Lab 1

Diode Circuits

Overview
In this lab we will measure the I-V characteristics of diodes and learn how to establish a desired bias condition (forward conduction current) using resistor networks. We will also construct several common diode circuits such as limiters, rectifiers, and voltage doublers.

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Background information

Diodes allow current to flow in one direction only, effectively an electronic “one-way street”. The inherent asymmetry of diodes requires that we distinguish between the two ends of the device. One end is called the anode (from Greek anodos meaning upward path) and the other is the cathode (from the Greek kathodos meaning “downward path”). The diode conducts when the anode is biased positively with respect to the cathode. The term diode (literally “two paths” but often taken to mean “two electrodes”) originated in the context of vacuum tubes\(^1\) and always refers to devices that have this one-way characteristic. Semiconductor diodes often have special marks on the packages to help identify the leads, as shown in Figure 1-1. The circuit schematic symbol forms an arrow that points in the direction of current flow when the anode is biased positively with respect to the cathode as shown.

Current-Voltage Characteristics and Modeling

The full current voltage characteristic of a typical semiconductor diode is shown in Figure 1-2a. Above the forward threshold voltage \(V_{on}\) the current increases rapidly. Under reverse bias only a tiny reverse saturation current flows unless the voltage exceed a critical “breakdown” value \(V_{br}\), at which point the reverse current increases rapidly as shown.

Real Diode Characteristic

![Real Diode Characteristic](image)

Simple Approximation

![Simple Approximation](image)

Figure 1-2 – (a) Diode I-V characteristic and (b) a simple approximation for DC circuit analyses. Note that the reverse saturation current in (a) is exaggerated for clarity, and the reverse breakdown voltage \(V_{br}\) is usually much larger than the forward turn-on \(V_{on}\).

\(^1\) Apparently the term “diode” was coined by British physicist William Henry Eccles in 1919 \([1]\). In a vacuum-diode the cathode is a heated tungsten filament and the anode a positively-biased conducting plate that collects electrons emitted from the hot cathode. A vacuum-tube “triode” adds a third control electrode, a “pentode” has five, etc.
The I-V characteristics of most semiconductor diodes are modeled reasonably well by

\[ I = I_s \left[ e^{qV / nkT} - 1 \right] \]  

(1.1)

where \( n \) is the ideality factor, \( I_s \) is the reverse saturation current, and \( kT / q \approx 25 \text{ mV} \) at room temperature (20°C, or \( T = 293K \)). This expression leaves out some details such as the temperature-dependence of \( I_s \) and the onset of breakdown in the reverse saturation region, but it does a reasonably good job of capturing the essential physics. In later coursework (2C and 137AB) we will add to this model to account for some additional affects that are relevant to high-speed operation. In ECE 132 you will see how the model is derived.

In the forward conduction region the exponential term dominates and we can use the simpler expression

\[ I \approx I_s e^{V / nV_T} \quad \text{for} \quad V > 0 \quad \text{(forward conduction)} \]  

(1.2)

where \( V_T = kT / q \). Conversely in the reverse saturation region the exponential term quickly becomes insignificant and

\[ I \approx -I_s \quad \text{for} \quad V < 0 \quad \text{(reverse saturation)} \]  

(1.3)

In most circuit analyses we can often get by with an even simpler phenomenological model that treats turn-on and breakdown as abrupt transitions, and neglects the reverse saturation current entirely. This is shown in Figure 1-2b. In this case there are basically three empirical parameters that we need to describe the operation: the forward conduction threshold \( V_{on} \), the reverse breakdown threshold \( V_{br} \), and the maximum current that the device can safely sustain during operation.

**Diode Types and Selection**

The impact of the diode parameters varies with application. For example, in an AM “crystal” radio where the signal levels are very small, a diode with a small turn-on voltage is desirable. In a power-supply application, devices that can sustain large forward currents and reverse voltages are often preferred. Diodes have been engineered specifically for these and other applications. In this lab we will explore the following types:

- **Rectifier diodes**: Designed to sustain large forward currents and large reverse voltages. Tend to be physically larger than switching diodes.
- **Switching diodes**: designed for speed so that the current can respond very quickly to changes on voltage, enabling the device to be turned on and off quickly. Tend to have lower breakdown voltages and current-handling than rectifier diodes. Many fast switching diodes are Schottky diodes (a metal-semiconductor junction).
- **Zener diodes**: designed to operate in breakdown with a well-defined breakdown voltage. Sometimes used as a simple stable voltage reference.
- **Light-emitting diodes**: Designed to generate light when enough current passes through the device. The threshold voltages are usually significantly higher than other diodes, upwards of 2V.

