Lab 3 Semiconductor Diodes

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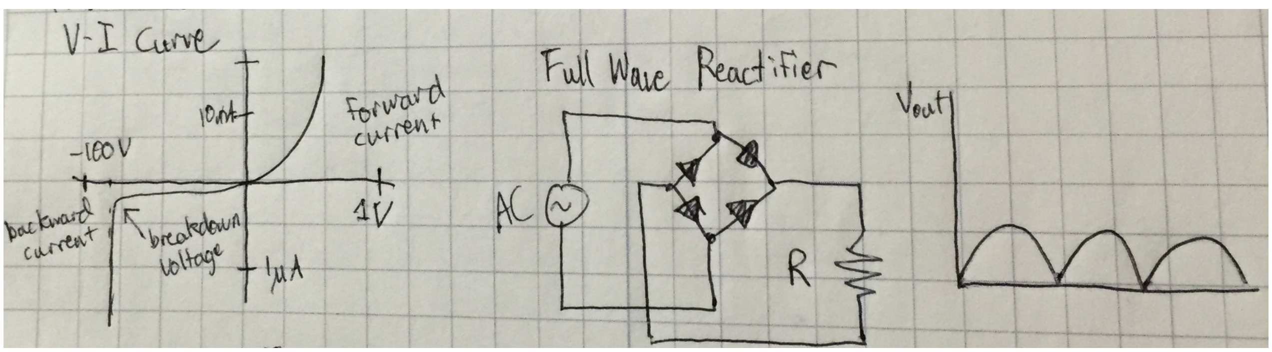
Introduction

The focus of this lab is studying the circuit characteristics of the diodes. In particular, the concept of non linearity is of interest. Diodes have non-linear behavior so the beginning of the lab focuses on characterizing and getting a feel for the diode circuit properties. After analyzing voltage and current relationships in a diode the lab explores the use of diodes in rectifiers. A rectifying circuit is a circuit which takes an AC signal and converts the signal to DC. Since diodes only allow current when forward biased, they can be used to chop off negative voltages in an AC circuit, thus rectifying the waveform. The last part of this lab touches on graphical load line analysis and perturbation analysis, which is useful for analyzing more complex linear circuits.

Pre-lab

1. In a few sentences, explain what diodes are and how they are useful.

Diodes allow current in only 1 direction. Ideally, a diode has low resistance in the direction of allowed current flow and very high or infinite resistance in the opposite direction. Diodes are typically made of PN junctions. They can be used as rectifiers, a class of devices that convert AC current to DC current.



2. Show that the second term in Eq (1) may be neglected for typical operating parameters:

$$i(V) = i_{sat}\left[\exp\left(\frac{eV}{nkT}\right) - 1\right]$$

typical parameters $V > .1V$

$I_{sat} = 10^{-9} A$

$n = 2$ for typical diodes

$\frac{eV}{nkT} \Rightarrow \frac{0.1}{2(kT)}$ if $kT << .05$ then the exponential will dominate, reducing the expression to $i(V) = i_{sat}\, e^{eV/nkT}$

3. Why is there a ripple on top of the DC voltage output by the circuit in 3.8?

The circuit in 3.8 uses an AC source, but the diode acts as a rectifier that curs off the negative peaks in the signal. This is not quite a DC signal though, since there are still large periodic variations in the voltage. The capacitor acts as a Low Pass to smooth out the rectified signal—what we are left with are ripples in a DC signal.

4.What is a load line used for? What are the relative advantages of graphical and iterative analysis?

The load line is a function of V vs I or the linear part of a circuit which may have non linear components such as a diode. The load line can be used in graphical analysis to find the equilibrium voltage and current by calculating the intersection of the line and the V-I curve of the non-linear device. Iterative analysis is a method of refining an initial guess to find the actual equilibrium point. Iterative analysis and graphical analysis should yield the same result.

Lab Questions

Problem 3.1 – Forward and Reverse Diode Behavior

The diode used in this problem and throughout the lab is the 1N4448 diode. We start the lab by measuring the resistance in the forward and backward directions across the diode in order to observe unidirectional behavior. With DMM was set to the 1k resistance scale, the diode's anode was connected to the positive mini grabber lead while the cathode was connected to the negative lead. In the forward direction, the resistance was 622±2Ω. With a DMM current of about 1mA, this results in approximately a 0.622V forward voltage drop across the diode. In the reverse direction (with the anode and cathode oppositely connected to the DMM), the DMM ohmmeter read OVERLOAD, which indicates a very high impedance which is off the measurable scale. According to the lab specification, a forward resistance of 650Ω is fairly typical of a diode; our 1N4448 diode falls within an acceptable margin of error. These results confirm the unidirectional characteristics of a diode: a diode which allows current flow in one direction is expected to have a low finite resistance in the allowed forward direction and very high resistance in the reverse direction.

Problem 3.2

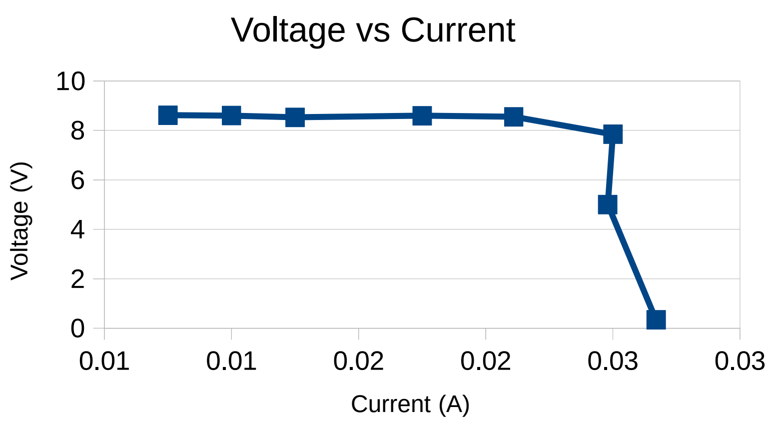
We obtain a stick-mounted 1N4448 diode to experiment with the effects of different temperatures on the diode behavior. To verify our previous diode measurements we re-measured resistances; the stick diode had a forward resistance of 620.4Ω and an overload resistance in the reverse direction. Next the diode was heated up by pinching the device in our hands. The DMM measured a forward resistance of 609±1Ω when heated to body temperature (as compared to room temperature in the controlled measurement). Then the diode was cooled significantly by dipping the probe into a cup of liquid nitrogen. At a temperature of about 77.2K, the diode measured a forward resistance of 1.06kΩ. These measurements demonstrate that a diode's resistance increases as it is cooled. It was not surprising that the liquid nitrogen had a larger appreciable effect—the nitrogen is many times cooler than room temperature while human body temperature is only 10K or so warmer.

