Experiment #06
Semiconductor Diodes and a Rectifier Circuit

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1 Objective

The most basic semiconductor device is a junction diode. One of its most common applications is in rectifiers used to convert AC to DC voltages. You probably (unknowingly) use these every day. In this experiment you will measure the unusual DC properties of a diode, and then build and test a simple rectifier circuit. A version of this rectifier circuit will be an important part of your final construction of an AM radio.

Tip 1

Note there is no notebook template this week! As you read through these instructions to prepare, organize a skeleton notebook with some sections, and code blocks you think you will likely need to use.

2 Learning Goals

After finishing the lab you will:

- know the I-V characteristics of a diode, forward and reverse biased
- know how to fit to a model for this IV characteristic
- gain experience designing and building a rectifier

3 The semiconductor diode and its I-V characteristics

Introductory material on the physics of semiconductor devices can be found on Canvas in a file called Semiconductorsnotes.pdf. This will give you background on how the device works, but is not essential to performing the experiment. A junction diode is the simplest semiconductor device and is used for many purposes such as converting of electrical energy into light (LEDs), converting light into electrical energy (solar cells), light sensors, particle detectors and rectification.

The junction diode is formed at the interface between an n-type semiconductor on one side and a p-type semiconductor on the other, with electrical connections to each side. The different electronic properties (doping) between the two semiconductors lead to a non-linear and asymmetric relationship between current and voltage across the diode. This is very different than a resistor where the $I-V$ relationship is highly linear (Ohm's law) and symmetric. Under ideal conditions and with certain restrictions the relationship between current and the applied voltage ($I - V$ curve) for a diode has an exponential form:

$$I = I_0[\exp(eV/k_BT) - 1] \tag{1}$$

where I is the current passing through the diode, I_0 is a constant depending on the properties of the diode, V is the voltage drop across the diode, T is the temperature in Kelvin, e is the charge of the electron, and k_B is Boltzman's constant. Note that the current is zero when $V = 0$. When the diode is reverse-biased ($V < 0$) the current is exponentially suppressed as a function of the magnitude of V whereas when it is forward-biased ($V > 0$) the current increases exponentially with applied voltage.

The goal in this first section of the experiment is to measure how the current passing through the diode varies as a function of the voltage drop across the diode (i.e. the $I - V$ characteristics) and thus test how well Eqn. 1 describes the data.

3.1 Part 1: Measuring the diode characteristic I-V

We will need a variable DC voltage source to measure the I-V characteristic of the diode. There are two options: (1) use the DC power supply on your breadboard and the potentiometer to build a variable power supply, (2) use the function generator to create a voltage ramp. Option 1 is described in detail below. Option 2 follows very closely the approach of using the square wave in the RC and LRC time domain labs, but using "ramp" to generate a saw-tooth or triangular waveform; note that you will need to measure both the input voltage (from the function generator) and the output voltage (across the resistor, proportional to current).

3.1.1 Powering a breadboard

To create a variable power supply, you will use the DC power supply attached to your breadboard (see fig. 1). This DC supply is powered by USB, so you will need to plug in the USB cable (be careful with the USB connection on the board! it is fragile!). Remember, that the breadboards have two sets of "rails" along the edges which are connected; the DC supply plugs into these rails to allow you to access the voltages supplied. Some boards are only continuous half-way and require jumper cables to connect along the full length. When the board has power green and red LED lights will turn on. The power supply provides +5V and -5V which you will need for the remaining experiments. The supplies have the output voltages labelled (albeit in small lettering). It is important to keep track of which voltages are applied to which rails including ground (GND) and the +5, and -5, or in some cases a variable voltage source tuned by a potentiometer on the board itself.