Note there are many other specialized diode types (PIN photodiodes, step-recovery diodes, laser diodes, tunnel diodes, varactor diodes, etc).

The turn-on voltage is largely governed by the choice of semiconductor material and the device design. Silicon-based PN junction diodes have threshold voltages of \( \sim 0.6-0.8V \); Germanium diodes have \( V_f \approx 0.2V \). Schottky-diodes can be made with most types of semiconductors and typically have low threshold voltages of 0.1-0.4V. Light-emitting diodes
have a higher threshold, typically around 2V. The current-handling capacity is often limited by thermal considerations (too much current and/or poor heatsinking and the device can be destroyed) but this can be manipulated by controlling the size of the device and package, so devices of many different sizes with a wide range of current-handling capacities are available.

![Diode Packages](image)

**Figure 1-3** – Some common diode packages: (a) DO-35/DO-41 axial-lead package (“DO=diode outline”); (b) TO-220 through-hole (“TO=transistor outline”); (c) SOT-23 surface-mount package (“SOT=small outline transistor”). Package name conventions describe the resulting physical footprint on a PCB board, not necessarily the electrical function.

In ECE 2 we will often use the 1N4148 diode in our circuits, and in a few cases one selected from the 1N4001-1N4007 family. These are very common and inexpensive parts. In fact, if you look up the 1N4148 on the web you will see that they are so cheap that the suppliers make you buy them in packages of ten at a minimum. The 1N4148 is usually listed under the heading of “small-signal diodes” or “switching” diodes, whereas the 1N400x is usually listed under the heading of “rectifier” diodes. As previously noted, the key difference between the two types is in their voltage and current handling capability. Look at the data sheet for each (on the course web site): the 1N4148 can handle currents of up to 300 mA and peak reverse voltages of 75V, and the 1N400x can handle up to 1A and voltages ranging from 60V (1N4001) to 1200V (1N4007). So the 4148 tends to be used in applications where the currents are small (usually the case for our circuits). The 400x, on the other hand, is obviously designed for abuse and is a good choice in power-supply applications.

Often packaging and availability are important considerations in device selection. As we noted in previous labs, the parts we use in ECE 2 are wire-lead parts designed for through-hole mounting, as opposed to surface mount parts which have tiny leads or sometimes no leads at all. A few popular diode packages are shown in Figure 1-3. Through-hole parts are great for educational purposes, but nowadays surface-mount parts are more common.

**Breakdown and Zener Diodes**

In the reverse saturation region the diode will conduct only a very small current until the voltage reaches some large critical value, $V_b$, at which point the reverse current begins to increase dramatically. This is called “breakdown”, but the phenomenon is not inherently destructive.

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2 Any part number beginning with “1N” is *always* a diode, but unfortunately not all diode part numbers begin with “1N”!
As long as the current is limited by the external circuit the device can be safely operated around breakdown with no adverse consequences.

Zener diodes are designed to operate at or near breakdown with a specific breakdown voltage. The breakdown voltage can be engineered for a variety of values, and zeners in the range of 3-12V are easy to find. The schematic symbol for a zener diode is shown in Figure 1-4 along with some representative breakdown curves for a few commercial devices.

There are two different physical mechanisms for breakdown in diodes. For breakdown >5V one process (avalanche breakdown) is dominant, and for <5V the other (zener breakdown) is dominant. This has at least two practical consequences: first, the higher-voltage zeners tend to have somewhat more abrupt breakdown characteristics than low-voltage zeners; and secondly, because the two breakdown mechanisms vary with temperature in opposite ways, zener diodes with ~5V breakdown tend to have very small variation with temperature, making them attractive as stable voltage references in some circuits.