Problem 3.3

The offset adder located on the breadboard is capable of supplying a range of DC voltages. Using the handheld multimeter, we quickly scanned a range of values from roughly -8.67V to 8.67V. Next we try to determine the rigidity of this power supply as a voltage source by loading the offset adder with several different resistor values. We used the DMM and handheld multimeter to quickly record current and voltage values while changing the resistors several times. The following data shows that the offset adder has fairly low impedance and can be regarded as a reliable and stiff voltage source as long as the output current is below 24mA.

Figure 3.3

Current (A)	Voltage (V)
0.0075	8.61
0.01	8.6
0.0125	8.53
0.0175	8.59
0.0211	8.55
0.025	7.84
0.0248	5
0.0267	0.341



Problem 3.4

Now we apply the offset adder across the 1N4448 diode. The DMM was connected in series with the circuit while the handheld multimeter was used to measure the forward voltage drop across the 1N4448, much like the circuit diagram from the lab manual in figure 3.4a. While taking data, we made sure to use the offset adder in its flat linear regime as noted in 3.3 (below ~25mA). Figure 3.4b shows the data we recorded and the accompanying linear and log-linear plots.

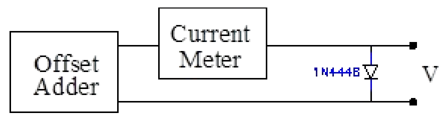
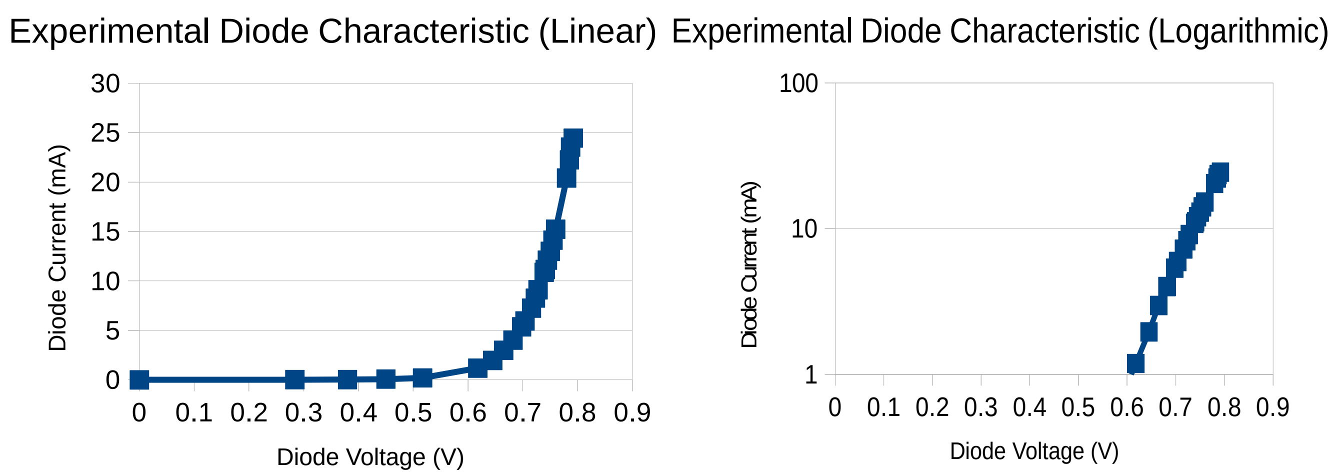


Figure 3.4a



Voltage (V)	0	0.284	0.38	0.45	0.517	0.618	0.645	0.665	0.682	0.698	0.704	0.716	0.723	0.728	0.739	0.741	0.745	0.75	0.755	0.76	0.78	0.785	0.787	0.792
Current (mA)	0	0.005	0.02	0.06	0.185	1.185	1.95	2.967	3.999	5.36	5.939	7.233	8.25	9.097	10.87	11.14	12.095	12.993	14.12	15.235	20.399	22.25	23.54	24.44

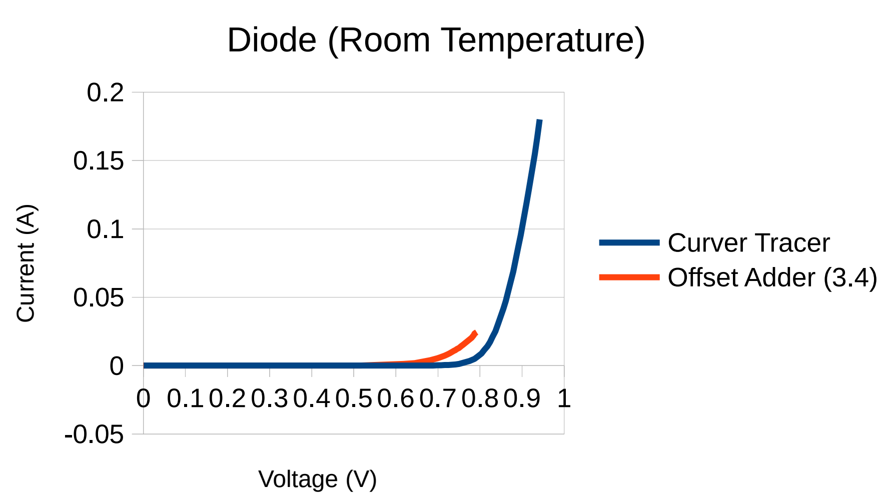
Figure 3.4b *Linear and Log-Linear plots of the data*

