ECE20007: Experiment 10

Semiconductors: Diodes and Protection Circuits

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1 Application

When designing any circuits for almost any application, you will want to ensure that your sources (such as batteries that may be sensitive) and your loads (such as picky sensors or motors) are well protected, and even protected from each other. Throughout the labs so far, there is a decent chance that you have accidentally damaged some components such as lamps or resistors, blown some fuses, or even popped a capacitor. Using a simple protection circuit with a diode likely would have prevented these situations from happening, and understanding how to properly setup the protection (as well as understanding the sacrifices that need to be made to do so) will allow you to protect your setups wherever you may need.

Almost every personal electronic device we use relies on DC power. This is fine, but the voltage we get out of the wall is AC, so we need to find a way to change that current to DC. Not only can we protect circuits with diodes, but we can also regulate and rectify our input sources by turning our AC input into DC and setting the proper voltage for our loads. There are still sacrifices that need to be made here, but the output is well worth the cost.

2 Experiment Purpose

This lab is going to be your first step into semiconductors, a branch of electronics that is responsible for your extremely fast computers and even your mobile phone. The tricky part is that semiconductor components, such as diodes and transistors, do not necessarily obey Ohm's Law by themselves, meaning they are non-ohmic devices. That said, we can still use Ohm's Law to analyze the components and understand their characteristics, the advantages they give us, and the drawbacks that come with using them.

3 The Diode

An ideal diode is a 2-terminal device that allows current in only one direction. The symbol for this device can be seen in Figure 1. The Anode is defined as the (+) side of the diode and the Cathode is the (-) side of the diode.

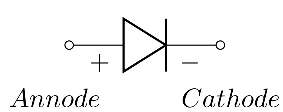


Figure 1: Diode Symbol

If current flows in the direction that the diode "points" (from the Anode to the Cathode), the diode is said to be "forward biased" or "on." The voltage drop across the ideal diode is 0V, a short circuit. If the voltage across an ideal diode is such that the Cathode to Anode voltage is positive, the diode is said to be "reverse biased", or "off." When reverse biased, no current flows through the diode and the diode looks like an open circuit. This is a component with "polarity" associated with its operation. Unlike resistors, inductors, and non-polar capacitors, the diode connections are not interchangeable in a circuit.

3.1 The P-N Junction Diode

A device that approximates the ideal diode is a semiconductor junction. We can introduce impurities into semiconductor materials (called "doping") to create current carriers in the structure—electrons for N-type and "holes" (absence of electrons) for P-type. If we join some P-type material to some N-type material, we create a semiconductor junction (a lot more theory and math for the full story). The semiconductor diode junction has a transition region between the P-type and N-type materials, called the "depletion" region. These relationships can be seen in Figure 2.

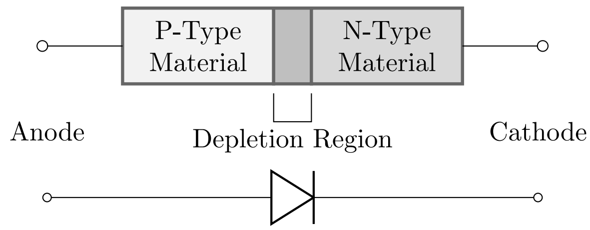


Figure 2: P-N junction diode with depletion region.

The electrical carriers (electrons and holes) have been depleted from this region. If we apply a reverse bias voltage to this diode, the depletion region grows wider and no current flows, similar to the ideal diode. If we apply a forward bias voltage to this diode, the depletion region shrinks until it is gone and current starts to flow. This is similar to the ideal diode, but a non-zero voltage is required to cause the diode to conduct current, referred to as the "forward bias voltage".

There are various types of semiconductor materials; silicon (Si), germanium (Ge), galium-arsenide (GaAs), silicon-carbide (SiC), and various other semiconductors. Silicon is the predominant semiconductor for general purpose diodes, with devices found in your lab parts kit. The Silicone diode deviates from the ideal diode in several ways, and we will explore those differences in the lab.

