Electronic Instrumentation

ENGR-4300 Fall 2004 Section ____

Experiment 6
Introduction to Diodes, Voltage Limitation and Regulation

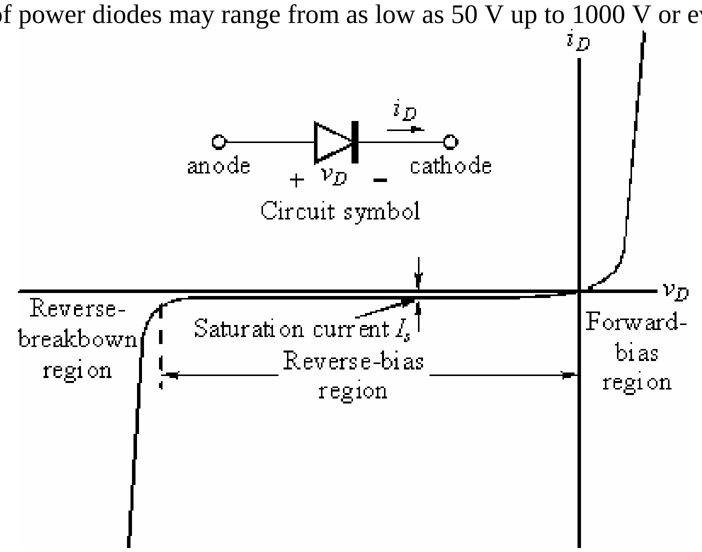
Purpose: This objective of this experiment is to become familiar with the properties and uses of diodes. We will first consider the I-V characteristic of a standard diode that we can use in the classroom. We will also see how the diode can work as a rectifier, which is an essential part of most DC sources that are driven by AC voltages. A serious problem with simple rectifiers is that the DC voltage they produce is dependent on the load. A common way to make the rectifier less sensitive to the load is to add some regulation. This we can do by utilizing the avalanching effect that occurs if we reverse voltage the diode too much. We will also see what kind of voltage limitation can be achieved with a forward biased diode. Such limitation of voltages is usually applied to protect circuit components.

Equipment Required:

- HP 34401A Digital Multimeter
- HP 33120A 15 MHz Function / Arbitrary Waveform Generator
- HP 54603B Oscilloscope
- HP E3631A Triple Output DC Power Supply
- Protoboard
- Resistors, Capacitors, Diodes, Zener Diodes
- HP Benchlink and OrCAD Capture and PSpice

Background: We should first review some of the basic properties of diodes before proceeding. Please read pages 150- 158 in Essence of Analog Electronics. Pages 166-190 show practical applications of the diode that we will be using in class. The particular diode we will be using in this experiment is the 1N4148. Please look at the information on this device at the bottom of the course webpage.

The figure below shows typical characteristics of a diode. Ideally, a diode is a device that allows current to flow in one direction only. In practice, diodes allow large amounts of forward current to flow when the positive voltage across them reaches a small threshold. They also have a small "saturation" current and a "breakdown" region in which a large amount of current will flow in the opposite direction when a large negative voltage is applied. In small signal diodes, the forward current will typically be up to a few tens of mA at a forward voltage of about 1 V. The reverse-breakdown voltage might be about 100 V, and the saturation current I_s may be of the order of 1 nA. Power diodes may allow forward currents up to many amps at forward voltage drops of 0.6 to 1.5 V or so, depending on the type of diode. The reverse-breakdown voltage of power diodes may range from as low as 50 V up to 1000 V or even much more.

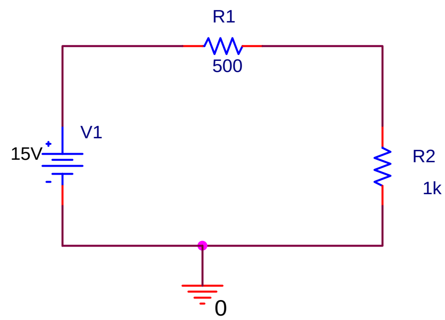


The Diode Equation gives a reasonably good representation of the V-I characteristics of a junction diode. I_s is the saturation current, usually measured in micro, or nano amps. V_T is the Thermal Voltage [K in your book] where $V_T = kT/q = 0.0259$ V at 300 K and n is a somewhat arbitrary parameter which depends on construction and usually lies between 1 and 2. Note that this equation characterizes the basic features of the diode I-V curve, but leaves out some details like reverse breakdown, junction capacitance, etc.