Problem 3.5

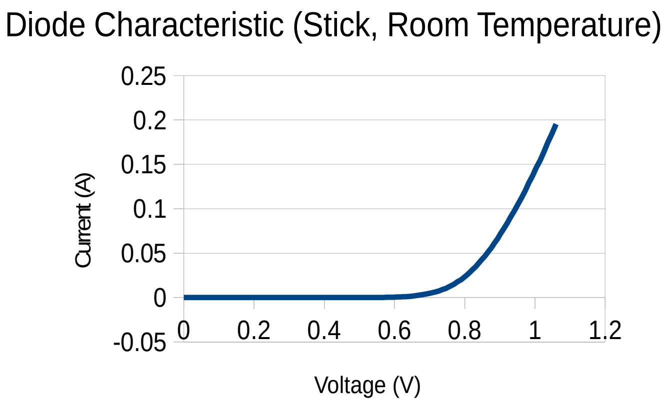
Diodes can be analyzed through the characteristic current equation:

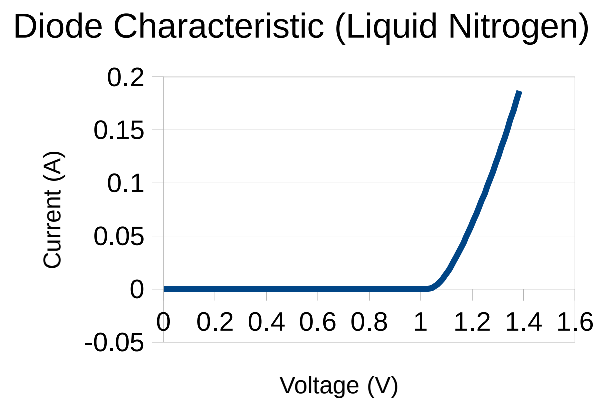
$$I(V)=I_{sat}[\exp(\frac{eV}{nk_b T})-1]$$

The Curve Tracer is capable of tracing out the diode's characteristic V-I curve and measuring values for I_{sat} and the Voltage Coefficient $V_c = eV/nkT$. Using the tracer and the data from the previous problem, we overlay both V-I characteristics and compare how well the curve tracer fits our empirical data:



We see that the circuit with the offset adder doesn't reproduce the diode characteristic perfectly, but it agrees well for very low currents and has a similar shape to the tracer in the non linear regime. The curve tracer was also used to make the following plots of the stick-mounted diode:





Then we recorded the measurements for I_{sat} and V_c from the curve tracer analysis:

1N4448 diode: $I_{sat}=1.77\times10^{-9}$ $Voltage\,Coefficient=19.81$

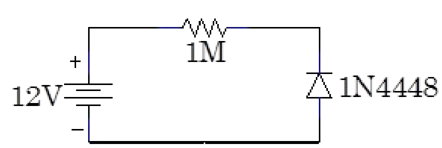
Stick diode, room temperature: $I_{sat}=2.89\times10^{-5}$ $Voltage\,Coefficient=8.59$

Stick diode, liquid nitrogen: $I_{sat}=1.77\times10^{-9}$ $Voltage\,Coefficient=19.81$

Room temperature is approximately ~298K and liquid nitrogen has a boiling point of ~77K; with these values of T, we calculate the "n" factor by solving the voltage coefficient formula for n = $e/V_c kT$. For the room temperature diode, we get a value of n=1.965. For the stick mounted diode at similar temperature, n turns out to be 4.529. The liquid nitrogen dipped diode had the worst results, with an "n" value of 19.011. Typical diodes have an "n" value between 1 and 2. Thus our first diode performed accurately while the stick-mounted diode had erroneous curve tracer data.

Problem 3.6

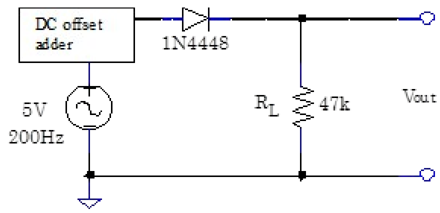
Now we want to measure the current in the diode when the forward voltage drop is -12V. In other words, we construct the following circuit where the diode is placed in reverse orientation (to measure the reverse diode current):



Since the resistor is linear and obeys Ohm's law, we measured the voltage across it to see how much current flows through the circuit. The 1.007MΩ (1MΩ nominal) had a voltage drop of 15.0mV. From Ohm's law the current through the resistor, and therefore the current through the diode, is 14.9nA. This confirms that the diode has weak current response when a positive voltage is applied across the diode's reverse direction.

Problem 3.7

We built the following half-wave rectifier with the diode as in this circuit diagram:



The DC offset was set to zero volts in order to prevent the rectifier from charging up the capacitor in the signal generator. We used a resistor with a measured value of 46.45k for the nominal 47k resistor in the diagram. The oscilloscope was used to probe the rectifier's input and output (Figure 3.7). A3s expected from the pre-lab, the smooth AC sine input gets rectified by the diode. No current is allowed to flow when the AC source swings negative, so the output is flat wherever the input is low. However, all of the positive peaks get through, so we have a nicely rectified periodic output.

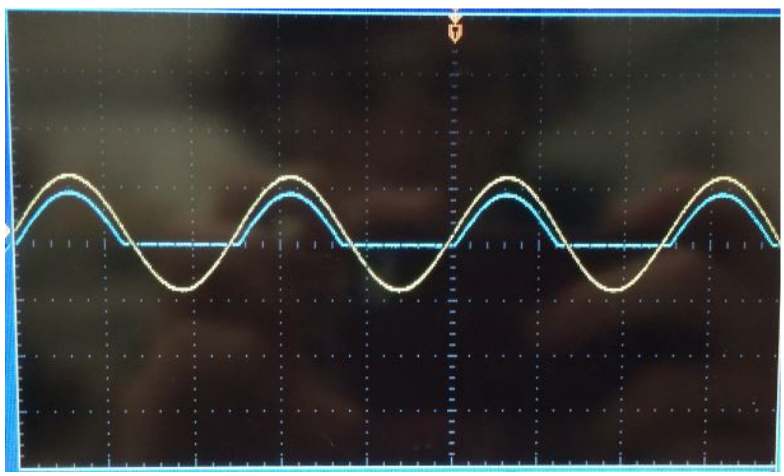


Figure 3.7 *An AC source (yellow) and the rectifier's output (blue)*

There is also a small discrepancy in the peak amplitudes of the input and output which is a consequence of the diode's forward biased voltage drop.