Other than the Silicon diode, there are a variety of other diodes that are used on a regular basis, all with their pros and cons, including the Zener, Schottky, and a diode you are likely already familiar with at least by name, the light-emitting diode.

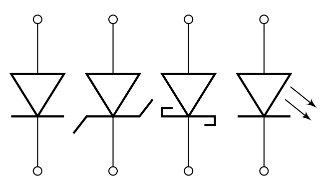


Figure 3: Diodes from left to right: Silicon, Zener, Schottky, light-emitting (LED).

3.2 Zener Diode

A Zener diode, named after Clarence Zener, has the electrical characteristics that allows current to flow in the reverse bias condition (backwards) when a certain reverse voltage is reached, called the Zener Voltage. Zener diodes of various voltage values can be manufactured. This allows us to use a Zener diode as a crude form of protection on a circuit buy placing a Zener diode as a shunt (in parallel) with a load, since if voltage in the circuit exceeds the Zener voltage, all of the excess voltage gets clipped by the diode. Often the Zener voltage is specified at a specific current value, so carefully review the data sheet for the desired operating conditions.

Zener diodes are very low cost diodes, and allow for simple voltage protection, but by definition, since some voltage is not going to the load, the diodes are inefficient by design, meaning there is unnecessary power loss. Zener diodes also cannot usually handle the same amount of current as a standard silicon diode.

3.3 Schottky Diode

The Schottky diode, named after Walter H. Schottky, is semiconductor diode formed by the junction of a semiconductor and a metal. The discussion is similar as to that of the P-N junction diode, except that one side of the diode is metal and the forward bias voltage is therefor half of the voltage of the P-N diode.

Thanks to the low forward bias voltage, Schottky diodes can switch on very quickly, so their application in high-frequency setups are very helpful, and are often considered more efficient than a silicon diode. That said, they are more expensive to produce which increases cost in a circuit, and their breakdown voltage is often significantly lower than a silicon diode which limits their applications as they will get destroyed if too much voltage is applied to the diode.

3.4 Light-Emitting Diode (LED)

A Light-Emitting Diode (LED) is a type of diode that emits light when current flows through it. LEDs are available for the visible, ultraviolet (UV), and infrared wavelengths, with various forward voltage values for the various colors and wavelengths. The LED electrical characteristics differ for various wavelengths and from the other diodes, and we will explore those differences in the lab.

LEDs are used all over the place and can be made in a variety of sizes, with some strong enough for vehicle headlights and others small enough to make pixels for a high-definition television. However, emitting light is not an efficient process and requires a very large forward bias voltage on the LED to produce light. Adding more LEDs in series increases the voltage demand, which is why LED drivers that you may use to light up your room require a high current and voltage.

Important! Note that the real diodes are not an ideal conductors, so the forward voltage will have some slope due to resistance as well as the diode voltage. The diodes also have some reverse leakage current, so they are not an ideal open circuit.

4 Diode Applications

Diodes have a wide variety of applications in almost any circuit setup. Some of the general applications will be discussed here, but they circuits can be enhanced using other components depending on the application.

4.1 Protection Circuits

As mentioned in the introduction of the reading, it is good practice to make sure that our circuits are safe for us to handle if at all possible and safe for the loads that will be attached to the circuit. Your first thoughts should go to diodes when you have to protect a circuit.

4.1.1 Battery Reversal

Many products that require a battery will have a scheme to prevent the application of the reverse battery voltage to the electronics, which could damage the electronics. The simplest electronic implementation would be to use a diode in series with the battery and the load.

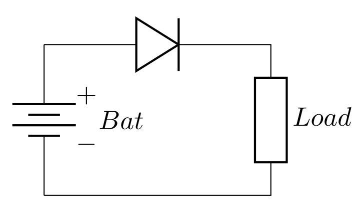


Figure 4: Battery Reversal Protection Diode.

The down side to this protection diode would be the voltage drop across the diode reducing the effective battery voltage to the load. The use of a Schottky diode will serve to reduce the diode voltage drop.