$$i_D = I_s\left(\exp\left(\frac{v_D}{nV_T}\right) - 1\right)$$

Part A I-V Characteristics

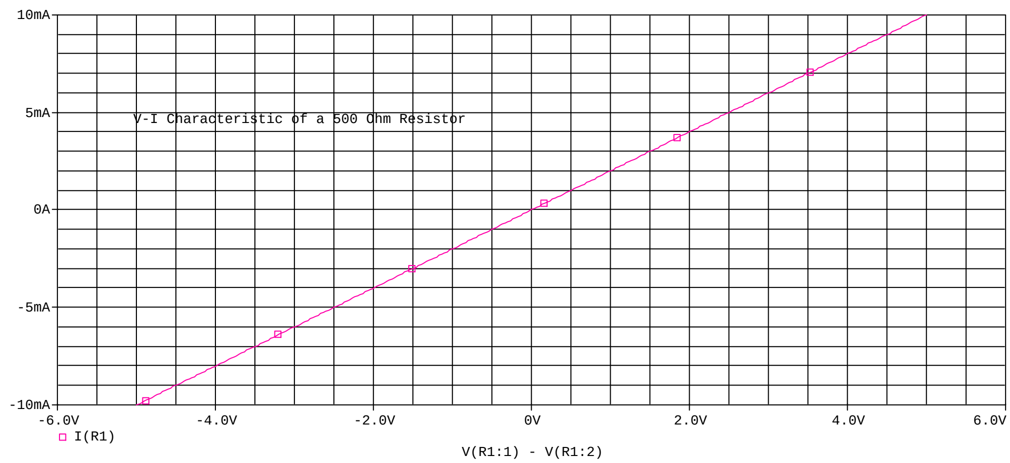
If one plots the current through a resistor, R, vs the voltage across the resistor, we will observe a straight line whose slope is equal to R^{-1}. This is in contrast to the I-V characteristic of a diode. To see the properties of each, we will simulate two circuits with PSpice. The first consists of a DC voltage source and two resistors, as shown below.



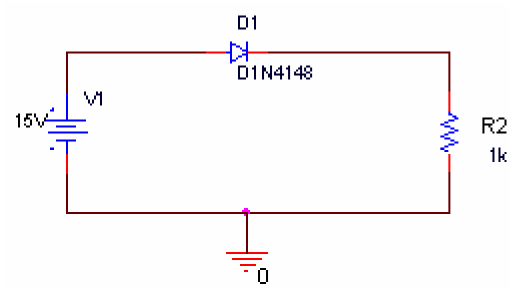
Observe the I-V Characteristic Curve for a Resistor

- Draw the circuit shown (use VDC for the source) in Capture.
- Perform a DC sweep from -15 to +15 volts in increments of 0.1 volt. (When you set up the DC sweep analysis, be sure that you name your source "V1.") *You do not need to add any probes.*
- Run the simulation. Select "Add Trace" to plot the current through resistor R1, I(R1). Recall that you must choose this current from the list you see when you use "Trace" and then "Add."
- Change the x-axis of your plot as follows: Right click on the plot and choose "Settings" Then click on the X-axis Tab. Click on the "Axis Variable" button at the bottom. Enter V(R1:1)-V(R1:2) as the new X axis variable.. This sets your x-axis to the voltage across the resistor R1, a value dependent upon the source voltage., which is sweeping from -15 to 15 volts. The plot produced will show the I-V characteristic for resistor R1.
- Your PROBE plot should look something like the one on the following page.