Problem 3.8

The following circuit diagram shows the same diode rectifier as in the previous problem with the exception of an extra 1uF capacitor. When we built the circuit the capacitor we used measured 938.68nF. This capacitor is known as a smoothing capacitor, because we expect it to flatten out our half-rectified wave much like a low pass filter. For the capacitor to appropriately remove the frequency dependence of the signal, the capacitor needs to be chosen such that the time constant is greater than the time between half rectified peaks

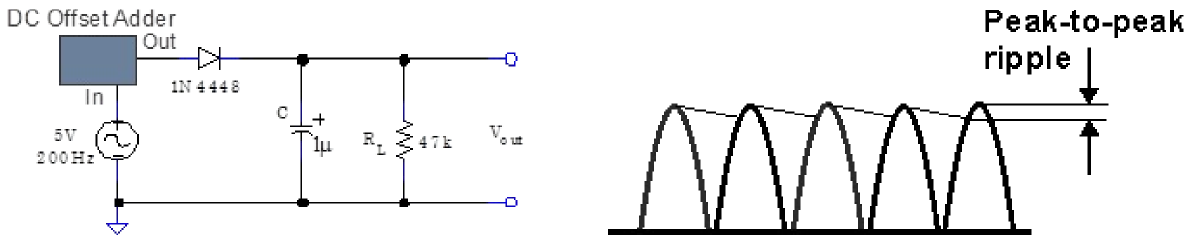
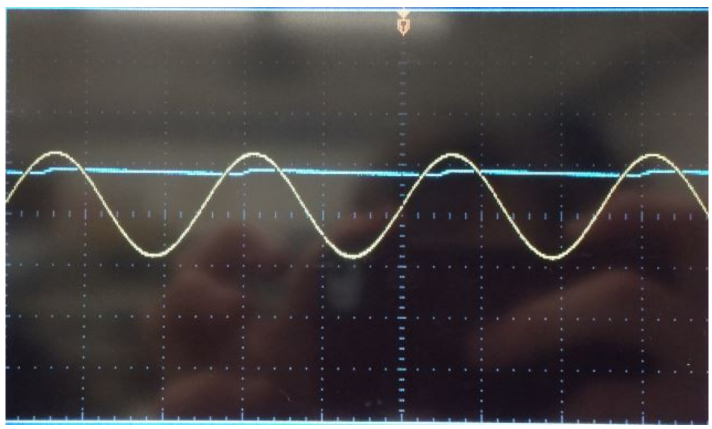
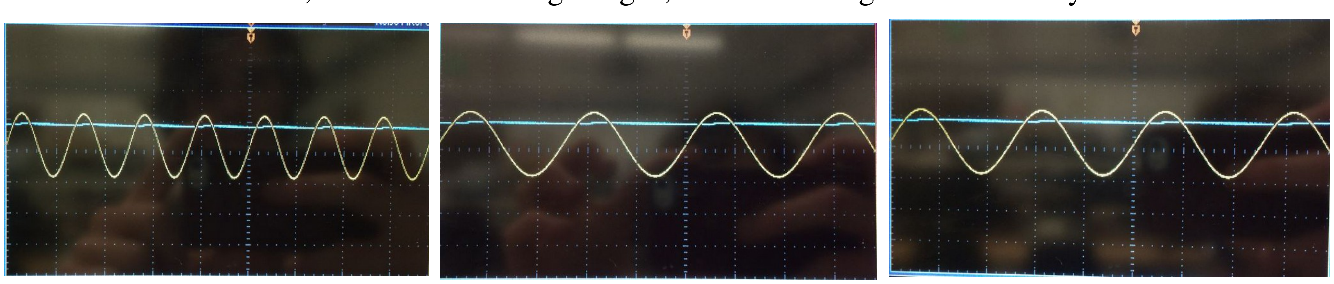


Figure 3.8 *Capacitor Smoothed Half Rectifier*



The oscilloscope picture above shows input AC signal in yellow (a sine wave), and the rectifier's smoothed output in blue. We note that because the capacitor takes time to discharge, the circuit's output is not a perfectly flat DC voltage; instead, we see a signal that has amplitude ripples with the same frequency as the input. In problem 15 further in this lab we derive the relationship $V_r \propto V_{in}/(f\,RC)$ which states that the peak-to-peak amplitude of the ripple V_r is proportional to the input amplitude V_{in} and inversely proportional to the input frequency f and the RC time constant. Thus we expect that doubling the input frequency will make a smoother rectified output, since there will be less time for the smoothing capacitor to discharge. We also predict that doubling the capacitance by adding a second 1uF capacitor in parallel or doubling the load resistor will increase the time constant and thus smooth out the ripple amplitude further. After making these modifications to the set up, we took several images to confirm our intuition; in all the following images, the rectified signal is noticeably smoother:



From left to right: double frequency, double capacitance, double resistance

Problem 3.9

In this section we use the offset adder and a resistor in order to determine how well the diode behavior fits the curve tracer data we plotted in problem 3.5. In particular, we will be using graphical load line analysis to see if the diode equilibria predicted by the plots match our experimental measurements. We start by building the following circuit, with the exception of disconnecting the signal generator so that we can study the DC response of the diode, and a 10.434kΩ (measured) resistor for the 10k nominal.