4.1.2 Voltage Clamp

Voltage Clamp diodes will sometimes be referred to as Transient Voltage Suppression (TVS) diodes, often Zener diodes. To protect a circuit, one could place a Zener diode to ground, which limits the max (+) voltage by the Zener voltage and the max (-) voltage by forward biasing the diode in the normal manner:

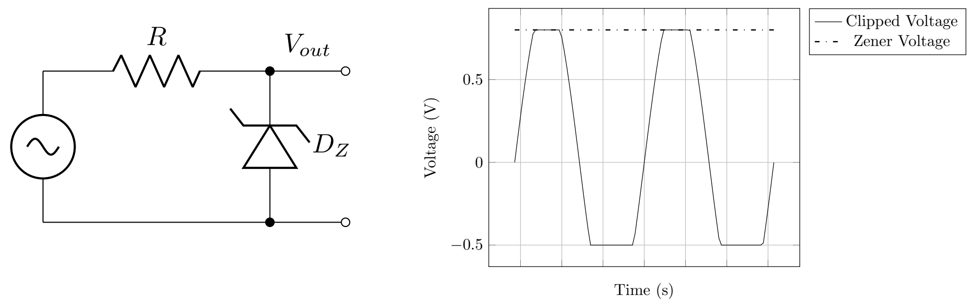


Figure 5: Zener Clamp.

Note that in Figure 11, the (+) voltage is clamped to the Zener voltage and that the (-) voltage is clamped to the forward diode voltage (-0.5V in this case).

Another application is to use protection diodes to prevent an input signal from exceeding the supply voltage rangeand damaging the circuit, such as during an ElectroStatic Discharge (ESD) event. Reverse biased diodes to the power and ground will help clamp the voltage:

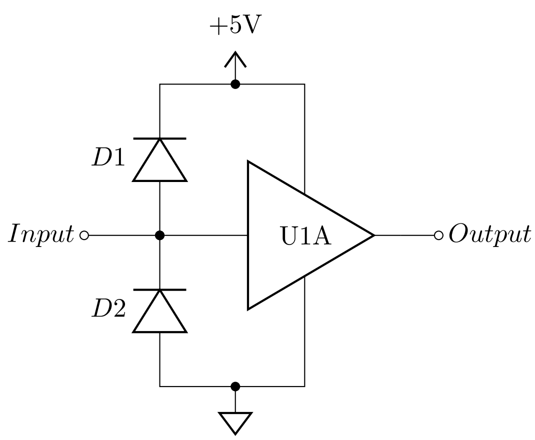


Figure 6: Input Protection Diodes.

D1 keeps the input voltage from exceeding +5V and D2 prevents the signal from going below GND. The circuit, U1A in this case, can be damaged if the Input voltage exceeds a diode voltage above power or below ground, so often the protection diodes are Schottky diodes for the lower forward voltage.

4.2 Power Distribution

In some applications, the system may have dual power options, such as a battery or wall adapter. Often the wall adapter is used to charge the battery, during which time we may wish to power the system from the wall adapter to better allow the battery to charge. The simplest approach is to use steering diodes, as shown in Figure 7.

Typically the AC/DC output voltage is higher (15V in this example) to allow charging of the battery (12V in this example). If the AC adapter is present (15V > 12V), then D1 forward biases, powering the equipment. The battery is at 12V, so D2 will reverse bias and no current will flow from the battery. If the AC adapter is unplugged, then

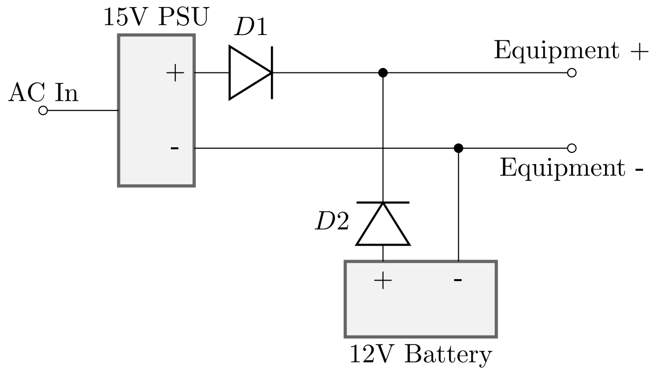


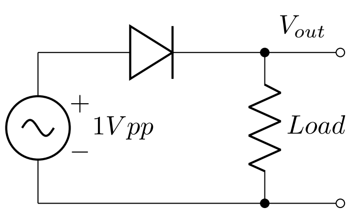
Figure 7: Power Steering with Diodes.

this supply goes to 0V, D1 reverse biases and D2 forward biases, and the battery supplies the current to power the equipment.