I-V Characteristic of a 500 Ohm Resistor



Observe the Characteristic Curve for a Diode



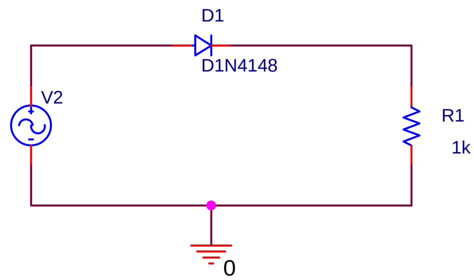
- Modify your PSpice schematic by replacing R1 with D1, a D1N4148 diode. You will find this diode in the parts list. It is in the "EVAL" PSPICE library.
- Plot the current I(D1) through diode D1 the same way you did I(R1) in the previous section.
- Change the x-axis of your PROBE plot as you did in part 1 to V(D1:1)-V(D1:2). This sets your x-axis to be the voltage across diode D1. The plot produced will show the I-V characteristic curve for diode D1. If it is upside down or backwards, change the sign of one or both of the parameters.
- **Print your plot**. Using the cursors, mark at least 5 points off of this plot. You will be using these 5 points in Excel to help you plot the characteristic curve of the diode. Choose points that accurately represent the features of your curve.

Assemble the Diode Circuit on Your Proto-Board

- Diodes look like very small resistors with only one stripe. The stripe corresponds to the straight line of the diode symbol at the cathode. When you wire the circuit, make sure your diode is placed so that the cathode faces toward ground as shown in the figure above.
- Supply a DC sweep voltage to your circuit. We cannot actually choose "DC Sweep", but a simple way to perform a DC sweep is to select the triangular waveform on the function generator, and connect it as the Voltage Input. Observe the output of the function generator Vin by connecting it to your 'scope. Select a slow repetition rate (frequency) of 100Hz, and a sweep from -10V to 10V.

- Using the 'scope, measure V_{out}, the voltage at the end of the diode connected to the resistor R2 and the input voltage.
- Take a sample in Excel of the input and output voltages. Eliminate all points except for one upward ramp of the input voltage (this represents a single DC sweep from -10V to +10V.
- You can now use this data to plot the I-V characteristic of the diode. You need to plot the voltage across the diode against the current through the diode. The voltage across the diode is equal to V_{in}-V_{out} V_{in}-V_{out} on the scope as the difference between the triangle waves. The current through the diode is V_{out}/R2.
- Now that you have a set of points corresponding to the behavior of the diode, you can determine the equation which governs it (see Part A question 1). Use the equation on the top of page 2. You already know the value of the constant, V_T, and you have a data set for i_D and v_D. You can pick a good guess for I_S from your PSpice plot. You will then have to guess values of n between 1 and 2 (and possibly modify I_S slightly) until the theoretical curve fits your data**. Include a copy of this plot in your write-up.**

Part B Rectifiers

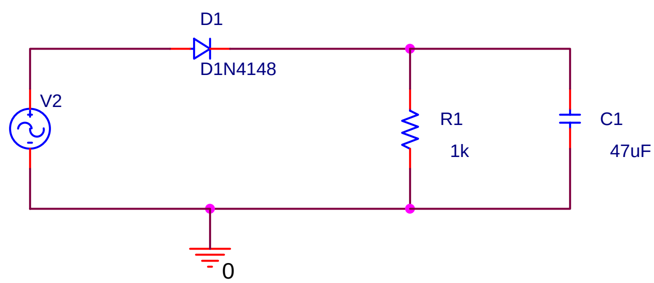


In the circuit shown above, the DC voltage source we used before is replaced by a sinusoidal source (VSIN). Such a circuit is called a rectifier.

Use PSpice to simulate the circuit above in which a diode is used as a rectifier with no smoothing

- Draw the circuit shown. Use VSIN for the source. Use the following parameters for VSIN: VAMPL = 5 (10V peak to peak), VOFF = 0, DC = 0, and FREQ = 60Hz.
- Perform a transient analysis in increments of 200us up to 80ms.
- Obtain a graph of the input and output voltages, V_{in} (V1) and V_{out} (voltage across R), vs time. **Print this plot.**

Add a capacitor across the resistor. Use PSpice to simulate the circuit below.



- Modify your PSpice circuit by adding capacitor C1 in parallel with R1.
- Perform a transient analysis as you did in the previous part.