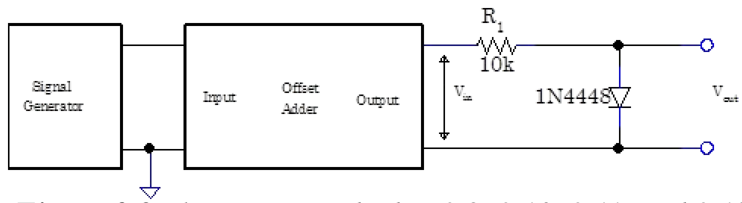
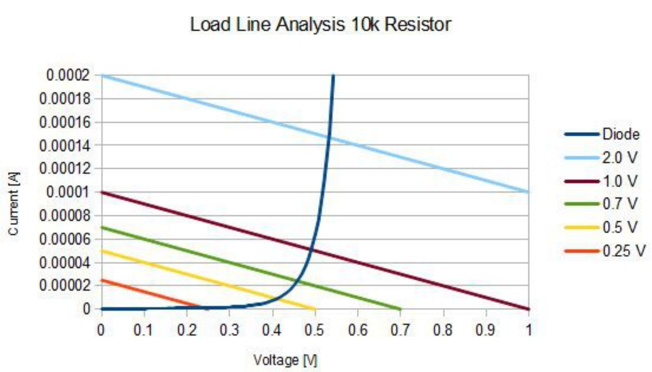


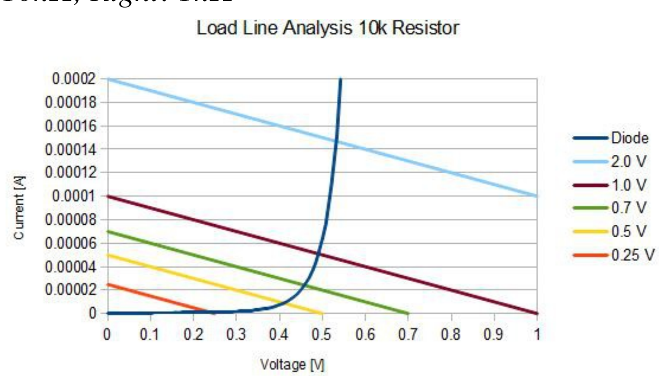
Figure 3.9 *The circuit studied in 3.9, 3.10, 3.11, and 3.12*

Using the multimeter to measure and scan through values of V_{in}, we recorded the data in the following tables. We then repeated the measurements for a 1k nominal resistor with a value of 972.85Ω

V_{in} (V)	V_{out} (V)	V_{in} (V)	V_{out} (V)
0.25	0.242	0.25	
0.5	0.395	0.5	0.2492
0.7	0.436	0.7	0.4618
1	0.47	1	0.5324
2	0.518	2	0.5761

Figure 3.9 *Left: 10kΩ; Right: 1kΩ*





The graphs show the characteristic data collected by the curve tracer and the load lines of the resistors at the voltages .25V, .5V, .7V, 1V, and 2V. The equilibrium current we would expect to see at X Volts is just the value given by the intersection of X's load line and the characteristic curve of the diode; thus the output voltage of the diode circuit would just be the x value of the intersection. For example, the 10k resistor would expect to see a voltage across the diode of about 0.5V since the 1V load line intersects the curve at around (0.5,.00005). Referencing the data table, a value of $V_{out} = 0.47V$ for a 1V input matches the 0.5V prediction reasonably well. Further inspection of the plots shows that the data is a good match in general for both the 10k and the 1k resistors.

Problem 3.10

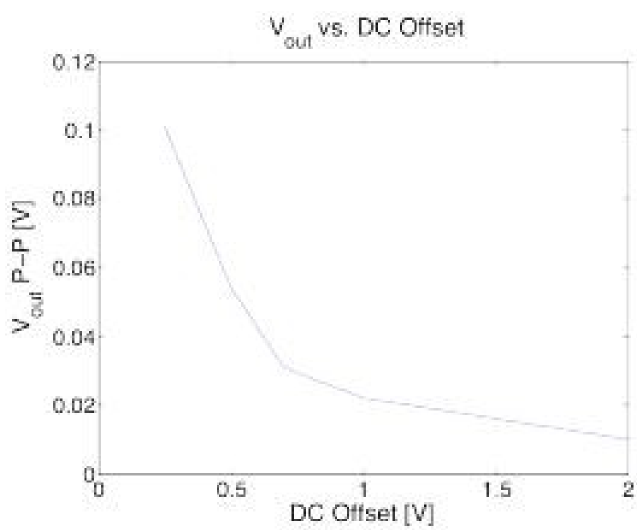
Here we explore how the Offset Adder can be used with the wave generator to provide a DC offset to an AC signal. The Offset Adder has a BNC input that can be connected directly to the signal generator. The output of the Offset Adder is the sum of the input and a knob adjusted DC offset. After setting the generator to a 1Vpp, 1kHz sine wave and disconnecting the diode and resistor, we used the oscilloscope to probe the Offset Adder's output. We found that by turning the Adder adjust knob clockwise, we could increase the DC offset of the wave. Counterclockwise rotations of the knob decreased the DC offset. By tuning the Offset Adder adjust, we can add any desirable DC offset in the range [-8.5V, +8.5V] to an AC input.

Problem 3.11

Next we reconnected the 10k resistor and diode to the original circuit in 3.9. The signal generator was then set to a $0.1V_{pp}$ sine wave, while the Offset Adder provided a DC offset of +1V. The output in the scope was an unperturbed sine wave with amplitude 0.1Vpp riding a DC offset. At first glance this circuit looks a lot like the diode rectifier circuit in 3.7, which cut off the lower troughs of the AC input whenever AC goes negative. However, this circuit with a DC offset does not have a rectified signal. The reason the signal is not rectified is because the DC offset ensures that none of the AC input ever goes negative, since a .1V signal is sufficiently small enough to ride a 1VDC offset.

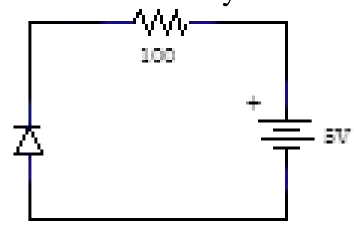
Problem 3.12

In problem 3.9 we tested the DC voltages 0.25, 0.5, 0.7, 1, and 2 with the diode. Now we scan through these values with the Offset Adder and the wave generator (in 3.9 we disconnected the generator). We recorded the output peak to peak amplitude of the signal for each offset. As we increased the DC offset, the amplitude of the AC wave riding the offset decreased. This data is summarized in the following plot:



Problem 3.13

An LED is essentially just a diode that emits light when forward biased. We explore an LED's property by constructing the following circuit where the diode symbol stands for the LED and its direction.