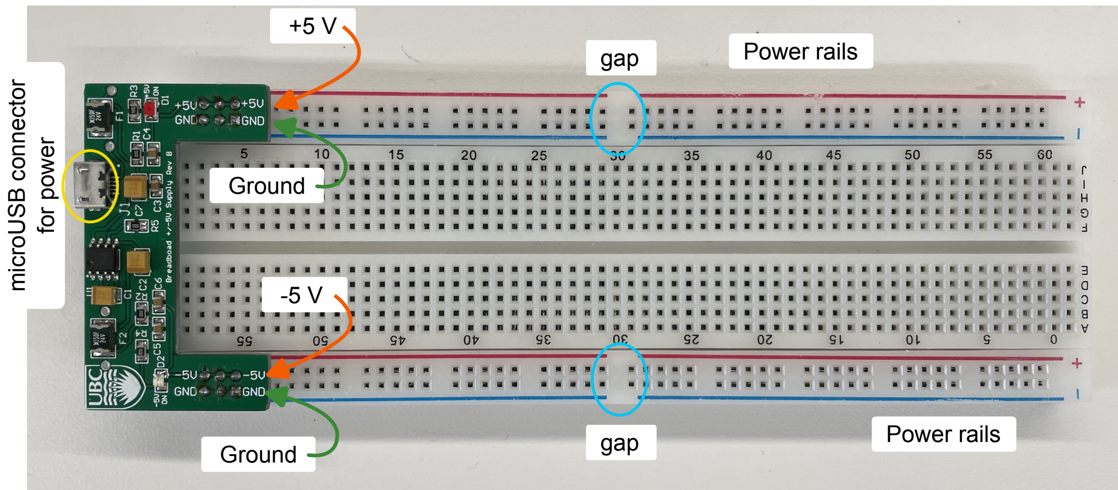

Figure 1: Protoboard used in this course. The power supply is on the left hand side, and is powered by a USB cable. If the USB cable is not already plugged in, do so gently as the connectors are only secured with solder and are easily damaged. The top two rows of holes and bottoms two rows are the "power rails", and are electrically connected horizontally. The bands in the centre have vertical connections in columns of five holes.

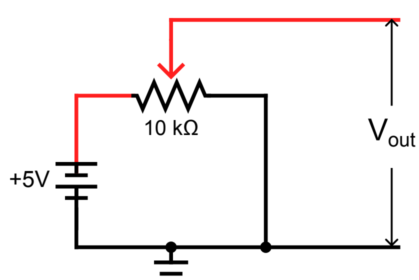

Figure 2: Circuit diagram to make a variable DC voltage source

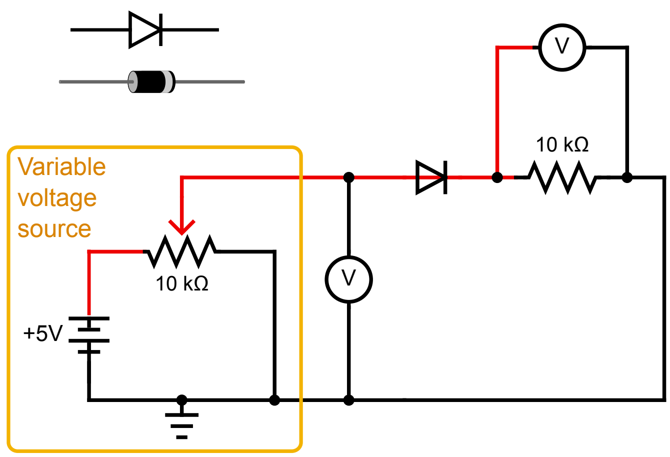

Figure 3: Circuit diagram to make a variable DC voltage source

3.1.2 Making a variable power supply

You can make a variable voltage source using the +5V power supply from the protoboard along with a variable resistor. This is shown in in Fig. 2. To do this follow the steps below.

Alternatively, you can use the function generator to create a linear voltage ramp using the "ramp" function: this will be a less intuitive measurement, and skips building a circuit with 2 blocks, but has the advantage of providing more data points. Try building the variable power supply first and taking some data this way for experience even if you plan to use the function generator.

- Plug in the power supply and use a small jumper cable to connect the +5V line to the right end of the variable resistor. Complete the circuit for the voltage divider by installing a small jumper cable from the left side of the variable resistor to ground. The current path will be from the +5V line, between the two ends of the variable resistor and then back to ground.
- Use the DMM to measure the voltage drop from the middle pin to ground. You should see a voltage that varies when you adjust the variable resistor with a small screwdriver.

3.1.3 The diode circuit

- Check which orientation of the diode corresponds to forward biasing. The DMM can be used to verify the polarity of the diode. Use the DMM's diode mode; connect the positive (red) side to one end of the diode and the negative (black) end to the other. If it is forward biased it will read approximately 0.6 Volts. If it is negatively biased, the DMM will be overloaded. The meaning of this is that at about 0.6 V a Silicon diode's current rises extremely fast (the exponential term in the equation) in the forward direction. The current is almost zero in the reverse direction.

- Use your variable voltage source to build the rest of the circuit in Fig. 3. Start with the diode forward biased (i.e. with current flowing from the end without a bar to the end with a bar).
- The 10 kOhm resistor in series with the diode provides a way to measure the current passing through the diode (via Ohm's Law). It also serves to limit the current so the diode will not be damaged.
- The variable voltage from the middle pin of the variable resistor is the voltage being applied to the diode and resistor in series. This is the input voltage applied to the circuit, V_{in}.
- By measuring V_{in}, and also the voltage drop across the 10 kOhm resistor V_R, you can determine the voltage drop across the diode ($V_d = V_{in} - V_R$).
- The current is simply V_R/R, where R is the resistance of your 10 kOhm resistor.

Investigate the $I-V$ characteristics when the diode is forward biased. i.e. when the current increases exponentially as a function of the voltage drop across the diode. Do a quick sweep of values of V_{in} first, to be sure you are forward biased. You should find an applied voltage where the current (and thus V_R) rises rapidly. You will need to record both your V_{in} and V_R values (with uncertainties) and use these to calculate the voltage across the diode and current running through the circuit. Make sure to get lots of points around the "knee" in the curve which is the region best described by 1.