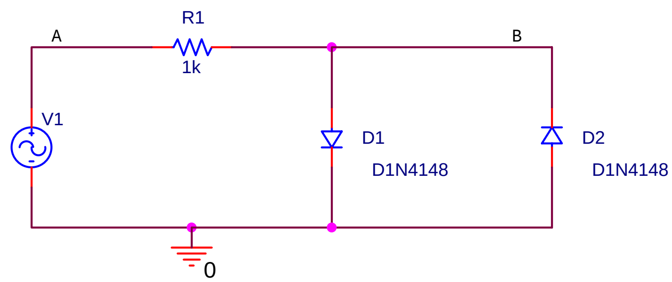
- Obtain a graph of the input and output voltages vs time. **Print this plot.**
- Modify the frequency of the source to 1k Hz, the time to 1ms, and the step size to 0.1ms. Generate a plot of the V_{in} and V_{out}. Note the time at which the output voltage reaches 4V.
- Keeping the time and step size the same, modify the frequency of the source to 1Meg and rerun the simulation. (It may take a bit longer.) Note the time at which the output reaches 4V. (You will need to delete the other trace to see it.) What is happening as the frequency increases?

Hardware Implementation

- Assemble the rectifier circuit *without* the capacitor. Use the function generator to supply an input sinusoidal signal of 60Hz, 10 volts peak to peak. Reminder – Always connect the function generator to one channel of the 'scope so that you can be sure that you have the signal you need. Also, as a rule, you should always connect your input signal to one channel of the 'scope and the output signal to the other channel. To see the effect of a circuit, it is essential to observe both the input and the output simultaneously.
- Observe both the input and the output voltages with the oscilloscope. Be sure that your 'scope is set to DC coupling.
- Repeat the procedure above with a 47uF capacitor in parallel with the resistor R. Note that the sine voltage from the generator will become distorted when you add the large capacitor. This is due to the finite, non-zero source impedance of the function generator (which we have been ignoring so far in this experiment) and the large variation in load seen during alternate halves of the cycle. In a more critical circuit, one might, for example, add a 50 ohm load (resistor) to the function generator. For our purposes here, we simply note the distortion.
- Measure approximately 5 points during one cycle, and **add the experimentally measured points to the plot generated with PSpice.**
- Vary the frequency of the function generator and observe both the input and output voltage of the rectifier with the capacitor. Try connecting and disconnecting the capacitor as you vary the frequency.

Part C PN Junction Voltage Limitation

When you performed the triangular wave sweep of the 1N4148 diode, you should have observed that the voltage across the diode remained near 0.6 volts when it was on. We can take advantage of this effect in the following circuit which permits small voltages to pass without distortion, but clips any voltage outside the range of about -0.6 to 0.6 volts.



Observe the diodes functioning as limiters (or clippers)

- Draw the circuit shown. Use VSIN for the source (VAMPL = 10, FREQ = 1k, everything else = 0). Perform a transient analysis in increments of 50us up to 5ms. Use PROBE to plot the input and output voltages. The input is the voltage source while the output is taken across the diode pair, as shown. **Print your PROBE plot.**

- Change the amplitude of the sinusoidal input, Vin, to 0.1 volt. Repeat the transient analysis. **Print your PROBE plot.**

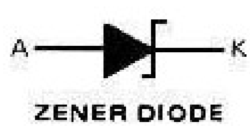
Assemble the diode limiter circuit on your proto-board

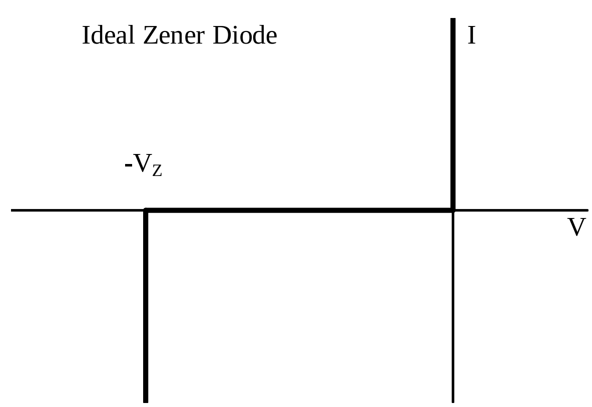
- Use the function generator to supply a 1 kHz, 10V, sinusoidal input. Use the 'scope to set up the function generator amplitude. Observe V_{out} and V_{in} with the oscilloscope. You will need to use both channels and to make sure that you connect your grounds to only one place. Be careful to adjust the function generator output such that the signal you observe on the 'scope looks as much like the PSpice output as possible. You might have to adjust the amplitude of the signal and the voltage and time scales on the 'scope. Add at least 5 experimental points to your PSpice output.
- Repeat the measurements with a 1 kHz, 0.1V sinusoidal input. Don't forget to add at least 5 points to your PSpice output.