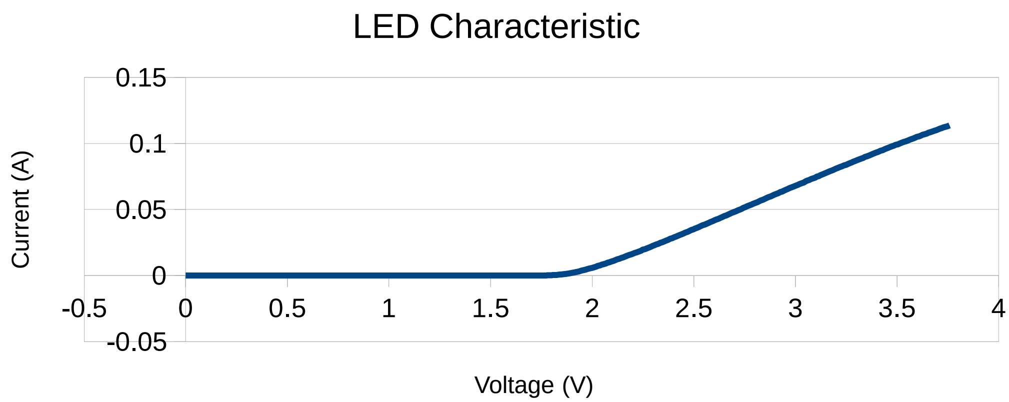


In this configuration, the LED diode is reverse biased, so no current can flow through the device. As such, the resistor has no voltage drop, which was confirmed with a quick multimeter measurement. Swapping the polarity of the LED (or the power source) should light the LED since this will forward bias the diode and allow current through. We confirmed that the LED turned on and then replaced the resistor with several other values: 300, 3k, 30k, and 300k Ohms. As we increased the resistance, we measured the voltage across the resistor and the LED and observed that the voltage across the LED decreased with increasing resistance. We also noted that the brightness of the LED decreased while changing the resistors. This makes sense, since smaller voltages mean that the LED is dissipating less power. The values of the LED voltages for the different resistors are in the following table:

Resistor	Voltage across LED
100 Ω	2.3502 V
300 Ω	2.078 V
3.3 kΩ	1.8763 V
33 kΩ	1.7739 V
330 kΩ	1.6846 V

Problem 3.14

The curve tracer was used to obtain the following characteristic V-I curve of the LED at room temperature:



Analysis

Problem 3.15

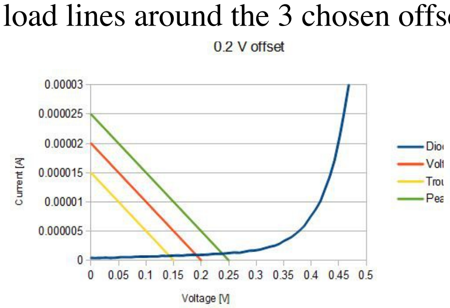
This problem references the capacitor smoothed rectifier circuit shown in Figure 3.8. Here we derive an approximate expression for the peak to peak ripple amplitude V_r as a function of the input amplitude V_{in}, the input frequency *f*, the load resistance R_L, and the smoothing capacitance *C*. Suppose that during the positive crest of the AC input signal the capacitor charges up to a voltage of V_o. When the input becomes negative, the diode rectifies the signal so that the capacitor starts to discharge with the equation $V(t)=V_o e^{-t/\tau}$. The amplitude of the ripple V_r is just the difference between V_o and the voltage of the capacitor after one period *T*: $V_r=V_o-V(T)=V_o-V_o e^{-T/\tau}=V_o(1-e^{-T/\tau})$. When we chose the capacitance C of the smoothing capacitor, we made sure the time constant $RC=\tau$ (which is in units of seconds) was much longer than a period. This allows the exponential term in the ripple amplitude to be approximated to first order: $e^{-T/\tau}\approx 1-T/\tau$. Plugging in this expansion in V_r:

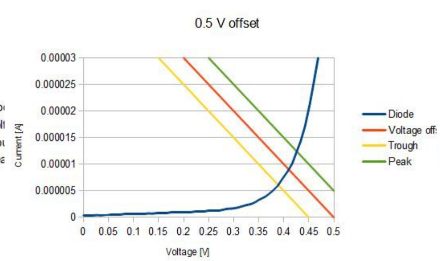
$$V_r=V_o(1-(1-T/\tau))=V_o(T/\tau)=V_o\left(\frac{1}{fRC}\right) \propto V_{\text{in}}\left(\frac{1}{fRC}\right)$$

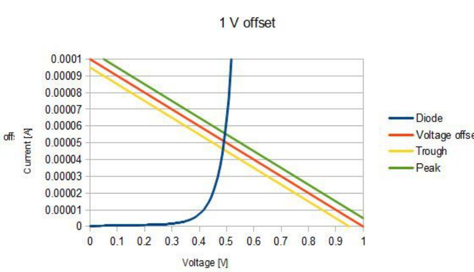
where T = 1/f and the charge of the capacitor V_o is proportional to V_{in}. This relation agrees with the results we found in problem 3.8. Increasing the frequency, load resistance, and capacitance all decrease the ripple amplitude, as observed in the data and this derivation.