4.3 AC Rectification

Please note that the following discussions are simplified a bit, assuming that the diodes are ideal. In real application, the diodes will have a small voltage drop. Please take into account that the rectified voltage will be reduced by 1 or 2 diode drops depending on the configuration.

Utilizing the one way current properties, we can rectify time variant signals, such as AC signals for various applications:



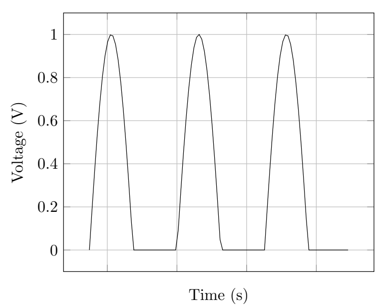


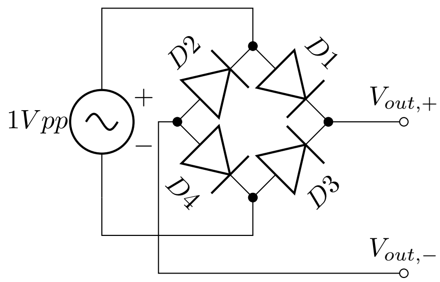
Figure 8: Half-rectified output wave. There is no negative half-cycle of the signal.

Using a single diode, the positive portion of the time varying signal can pass through and negative portion can be blocked. In the case of a sine wave (as shown above), only the (+) part of the waveform is passed, and the (-) part is blocked.

Using 4 diodes, we can make a diode bridge and do full wave rectification as shown in Figure 9.

In Figure 9, if the AC Supply voltage is greater than 0V, D1 and D4 are forward biased and conducting current, and D2 and D3 are reverse biased and "off," or an open circuit. If the AC supply voltage is less than 0V, D2 and D3 are forward biased and conducting current, and D1 and D4 are reverse biased and "off," or an open circuit. Take a moment to walk through both a positive and negative signal in the rectifier to better understand both how the signal moves through the circuit and ultimately ends at the same location regardless if the signal is positive or negative.

Note that there is NO CONNECTION at the intersection below D4 (no dot to state a connection) in Figure 9. Also note that there is not a common ground in this circuit, as measuring V_{out} in reference to the source will only get you half of your signal. Measuring a fully rectified wave with an oscilloscope (at least our oscilloscopes, since our probes are internally grounded) requires differential operations, such as using an instrumentation amplifier or math mode on the oscilloscope. In practice, components only need to have a proper voltage difference between the



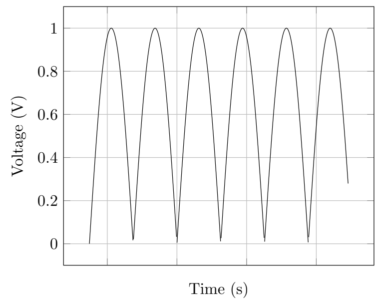


Figure 9: Fully rectified wave. The negative portion of the signal is inverted to the positive.

output leads, so once the wave is rectified (and ideally smoothed out as shown below), it can be used in operation. Adding a low pass filter to the output, we can make useful circuits, such as an Amplitude Modulation (AM) demodulator. Selecting the proper values for R and C, the filter can reject the high frequency "carrier" waveform and output the lower frequency "envelope," in this case the audio signal. If the input signal is a non-modulated sine wave (as close to a pure sine wave as we can get, no other signals affecting it) and the time constant for R and C are sufficiently large, then we can develop a power supply. Below is an example of a full bridge supply.