Background, Continued

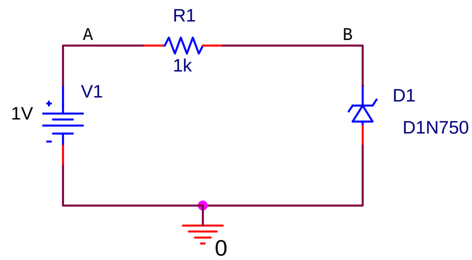
If you recall the figure above showing the I-V characteristic of a diode, you will see that, if a diode is sufficiently reverse biased, it will conduct in the reverse direction. Furthermore, the diode voltage will remain approximately constant over a wide range of currents. This property is known as breakdown; the breakdown voltage is called $-V_Z$, where the subscript Z indicates that this is also known as the Zener voltage. Diodes that are designed to work in the breakdown state are usually known as Zener Diodes.

In a semiconductor diode, charge carriers (holes and electrons) are continually being thermally generated, which results in the small, voltage independent reverse saturation current when a diode is reverse biased. If the reverse voltage becomes too large, two phenomena occur to dramatically increase current. As the reverse bias voltage increases, so does the size of the depletion region (the insulating region between the holes and electrons). In this region, the charge carriers experience an electric field force which increases their energy. If this energy is large enough, the collision of a carrier with an ion will generate a new hole-electron pair. The electric field itself can also pull electrons from the ions once it becomes large enough. Both processes increase the number of charge carriers and thus increase the ability of the diode to carry current in the reverse direction. By appropriate doping, it is possible to design a Zener diode that breaks down at anywhere from a few volts to a few hundred volts.





Part D Zener Diode Voltage Regulator



In the circuit shown above, D1 is a Zener diode. Be sure you have its orientation correct.

Obtain Zener diode characteristic.

- Draw the circuit shown. Perform a DC sweep analysis from -10 to +20 volts in increments of 0.1 volts. Be sure that you enter V1 for the name of the device that is swept. Plot the current through the Zener diode I(D1) vs the voltage across the diode -V(D1:2) to obtain the I-V characteristic of the Zener diode in the same manner as we addressed the standard diode in the last experiment. ie. make the X-axis variable -V(D1:2). Note that your plot should look like a typical Zener diode characteristic. If, for some reason, the current or the voltage look upside down or backwards, reverse one or both of the signs until the plot looks correct. **Print this plot.**
- Look up the typical Zener voltage in the spec sheet for the 1N750A diode. (You can find a link to this spec sheet on the links page.) Draw a vertical line in the reverse bias region on your output plot corresponding to the rated Zener voltage. Note that this diode will keep its reverse bias voltage quite close to the Zener voltage for a wide range of currents. The smallest current for which the bias voltage is about equal to the Zener voltage is called the knee current. What is the minimum current (or knee current) for which the reverse bias voltage is no more than 0.1 volts less than the rated zener voltage? **Mark the knee current on the plot.**

Hardware Implementation

Assemble the circuit on your protoboard. Connect the DVM to measure the current through the diode**.** Unlike voltage measurements, current measurements are made in SERIES with the circuit. Use the DMM inputs labeled with the letter "I" and set it to measure current (DC I) with the shift button. Adjust the *DC source voltage* until the current reads 1mA, 3mA, 5mA. Measure the voltage across the diode for this condition. Repeat this for a current of -1mA, -3mA ,-5mA. *If you have questions about measuring the current PLEASE check with a TA.* **Mark these six points on your PSpice output of the characteristic curve of the zener diode.**

Report and Conclusions

The following should be included in your written report. Everything should be clearly labeled and easy to find. Partial credit will be deducted for poor labeling and unclear presentation.