Problem 3.16

From problem 3.12 we choose the 3 DC offsets 0.2V, 0.5V, and 1V to do perturbation analysis for. In graphical perturbation analysis, we linearize the diode characteristic around a voltage point. We know the AC voltage has an amplitude of .05 V, so we can offset plot the load line plus and minus .05V against the diode characteristic to find an estimate for the AC voltage. The following plots show the load lines around the 3 chosen offset points:





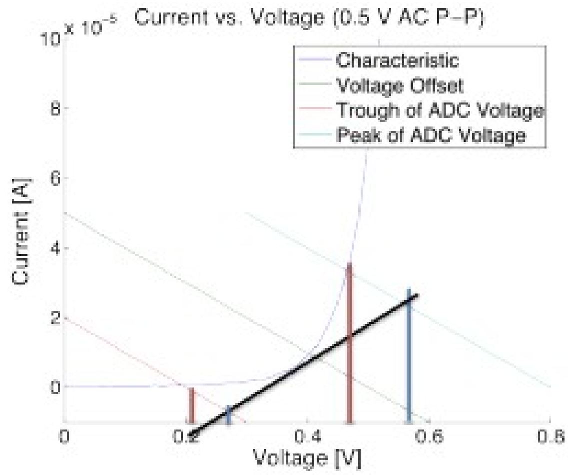


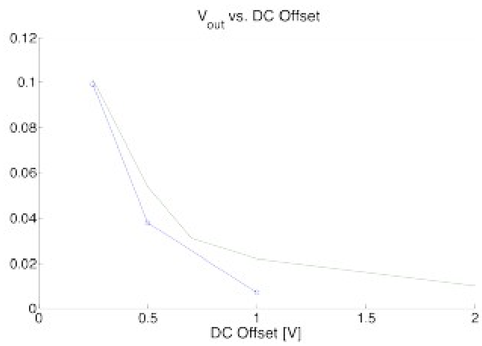
For the .2V offset, we found an amplitude of .95V, for .5V an amplitude of .025V, and for 1V an AC amplitude voltage of .015V.

Problem 3.17

Now we make a new set of predictions by calculating the small signal impedance of the diode at each operating point 0.2V, 0.5V, and 1.0V. We can do this by making a tangent line at the operating points and computing the resistance of the diode for each point. Doing so, we get the values of 1.76M, 6.06k, and 733 Ohms for 0.2, 0.5, and 1V respectively.

DC Offset	Zdiode	Vin	Vout
0.25 V	1.76 MΩ	0.1 V	0.099 V
0.5 V	6.06 kΩ	0.1 V	0.038 V
1.0 V	733 Ω	0.1 V	0.0068 V

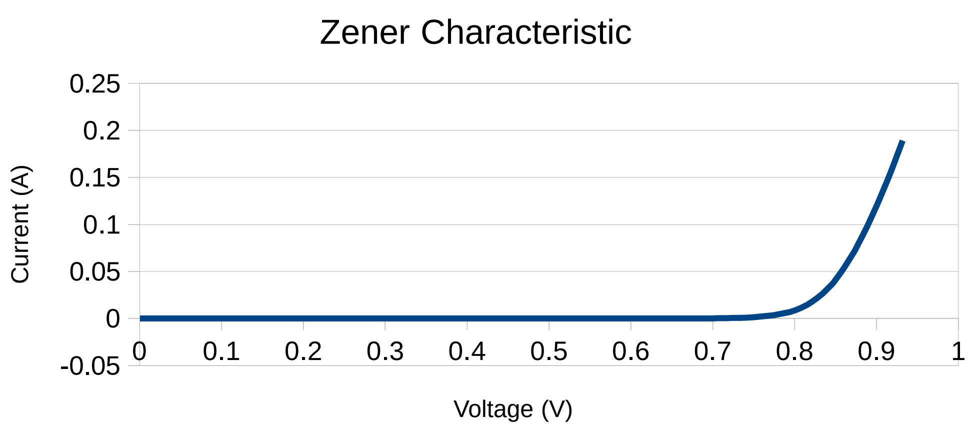




We used a voltage divider equation with the calculated impedances of the diode to predict the output voltage given a 0.1V input. We then plot these calculations on the same graph as question 3.12. We see that the values are approximately the same order of magnitude as these values, so the predictions match the result.

Problem 3.18

We used the curve tracer to obtain a characteristic curve for the 6.2V Zener diode:

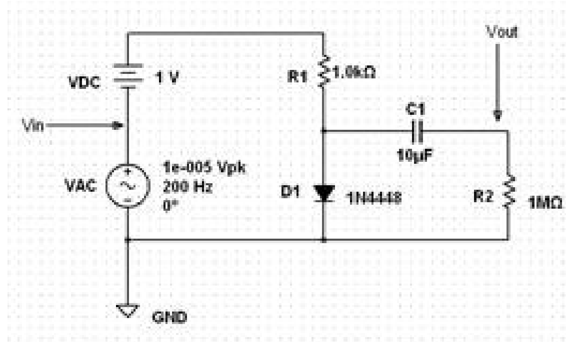


The curve tracer analyzed the Zener diode and found a saturation current I_{sat} of 1.36e-7A and a voltage coefficient V_c of 25.46. Using the current model for a diode with properties I_{sat} and V_c presented in the pre-lab, we estimated that we needed a resistor of 386.7 Ohm in order to reduce a 12V power supply down to 6.2V. We constructed the voltage reducer circuit with a resistor that measured 392.5Ohm and noted that the current was right at 15.2mA and the voltage was 6.3V. We explored a range of other resistor values and found that resistors in the range ~350 to ~10k had currents smaller than 15mA and voltages acceptably close to 6.2V.

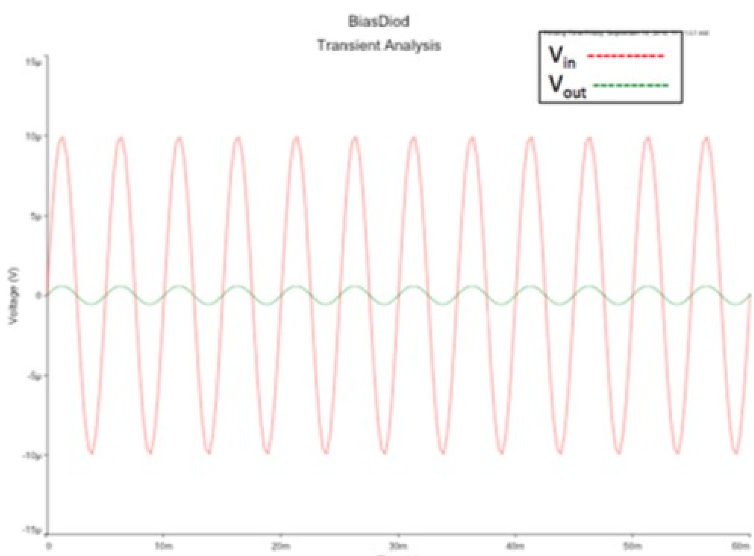
Resistor	Current	Voltage
392.5	15.2mA	6.30V
9.85k	.616mA	6.197V
987	6.125mA	6.245V
104.2	55.29mA	6.548
478.5	12.507mA	6.285
336.1	17.80mA	6.318