Checkpoint 1

Once you have built the circuit and explored the qualitative behaviour, call a TA over to review your plan to get the data you need.

Analysis: Use a least squares fit to determine how well your data is described by Eqn. 1. Take another look at this equation and note that temperature is one of the variables in the exponent: you can use the reading on the thermostat for the temperature of the room. The free parameters are Boltzman's constant, k_B, divided by the electric charge, e (k_B/e) and I_0 in units of Amps. Calculate the expected value of k_B/e to use as the "guess" and compare with your fit results.

Describe how and where your measurements deviate from the theory given by Eqn. 1. Reduce the fitting range to see how this effects the fitted parameters and quality of the fit. Estimate the uncertainties in the two fitted parameters. Compare your fitted value of k_B/e with the literature value. What is your conclusion about the measurements and how well the data is described by the simple theory given by Eqn 1? Under what circumstances does this function describe the data reasonably well?

Tip 2

You have two options here: a non-linear fit of eqn. 1, or you can linearize the data and do a linear fit like in the week 5 analysis.

Checkpoint 2

Perform an initial fit and discuss with a TA if you need to obtain more data.

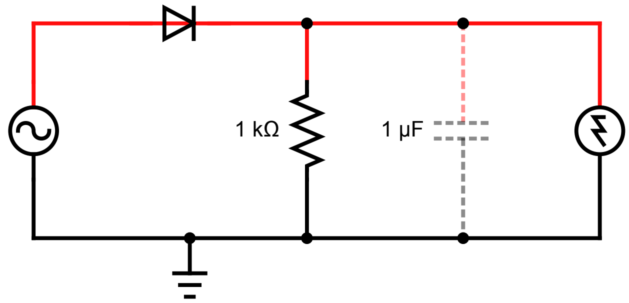

Figure 4: Circuit to measure rectification properties of a diode. Initially build the circuit without the capacitor, but leave space to add it in parallel as shown here.

3.2 Part 2: Use of the diode to make a rectifier

It is sometimes necessary to convert an AC voltage into a DC voltage, a process called rectification. To demonstrate rectification set up the circuit in Fig. 4 on the protoboard. All you need is one Si diode and a 1 kOhm resistor. Install them on the protoboard so they are connected in series and then to ground as shown in Fig. 4.

To measure the rectification properties of the diode:

- Apply a 60 Hz sinusoidal voltage to the diode with an amplitude of 2.5V and no offset Monitor the input voltage signal $V_{in}(t)$ (the voltage across both the diode and resistor) on CH1 of the scope and output signal voltage $V_r(t)$ across the 1 kOhm resistor on CH2 of the scope. The scope inputs should be DC coupled (this option is found inside the CH1 and CH2 menus). Save data sets of *both* signals.
- Explain the observed $V_R(t)$ based on the $I - V$ characteristics of the diode.
- Now place a capacitor (e.g.1μF) in parallel with the 1 kOhm resistor to ground. Take a picture of your circuit showing the connections and put the image in your notebook. Explain what you observe.
- Make plots of $V_R(t)$ with and without the capacitor and record them in your notebook.

Checkpoint 3

When you have this circuit set up and working, show the circuit and signal to one of your TAs.

The resulting signal, which is non-sinusoidal, should vary periodically between a maximum value V_{max} and a minimum value V_{min}. The ripple, defined as

$$V_{ripple} = \frac{V_{max} - V_{min}}{V_{max} + V_{min}} \quad (2)$$

is a measure of the oscillating part of the signal relative to the time independent part of the signal. Find a resistor with reduces this "ripple" to less than 5%. You can use the cursors to measure this while you are working. The central idea here is to make the RC time constant longer than the period of the 60Hz signal.

Measure R with the DMM and save a screenshot from the oscilloscope (swipe up from the bottom, and select the camera icon with your USB stick connected) of the signal for each resistor you try and put them into your notebook (drag and drop into a markdown cell). Save .csv files of CH1 and CH2 for the final rectifier output with a less than 5% ripple. Re-calculate V_{ripple} from your saved data, and calculate τ from your component values. Comment on how τ compares to the periodicity of the 60Hz signal.

Congratulations! You have just made a AC voltage adapter that converts an oscillating voltage at 60Hz to a (almost) DC voltage.

Before you leave the lab!

Make sure you have:

- a set of I-V data that characterizes the "knee" of the diode
- at least an initial fit of the I-V characteristic to ensure you have enough data in the region needed
- a plot of the diode response to an AC signal
- capacitance measurement of the nominal $1\mu F$ capacitor with the DMM
- screenshots of the rectifier output and measurements of V_{ripple} with different resistances measured by DMM
- final rectifier dataset with $V_{ripple} < 5\%$