 438mV, 563mV, and 1.0V respectively)

Step #33: What is the effect of R_L on average DC output as well as its ripple? What is its effect on % voltage regulation? Why? Use the equations below to solve.

$$V_{ripple} = |\mathbf{max}(V_L) - \mathbf{min}(V_L)| \; in\ V \tag{4}$$

$$voltage\ regulation = \frac{V_{ripple}}{\underbrace{V_L^{nom}}_{2.8V}} \; in\ \% \tag{5}$$

Step #34: Would this design operate correctly for AC input with amplitude of $50V$? Why or why not?

Step #35: Have instructor verify that dc power supply works properly. Make sure this is complete before end of lab sessions; it is an important part of the grade.

F. Conclusion

- **Background and Research:** The students should describe areas that they studied in order to complete the lab report. In this paragraph, they should refer heavily to specific schematics and theoretical equations in the body of the report by equation and figure number.
  - In the students' eyes, what were the objective(s) of the laboratory experiment?
- **Hypothesis:** If one exists, clearly state the hypothesis of your experiment.
- **Procedure:** The students should discuss the steps they took to complete the lab. In this paragraph, they should refer heavily to specific schematics and test setup photos in the body of the report by figure number.

- What problems did students encounter? Examples include equipment failure or problems with the lab document.
- What suggestions do students have? Examples include changes to the test setup or utilization of more advanced analysis techniques.
- What step in the lab did the student find most interesting?

- **Analysis and Results:** The students should discuss the quality of their results as well as conclusions to be drawn from them. In this paragraph, they should refer heavily to specific tables and graphs in the body of the report by figure number.
  - Did the lab generate viable results? Can the experimenter distinguish trends from noise and other random forces? Why?
  - Does observed data match the expected (generating via theoretical calculation or simulation)? If not, what potential sources of error exist? For example, does the experiment require components with lesser parameter tolerances.
  - What is the student's most interesting observation from the data? Why?
- **Closing Ideas:** The students should tie together ideas from the different sections described above. They should address higher-level concepts directly related to the lab's hypothesis (if applicable) as well as its effect on their education and understanding of electrical engineering.
  - What lessons do students take away from this experiment?
  - How will this experiment help students excel in the lecture of this as well as future classes?
  - What are the students' most positive and negative comments regarding this experiment?