Problem 3.19

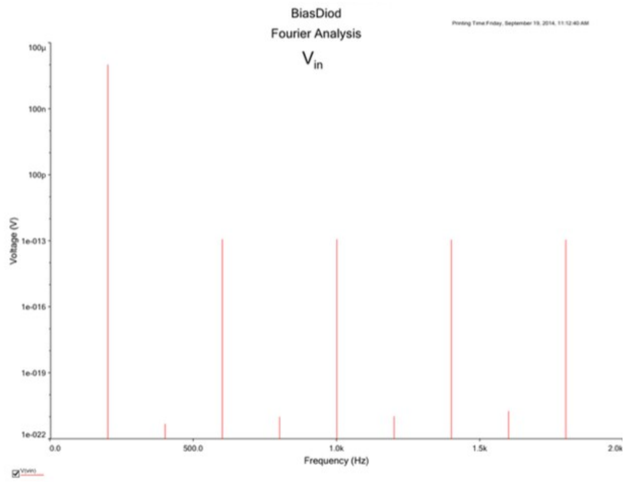
Here we explore frequency doubling in a MultiSim circuit similar to the diode circuit seen previously in this lab, with an extra high pass filter to block the DC component of the signal across the diode.

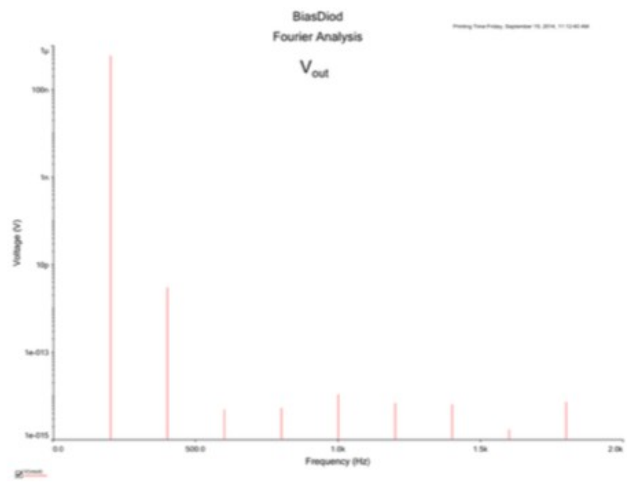


With a $0.00001V_{pp}$, the output in the model oscilloscope is attenuated but relatively undistorted:

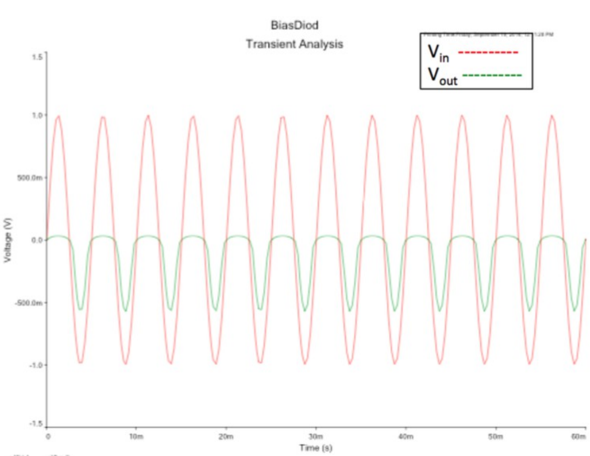


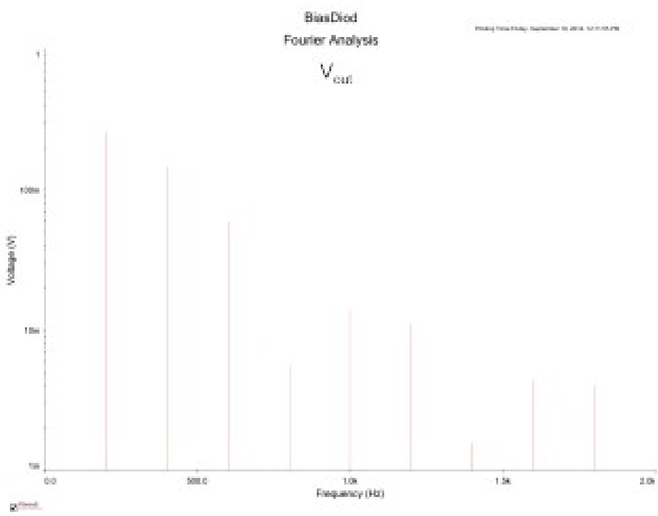
The Fourier decomposition of the signals are shown here as well:





We then reran the simulation with a $1V_{PP}$ source. The output wave is greatly distorted:





In the FFT of the output we see that the harmonics have doubled. We found that for voltages higher than .3V we saw significant frequency doubling.

Conclusion

Previous labs were limited to linear circuit components; in this lab we begin to develop the techniques to deal with non-linear elements. In particular, graphical load analysis and perturbation analysis were a useful tool in make predictions and verifying results when we needed to linearize or approximate the diode characteristic. This technique will prove to be useful in future labs, for example when we work with transistors, because nonlinear circuit modeling will be needed. The diode itself acted as a good half wave rectifier. When we added a smoothing capacitor, we saw how a diode can be used to convert an input AC signal into an almost flat DC signal. The DC output was not perfectly flat because it had amplitude ripples, a result of the smoothing capacitor discharging at a much slower rate than the AC input. Through this lab we have demonstrated and achieved a thorough intuition of diodes and their properties. Since transistors use diodes, this lab was very foundational for studying more complex non linear circuits.