**Light-Emitting Diodes and Displays**

Light emitting diodes (LEDs) are diodes made with direct bandgap semiconductors (GaAs, GaN, etc.) and designed to generate light when enough current passes through the device. LEDs are functional similar to any diode, but they typically have a much larger threshold voltage (~2V for red and green LEDs, and upwards of 4V for blue and white LEDs). The packaging is also necessarily different, with a variety of sizes and lens configurations for various display requirements. In addition to the maximum forward current $I_f$ and the forward voltage drop $V_f$, the brightness is obviously an important factor and is specified in units of millicandela (mcd) at some forward current level.

![Figure 1-5 – Anatomy of a plastic 5mm diameter (T1¾) LED.](image)

The cathode leg of the LED is the shorter of the two as shown in Figure 1-5. If for some reason the two legs have been cut to the same length you can often tell which is which by peering through the plastic lens: the cathode is usually the one connected to the big piece of metal on which the diode chip is mounted. On circuit schematics LED symbols are the same as a regular diode with little arrows to suggest light emission, and occasionally the color is printed beside the symbol if relevant.
LEDs are used in lots of applications and come in a variety of packages. Standard wire-lead LED packages like those in Figure 1-5 are usually organized by the diameter of the lens and its color. The most common package sizes are 3mm (T1) and 5mm (T1¾). LEDs are also available in some very tiny surface mount packages. LED displays include multiple LEDs arranged in a fixed pattern with shaped lenses, the most familiar pattern being the 7-segment displays for showing numbers (digits 0-9). Figure 1-6 illustrates some of the popular designs. You will use some 7-segment displays in ECE2 and later in ECE 152A.

![LED displays](image)

Figure 1-6 – A few common LED displays: (a) Bargraph (b) 7-segment (c) Starburst (d) Dot matrix.

References

http://en.wikipedia.org/wiki/Light-emitting_diode


[3]  A useful site on voltage multipliers (among other things!)  
Pre-lab Preparation

Before Coming to the Lab

- Read through the lab experiment to familiarize yourself with the components and assembly sequence.
- Before coming to the lab, each lab group should obtain a parts kit from the ECE Shop.
- Review on-line data sheets for parts as needed
- Read through background section and relevant sections of the course textbook

Calculations

- Estimate the resistor values you will need for the circuits in Figure 1-8 and Figure 1-9

Parts List

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<th>Description</th>
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</tr>
<tr>
<td>2</td>
<td>LED, Red diffused, 5mm (T1 3/4) 20mA</td>
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<td>2</td>
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</tr>
<tr>
<td>2</td>
<td>1N4001 Rectifier Diodes DO-41 axial</td>
</tr>
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<td>2</td>
<td>1N746A 3.3V Zener DO-35 axial</td>
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<td>LF351 op-amp DIP-8</td>
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<td>10 Kohm 1/4W, Resistor</td>
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<td>2</td>
<td>PC Mount Tactile push-button switch (PB1)</td>
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In-Lab Procedure

Follow the instructions below CAREFULLY.

☐ Each critical step begins with a check box like the one at the left. When you complete a step, check the associated box. Document your results with each step for inclusion in your lab report.

1.1 Diode I-V Curves and Biasing

Diode Forward I-V Characteristics

☐ Using the 1N4148, build the circuit in Figure 1-7 using the bench power supply as the voltage source. Use your hand-held DMM (or the oscilloscope) to measure the diode voltage and the bench DMM as the ammeter.

☐ Adjust the power supply output until the ammeter reads a current of 10μA through the diode. Record the voltage drop across the diode at this current.

☐ Repeat for 20μA, 50μA, 0.1mA, 0.2mA, 0.5mA, 1mA, 2mA, etc. up to 20mA. You will plot this data in your lab report as described later. How much does the forward voltage drop change for a factor of 10 change in current?

☐ Use this same procedure to measure/record the forward I-V curve of the 1N400x device.

Diode Biasing Calculations

Your measurements demonstrate that the forward voltage drop does not change much over a large range of currents, so we assume a constant drop for bias circuit calculations:

☐ For the circuit in Figure 1-8, determine the value of resistance that will give a diode current of ~10mA, assuming a diode forward drop of 0.7V. Choose the nearest value resistor you can find and verify your design for both the 1N4148 and 1N400x.