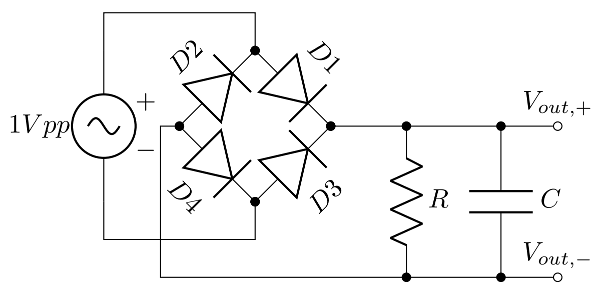


Figure 10: Fully rectified wave with RC filter to smooth the wave at V_{out}.

Please note that the diode bridge will rectify the signal, resulting in only positive voltage. If C is sufficiently large and not discharged much between cycles by R, then we have a DC voltage supply with some AC ripple. Finding C can be done experimentally, or by treating R and C as a timing circuit, with a goal of reducing the amount of ripple (the amount the DC signal fluctuates) between the maximum and minimum voltage values.

$$C = \frac{V_{DC} \cdot T}{R \cdot \Delta V} \tag{1}$$

Where T is the period of the rectified wave in seconds. For example, a USB charging block that gets plugged into the wall to charge a phone or other mobile device has a rectified output voltage of $5V$ with a 5% ripple, or about a $0.25V$ voltage fluctuation. The 120Hz signal coming from the wall outlet will have a rectified frequency of 240Hz, or a period of 4.1ms. If the device that is charging has an equivalent load resistance of $1K\Omega$, the capacitor that would effectively smooth the rectified wave would be about $82\mu F$. Bumping this capacitor to a bit more standard value of $100\mu F$ would be fine, and decrease the ripple even more, but might reduce the reaction time of the circuit. This calculation can be used with a half-wave rectifier as well like the circuit in Figure 8, but the frequency will be the same as the input wave instead of double, effectively doubling the capacitance needed to make an equally smooth signal when compared to the full-wave rectifier.

4.4 Power Regulation

The Zener diodes have historically and still are used to generate voltage supplies using the parts as a shunt regulator. This is done by placing a diode of the desired voltage in parallel with the load and a bias resistor is placed in series to limit the current, as shown below:

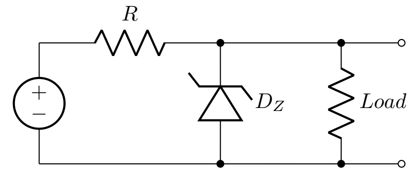


Figure 11: Voltage regulator using a Zener Diode.

A Zener diode is selected with the desired Zener breakdown voltage, and R is calculated to provide sufficient current to the load and to the Zener to maintain the load voltage. The shunt regulator is typically used for loads that are fairly constant and not high current. This looks very similar to a voltage clamp but is being used with a DC source instead of AC.

5 Determining Resistor Pairs for Real Diodes

Diodes are extremely helpful in helping regulate and rectify circuits, but they do come at a cost. As mentioned throughout the reading, diodes require a certain voltage to "turn on," known as the turn-on or forward voltage. When a diode uses that voltage, it appears as a voltage drop similar to what we would see on a resistor. When a diode is turned on, its depletion region becomes very small and current can pass through as if the diode had almost no resistance. The last two phrases may sound a bit counter-intuitive. How can we have a voltage drop without resistance? That is why it is stated that diodes are non-Ohmic components, or that they do not follow Ohm's Law. This phenomenon has its limitations, just like every other component in electronics.

One of the most important things to monitor with a diode is the current going through it, which is why most of the lab tasks for the lab involve making IV curves for the diodes. Diodes are rather sensitive with how much current they can handle and fail in a variety of ways if the current flowing through them is too high. Take a look at the datasheet for the 1N4148 diode, a standard silicon diode. The 1N4148 has a forward voltage of 1V, but can only handle 300mA at an absolute maximum current. If we were to put the diode in series with a source without any sort of current-limiting device, such as a resistor, Ohm's Law tells us the current would surely exceed the current limit of the diode since we would have 5V and 0Ω, leaving current to move to infinity. To play it safe, let's assume that we are using a 5V source, and expect only 150mA (the maximum average current through the diode) to pass through the diode. To determine the resistor that will limit the current through the diode to 150mA, we will first subtract the voltage drop from the diode from our total voltage, and then use Ohm's Law to determine the resistance of the circuit.