Part A

Include the following plots:
1) I-V Characteristic curve PSpice Plot with 5 points marked (1 pt)
2) Excel sample of characteristic curve taken using agilent software. This should include the data points and a line found using the diode characteristic equation. (1 pt)

Answer the following questions:

1) Use the data you took for the I-V characteristic of the 1N4148 diode to determine the mathematical representation of the I-V curve. What values did you find for I_S and n? (2 pts)
2) Why do you know that the current through the diode is $V_{out}/R2$? (1 pt)
3) What differences, if any, did you notice between the I-V characteristic given by PSpice and the one you measured experimentally? (1 pt)

Part B

Include the following plots:
1) PSpice plot of rectifier (1 pt)
2) PSpice plot of rectifier with smoothing with 5 experimentally obtained points marked (1 pt)

Answer the following questions:
1) What is the function of a rectifier? (1 pt)
2) Explain why V_{out} changes when you add the capacitor in parallel with R. Explain why this circuit would be better for use as a DC source than the circuit without the capacitor. (1 pt)
3) Did the circuit with the capacitor work better (more like a DC source) at high or low frequencies? (1 pt)
4) Based on your knowledge of the theoretical behavior of the capacitor at very low (open) and very high (short) frequencies, how has the diode changed the expected behavior? Why? (1pt)

Part C

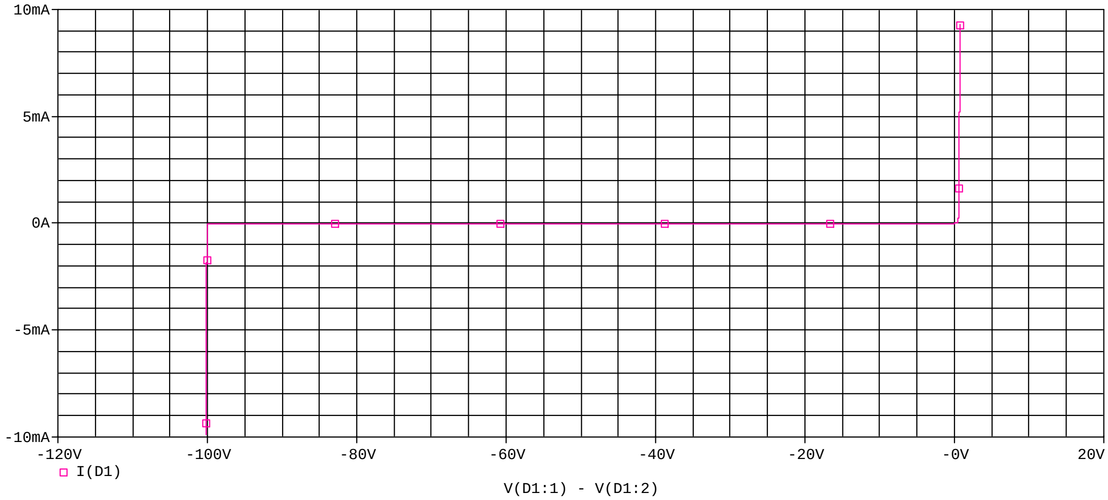
Include the following plots:
1) PSpice plot of voltage limiter at 10V (with 5 experimental points marked) (1 pt)
2) PSpice plot of voltage limiter at 0.1V (with 5 experimental points marked) (1 pt)

Answer the following questions:
1) Why do the two plots look the way they do? (1 pt)
2) Why is this circuit called a limiter? (1 pt)
3) When and why might this circuit be useful? (1pt)
4) Comment on the similarities and differences between the Pspice and experimental results. (1 pt)

Part D

Include the following plots:
1) Zener diode characteristic curve with vertical line and knee current marked (1 pt)

Answer the following questions:
1) What are the Zener voltage and knee current for the diode you simulated? (1 pt)
2) Shown below is the I-V characteristic of the 1N4148 non-Zener diode we looked at in part A, but obtained over a much wider voltage range. Compare this plot with the one you obtained for the Zener diode. (1 pt)



3) We have seen that the voltage across the Zener diode will remain equal to the Zener voltage, as long as we provide enough voltage and current from the source. However, the circuit configuration we have studied does not include a load. A load resistor would be added in parallel to the Zener diode. Discuss how this circuit will perform for a load that is much smaller than 1k ohm (eg 50 ohms), equal to 1k ohm, and much larger than 1 k ohm (eg 1 megohm). That is, under what conditions will it produce the desired regulated voltage? Support your discussion with calculations, simulations, or experimental results. (2 pts)

Summarize Key Points (1 pt)

Mistakes and Problems (0.5 pt)

Member Responsibilities (0.5 pt)