☐ Now do the same for the red and green LEDs: find a bias resistor that will give a forward current ~20mA, assuming a forward drop of ~2V. Verify your design by recording the actual current and voltage in the circuit. Is this current sufficient to generate a reasonable level of brightness for the LED? For future work you may wish to experiment a bit to determine/record the minimum current level for a reasonable brightness.

☐ Now let’s try to bias the zener diode in your kit. The design principle is essentially the same except that the diode is intentionally reverse-biased, and we must use the diode’s reverse breakdown voltage in the calculations instead of the forward voltage drop (your kit should have a 3.3V zener). The correct orientation for biasing a zener diode is shown in Figure 1-9. Determine the value of...
resistance that will give a diode current of \( \sim 10\text{mA} \), then build the circuit and record the resulting diode voltage and estimate the actual current from Ohm’s law.

- Using the same zener circuit, gradually lower the power-supply voltage and monitor the diode voltage drop. At what supply voltage does the diode voltage depart significantly (say, 20%) from the value measured above?

**Diodes in Series**

Since forward-biased diodes have a relatively constant voltage drop, series combinations are sometimes used in circuits to set a certain DC level or shift it up or down by a fixed amount. Consider the circuit in Figure 1-10; can you predict the output voltage?

- Construct the circuit in Figure 1-10 using 1N4148s or 1N400xs and record the output voltage. Vary the supply voltage \( \pm 2\text{V} \) and record how much the output voltage changes.

Clearly a zener would be more economical for larger voltages. In any case it is important to remember that diodes only maintain the constant voltage drops if the circuit permits enough current to flow through them! The next step illustrates this point:

- Using the decade box at your bench, place a load resistor across the output of the previous circuit as shown in Figure 1-11. Starting with a load resistance of \( 1\text{k}\Omega \), steadily decrease the resistance until the output voltage deviates by more than 20%. Can you understand what is happening? For large load resistance the diodes “clamp” the output at 3 forward voltage drops, but for smaller load resistance the bias current is shunted through the load and the circuit behaves more like a resistive voltage divider.

- Naturally you can cascade LEDs in series too, they just have a larger threshold voltage and often need a specific minimum current for good visibility. In the circuit of Figure 1-12, what supply voltage is required to keep the devices biased at \( \sim 15\text{mA} \)? Build the circuit to verify your prediction.

**Diodes in Parallel**

You might think that diodes in parallel would be useful for splitting a large current among a number of smaller devices, but unless the diodes are very well matched, one device ends up carrying most of the current. This is because the diode current depends exponentially on the ideality factor and temperature, so small differences in device parameters or environmental conditions can lead to rather large differences in current.
between devices. Consequently the parallel connection of Figure 1-13a is considered bad practice. As a general rule diodes or LEDs in parallel each one should have its own bias resistor, as shown in Figure 1-13b. A possible exception is within an integrated circuit where we can often count on the devices being well matched.

On the other hand there is some merit to the use of anti-parallel diodes, that is, diodes that are in parallel but with an opposite orientation of cathodes. In the next section you will build a limiter circuit that uses this configuration. Figure 1-14a shows a how anti-parallel LEDs can be used to create a polarity indicator, giving a visual display of the polarity of the supply voltage. Such devices are packaged and sold as “bi-color” LEDs. A variant of this idea is the bicolor/tri-state LED shown in Figure 1-14b; this three terminal device includes two LEDs of different color that can be switched on and off independently.

![Figure 1-14](image)

Figure 1-14 – (a) A current polarity indicator using two LEDs (dashed box represents a part packaged and sold as a “bi-color” LED). (b) Configuration for bi-color/tri-state LED.

### 1.2 Clipping Circuits and Rectifiers

**Clippers or Limiters**

Thus far we have been working with DC signals, let’s switch gears now to AC signals. Consider the circuit in Figure 1-15 with a sinusoidal input voltage. When the signal exceeds the diode forward voltage drop the diodes will conduct, restricting the output voltage to the range $V_{out} < 0.7\,\text{V}$. This is sometimes called a “clipper” circuit because the tops of the sinusoidal waveforms (signals exceeding 0.7V in magnitude) appear to be clipped off. It is also called a “limiter” for similar reasons. This is useful in some applications, for example at the input of a sensitive high-gain amplifier or wireless receiver where the input signal needs to be limited to prevent overdriving the amplifiers.