$$I_D = \frac{V_S - V_D}{R_{reg}} : \; 150mA = \frac{5V - 1V}{R_{reg}}, \;\; R_{reg} = 26.66\Omega \tag{2}$$

We remove the diode forward voltage from the equation because the voltage that is consumed by the diode does not impact the current in the circuit, meaning we only have to focus on the remaining voltage. If you add more diodes in series, their forward voltages keep dropping the current-limiting voltage too. Having two 1N4148 diodes in series would increase the total forward voltage drop to 2V, which means you would only need 20Ω to limit the current to 150mA. $20 - 27\Omega$ may seem like a really low resistance for a circuit, but it would limit the current in the circuit to 150mA. Depending on your voltages and the type of diodes you are using, the resistances might be quite low. A television remote that uses a AAA battery (1.5V) with an IR LED (forward voltage of 1.2V) only needs a 15Ω resistor to limit the current to the required 20mA!

Prelab

6 I-V pots

Often the data sheets for discrete semiconductor parts will have V-I plots for the components so that the engineer can estimate the electrical operating characteristics for a given part. In the lab, these voltage-current values will be explored. Each device has data for an operating voltage and/or current range specified. We will be placing a resistor in series with the diode to monitor the current ($I = V/R$). Review the data sheets for the various diode types from your kit and select an appropriate resistance value. A possible current range may center on the current for the forward voltage found in the Electrical Characteristic table. We will be using the function generator to generate a low frequency waveform to drive the circuit and monitor the voltage(s) on the scope. Assume a maximum drive voltage of about ±10V, so select a resistor to provide a reasonable voltage across the current sense resistor.

Si Diode – 1N4148
Zener Diode – 1N5226B
Schottky Diode – 1N5819
LEDs – TLHG6400 (Green), TLHY6400 (Yellow), TLHR6400 (Red)

The Zener diode has a voltage range at a specific current. Please use this current for the 3 diodes and size the resistor to allow measurements for a reasonable range of currents (max current of 20mA). We will be calculating the "effective" resistance for the diode by measuring the diode voltage at several current values.

1. Review the data sheets for the parts to determine the expected voltage and stated current values.
2. Select a series current sense resistor to best fit the test conditions. Remember that the function generator has an output impedance. Calculate a resistor for 1N5226B and use it for the 1N4148 and 1N5819, if appropriate.
3. Review the data sheets for the LEDs. Determine the test current for the LEDs. Calculate the appropriate current limit resistance values for the LEDs.

7 Rectification

Figure 8 can also be used for half wave power supply, given that the input waveform is a sine wave and the capacitor is of sufficient value to not allow the load to discharge the capacitor between cycles. Assume that the load is 1KΩ and the frequency is 1kHz. Calculate a value for the capacitor to ensure that the value does not sag below 10%. Use Spice to do a simulation, assuming that the input voltage is 10Vpp and the diode is a 1N4148.

In Lab

8 Diode IV curves

In this part of the lab, we will be generating V-I curves for the various diodes. We will test 2 “identical” circuits with the diode and resistor swapped on 1 set to allow ground reference for a diode and a resistor so that we can do X-Y plots on the scope due to the GND issues with the probes.

When constructing your circuit, make sure you are setting your diodes in the right direction. Axial diodes, or diodes that have their wires coming off of either side like a resistor, will have a stripe or bar on the cathode side of the diode, or the side that goes towards ground. Capped LEDs with the leads coming off of the same side will have a flat edge on the side that goes towards ground.

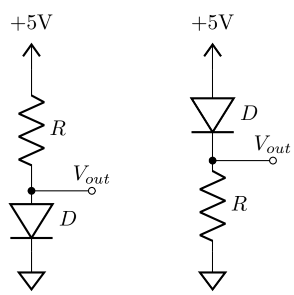


Figure 12: Diode measurement setup using 2 circuits. These circuits should act identically in operation.

Bonus option (+10%): Instead of using 2 circuits as shown above, develop a method to use only 1 circuit and use methods described in previous labs, such as different oscilloscope operations, or physical circuits (Look up Instrumentation amplifier, you have one in your lab kit (INA121)).

Regardless of the method that you choose to perform this experiment, explain why these approaches are necessary. For example, why would we bother making two “identical” circuits as shown in Figure 12?

Note: The below steps are written in reference to the “normal” version of the lab using the two identical circuits in Figure 12. If you decide to use a different method for extra credit, please make sure to adjust accordingly.

8.1 DC analysis of a Diode: Finding Turn-on Voltages

1. Use a lab power supply and connect the calculated 2 identical circuits for the 1N4148, 1N5226B, 1N5819, and the light emitting diodes used above. Use resistor values that are appropriate for each diode (calculated in Prelab). This will be done one diode type at a time, and repeated for each type of diode. It might be worth starting with the LEDs so you can see when the effect occurs more visually.
2. Adjust the supply voltage until the desired current is observed, or until the diode “turns on”. **Important!** If you are measuring both circuits in Figure 12 at the same time, you will be drawing double the current from the source. The current going through one diode will be HALF of the supplied current shown on the PSU. Don’t overload your diodes!
3. Measure the voltage at V_{out} in each circuit, once across the diode and once across the resistor, then record the value.
4. Generate a spreadsheet with the values measured.
5. Record your observations on the diode voltage values.
6. Repeat the measurements for all 6 diode types. Also do a reverse-bias measurement set for the Zener Diode.

8.2 Using an Oscillosocpe to view an IV curve

Swap out the PSU for a function generator and connect the circuits. Set the scope to X-Y mode and connect scope probes to the diode to GND and another to the resistor to GND. Use the function generator to provide a low frequency (50-500Hz), 10Vpp-20Vpp periodic waveform (sine or triangle) to the circuits and observe the X-Y plot on the screen. Adjust the function generator and scope settings to good representation. For the 1N4148, 1N5226B, 1N5819, and 2 of the light emitting diodes used above (your choice). Use resistor values that are appropriate for each diode (calculated in Prelab).

1. Capture a screenshot of your display using BenchVue or using a USB drive that can be plugged into the oscilloscope. **DO NOT take a picture with a camera!** Images like these can cause glare and inconsistent resolution.
2. Export your oscilloscope data as a .CSV file and import into your preferred data analysis tool (spreadsheet editor, MATLAB, Python...).
3. This is technically a Voltage-Voltage plot right now. Use your preferred data analysis tool to generate and plot an I-V curve using the data exported from the oscilloscope.
4. Repeat the measurements for the 4 diode types. Also do a reverse-bias measurement set for the Zener Diode (apply the voltage in the opposite direction).
5. Is the X-Y plots what you expected? Do they match the cutoff locations as expected from the data sheets? If not, why not?

9 Rectification

1. Construct the circuit in Figure 8 using a 1N4148 diode and a 1KΩ resistor for the load. Use the function generator to generate a sine wave of 1kHz and 5Vpp.
2. Use the scope to capture the waveform across the 1KΩ load.
3. Capture a screenshot of your display using BenchVue or using a USB drive that can be plugged into the oscilloscope. **DO NOT take a picture with a camera!** Images like these can cause glare and inconsistent resolution.
4. Is the image what you expect? If not, why not?
5. Add the calculated filter capacitor to the output.
6. Capture a screenshot of your display using BenchVue or using a USB drive that can be plugged into the oscilloscope. **DO NOT take a picture with a camera!** Images like these can cause glare and inconsistent resolution.
7. Is the image what you expect? If not, why not?

10 Bonus Task: Diode Steering (+10%)

1. Construct the circuit in Figure 7 using the two 1N4148 diode, a 1KΩ resistor for the load, and 2 power supplies for the AC IN and battery. Adjust the power supplies independently between 2V and 6V and record the load voltage.
   Note: This should be 5 x 5 entries.
2. Are the results what you expected? If not, why not?
3. Repeat the tests with two 1N5819.
4. Are the results what you expected? If not, why not?