- Construct the circuit in Figure 1-15 using the 1N4148s. Set the function generator to produce a 4VPP (peak to peak) sine wave at a frequency of 400Hz for $V_{in}$, and set up the oscilloscope to measure $V_{in}$ on CH1 and $V_{out}$ on CH2.
- Record/sketch the input and output voltages shown on the oscilloscope. (Make sure you align the axis of CH1 with the axis of CH2 and use identical vertical scales.) Label your graph and note the maximum and minimum values of the input and output signals.

![Figure 1-15](image)

Figure 1-15 – A simple bipolar limiter
Zener-Based Clamp

Figure 1-16 illustrates a functionally similar circuit using two zener diodes. In this case the output is limited to a voltage that is the sum of the zener breakdown of one diode and the forward voltage drop of the other.

- Construct the circuit in Figure 1-16. This time set the function generator to produce a 12Vpp (6V amplitude) sine wave @ 400Hz for $V_{in}$.
- Record/sketch the input and output voltages shown on the oscilloscope, again marking key features of the plot (max/min values, time-scales, etc).

Half-Wave Rectifier

A “rectifier” circuit is also a kind of clipping circuit except that the diode is configured to clamp the output to only positive or negative voltages. Figure 1-17 illustrates “half-wave” rectifier that passes only the positive half of a sinusoidal signal:

- Construct the circuit of Figure 1-17 using a 1N400x, and set the function generator to produce an 8Vpp sine wave @ 400Hz.
- Record/sketch/annotate the input and output voltages shown on the oscilloscope. You should observe something like the waveforms shown in Figure 1-18.
- Decrease the amplitude to 2V p-p and repeat: do you see evidence of the diode forward voltage drop? Describe.

“Rectification” is an old term that describes the process of converting AC signals into DC. By allowing only positive voltages to pass through, a waveform with a non-zero average (DC) level is produced. This forms the basis for many simple DC power supplies and is one of the most common uses of diodes. But rectifiers have other uses, for example as signal-level detectors in RF circuits, or to demodulate AM radio signals. Figure 1-19 shows another common use of a rectifier diode to implement a cheap “three-way” switch used in some indoor lamps.

Capacitive Smoothing

For a true DC output we need to “smooth out” the rectified AC signal; this can be done with a capacitive load as in Figure 1-20:

- Connect a 1μF capacitor across the output of your half-wave rectifier circuit (in parallel with the 10kΩ resistor). Be sure to hook up the capacitor
with the correct polarity. How does the waveform change? Explore the influence of frequency on the waveform. Can you explain the results in terms of the RC time constant of the load? There are some slides on the course web-site to help here.

□ Repeat with a 10uF and 100uF capacitor. Describe the results.

**Full Wave Rectifier**

By adding two more diodes as in Figure 1-21 we can make a circuit that gives a positive output for all parts of the input waveform, as shown in Figure 1-22.

You are not required to build this circuit here, because we will return to it in the next lab as part of our linear power supply. But if you finish early you might find it instructive to build it anyway, using LEDs for the diodes and driving it with a very low frequency input signal (1 Hz or less); the diodes will then light as they conduct, effectively illuminating the current path on each part of the AC cycle. Notice one rather important point about the full-wave rectifier: the input and output voltages do not share a common reference! For this reason you can not monitor the output voltage on an oscilloscope using the configuration shown in Figure 1-21

![Figure 1-21 – Full-wave rectifier.](image)

1.3 **Diode Voltage Multipliers**

**DC Restorer Circuit**

Interchanging the position of the diode and capacitor in the previous rectifier circuit gives Figure 1-23. The circuit operation is essentially the same: the capacitor will charge up to a nearly constant DC voltage \( V_p \), but now the output voltage is taken as the sum of the input voltage and capacitor voltage. So for zero-average AC inputs that vary between \( \pm V_p \), the output signal will then vary between \( -0V \) and \( 2V_p \). In other words, the output signal is a level-shifted version of the input signal. This is sometimes called a DC restorer circuit.

□ Construct the circuit using the 1N400x (be sure to use the correct polarity on the capacitor). Use an 8Vpp sine wave @ 400Hz.

□ Record/sketch/annotate the input and output voltage waveforms. Make sure to align the 0V reference of CH1 with that of CH2.
**Voltage Doubler**

The DC Restorer circuit has multiple uses. One interesting possibility is to follow it by a half-wave rectifier, yielding twice the DC voltage that was obtained in the earlier half-waver rectifier. Let’s try this:

- Construct the circuit of Figure 1-24 using 1N400xs and the 1μF capacitors. Note the large load resistance.

- With the same 8VPP sine wave @ 400Hz used in the previous step, record/sketch/annotate the input and output waveforms. Of particular interest is the value of the output DC voltage relative to the peak AC input; compare this with your capacitively loaded half-wave rectifier earlier.

- Now decrease the load resistance to 1kΩ; is there a degradation in the output voltage? If so, can you compensate by increasing the capacitance in the circuit? Try it! The capacitors store the charge that ultimately flows into the load, so the only way to supply more current is to increase the stored charge.

**Cockroft-Walton Multipliers**

By cascading voltage doublers in a certain way we can continue to increase the output voltage; this is illustrated in Figure 1-25. These circuits are called *Cockroft-Walton voltage multipliers*. Using a large input voltage and many stages of multiplication, DC voltages up to 2 MV (2 million volts) have been demonstrated using such devices.

![Cockroft-Walton Multipliers](image)

Vin | Vout
---|---
Vin | Vout

Figure 1-24 – Voltage doubler circuit.

Vin | Vout
---|---
Vout

(a)         (b)

Figure 1-25 – (a) The voltage doubler of Figure 1-24, just drawn differently. (b) A cascade of $N$ doublers, yielded an output voltage of $2V_p$.

The analysis of Cockroft-Walton generators is a little tricky but it can be shown that most of the capacitors in the circuit will have a voltage of $2V_p$ across them. So for high-voltage operation where the input AC signal is large, the voltage-handling capacity of the capacitors becomes an important design issue, as well as the reverse breakdown voltage of the diodes. Obviously a 2MV generator would require some very special diodes and capacitors!

As a point of interest, Figure 1-26 illustrates a cheap little “ion generator” kit that uses a Cockroft-Walton design with a cascade of 15 voltage doublers. With a 120VAC input (120V rms = 170V peak) this circuit generates over 5000V, and when applied to a thin/sharp wire electrode the resulting high fields can ionize the air around the electrodes. This kind of

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3 DIY kit 57, see [http://kitsrus.com/kits.html](http://kitsrus.com/kits.html)
circuit finds use in static-sensitive work environments since it generates charges that can subsequently neutralize other charged objects or surfaces. Note that in this circuit the capacitors are rather small and there are a few large resistors in series with the output that safely limit the amount of current.

**Congratulations!**  
**You have now completed Lab 1**  

Keep all your leftover electrical components!

**Notes on the Report**

You do not need to regurgitate every measurement outcome in your report! Just include important points and answer key questions that were posed in the steps. Some especially important items for inclusion and discussion:

- **I-V Curves**: Include the I-V curves you measured, using Excel or some similar program, and fit your data to the exponential function (1.2) to determine the ideality factor and saturation current. A handout is posted on the web explaining how to use Excel.

- **Diodes in Series**: the important concept here is that the diode voltage drops add up in series, but the “regulation” of the voltage drop is imperfect and depends on the bias current. Discuss how much the output changes in Figure 1-10 with respect to variations in the supply voltage, and how the load resistance in Figure 1-11 impacts the output voltage regulation.

- **Clippers and Limiters**: the key idea is to use the “one-way” characteristic of the diode and associated voltage drops to clip or shape waveforms in some desired way. Discuss and illustrate the behavior of the circuits you built. Using what you now know, could you design a new circuit that clips a waveform at +3.6V and -0.7V?

- **Rectifiers**: these are important in many power-supply circuits. Present your results for the half-wave rectifier and discuss the selection of a capacitor to “smooth” the output to a nearly constant DC value for a sinusoidal input signal.

- **Multipliers**: present your results for the DC restorer and doubler and discuss the impact of the load resistance and capacitance.

As always, be concise. Some descriptions or analyses may only require a sentence or two to get the point across. The lab report is not meant to be onerous busy work, it’s meant to help you sort-out the key points of the lab, much like preparing a “cheat sheet” for an exam helps you organize key concepts in the textbook and lecture.