
Experiment II:

Diodes and the Rectification of AM signals

I. References

Horowitz and Hill, *The Art of Electronics*.

Fortney, *Principles of Electronics: Analog and Digital*

Tipler and Mosca, *Physics for Scientists and Engineers*, 5th Ed., Chap 38.

II. Equipment

Digital Oscilloscope

Signal Generator

Differential Amplifier

Digital Multimeter

Resistance and Capacitance Box

Germanium diodes, silicon diodes, and LEDs

III. Introduction and Theory

We are going to start the semester by examining a component that you might not have studied before in your physics classes, but you have certainly seen them in your everyday life. **Diodes** are ubiquitous in modern electronics, and light emitting diodes, better known as “LEDs” have recently become common in everything from back lighting in flat screen TVs to energy efficient light bulbs and the headlamps on cars. Most importantly for our purposes, a diode will serve as a “detector” for AM radio signals.

A diode is the simplest example of a **p-n junction**, which forms the basis of all semiconductor devices. Semiconductors have electrical resistivity that varies dramatically with temperature, with incident light, applied voltage, or with a small addition of impurities. More sophisticated semiconductor devices, such as computer processors, contain many p-n junctions ($\sim 10^9$ in fact).

A diode consists of a single junction of two semiconductor materials, called “n-type” and “p-type”, in which the degree of mobility of the electrons is different. N-type semiconductors are crystals in which a small amount of impurity atoms have been added that have one additional electron in the outer shell than the bulk material, for example, adding antimony atoms to bulk silicon. This impurity adds an extra electron that is not used in the crystal bond and is therefore relatively free to move about the material and conduct. P-type materials have impurities added with one less electron in the outer shell, for example adding boron to bulk silicon. This creates a “hole” in the crystal lattice that can readily accept electrons. When p-type and n-type materials are brought in contact with each other forming a junction, the excess electrons in the n-type material can drift into the p-type material, filling the holes in the crystal lattice as shown in the figure below. However, since each material is electrically neutral prior to their joining, the flow of electrons across the junction leaves each side with a net charge, setting up a small potential difference, and consequentially, an electric field.

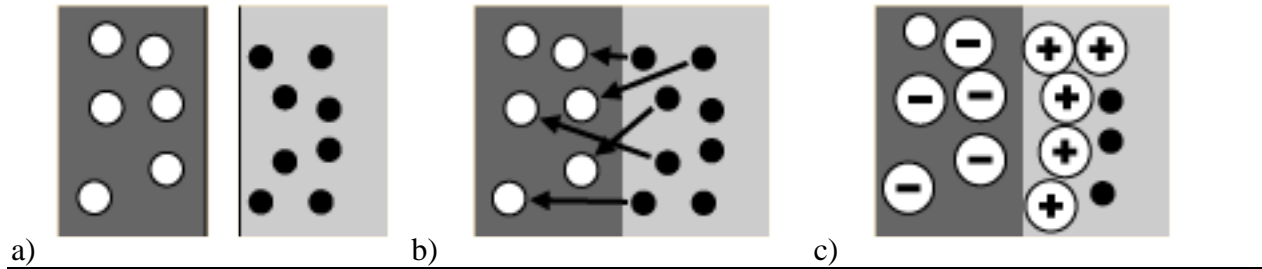


Figure 1: a) The dark gray area represents p-type semiconductor with holes (white dots). The light gray area represents n-type semiconductor with donor electrons (black dots). This is the situation before contact. b) When the materials are brought in to contact, the donor electrons drift into the p-type filling the holes in the crystal lattice. c) This forms a layer of ions near the contact plane and sets up a potential difference across the junction.

Current will not flow through the diode until this potential “barrier” is overcome, but once a sufficient amount of voltage is applied, electrons flow very freely across the junction. Current will not flow across the junction in the other direction, however, except for a small amount of “leakage” through the junction. The symbol for a diode is this;



where the tip of the triangle indicates the direction that current is expected to flow if the vertical line is at a more negative potential than the base of the triangle. The stripe on the diodes that you are using indicates the end corresponding to the tip of the triangle (see also next figure).

The take home message here is that diodes only allow current to flow one way: toward the vertical line in the symbol (cathode). The diode's arrow (going from anode to cathode) points in the direction of forward current flow: from the P-type material to the N-type.

So if that’s all you need to know, why bore you with all of those details? Well, in order to understand some of the cooler aspects of diode applications, like LEDs, you need to understand that inside of them, electrons are falling into holes and releasing potential energy. Also, since most of you are physics majors, and presumably interested in physics, you might enjoy an introduction to the subject.

Unlike resistors, we will see in this experiment the current-voltage (I-V) curve of a diode is highly non-linear. The diode (Fig. 2(a)) is an important and useful two-terminal passive *non-linear* device. The characteristic current-voltage (*IV*) curve of an idealized diode is shown in Figure 2(b). This idealized device will conduct current with zero resistance in the forward direction and allows no current in the reverse direction. For many circuit applications, this ideal diode model is an adequate representation of an actual diode and simply requires that the circuit

analysis be separated into two parts: forward current and reverse current. For other applications, a more accurate description may be needed.

The ideal P-N junction has an I-V relationship (shown in Fig 2(c)) that can be given by

$$I = I_0(e^{V/V_T} - 1), \quad (\text{VI-1})$$

where V_T is a threshold voltage and both I_0 and V_T are temperature dependent. Nominal values for the constants I_0 and V_T depend on the material. For a Si diode at room temperature they are $I_0 = 1 \text{ nA}$ and $V_T = 50 \text{ mV}$. In this lab, we will compare the behavior of a silicon diode with a germanium diode and an LED (typically gallium arsenide).

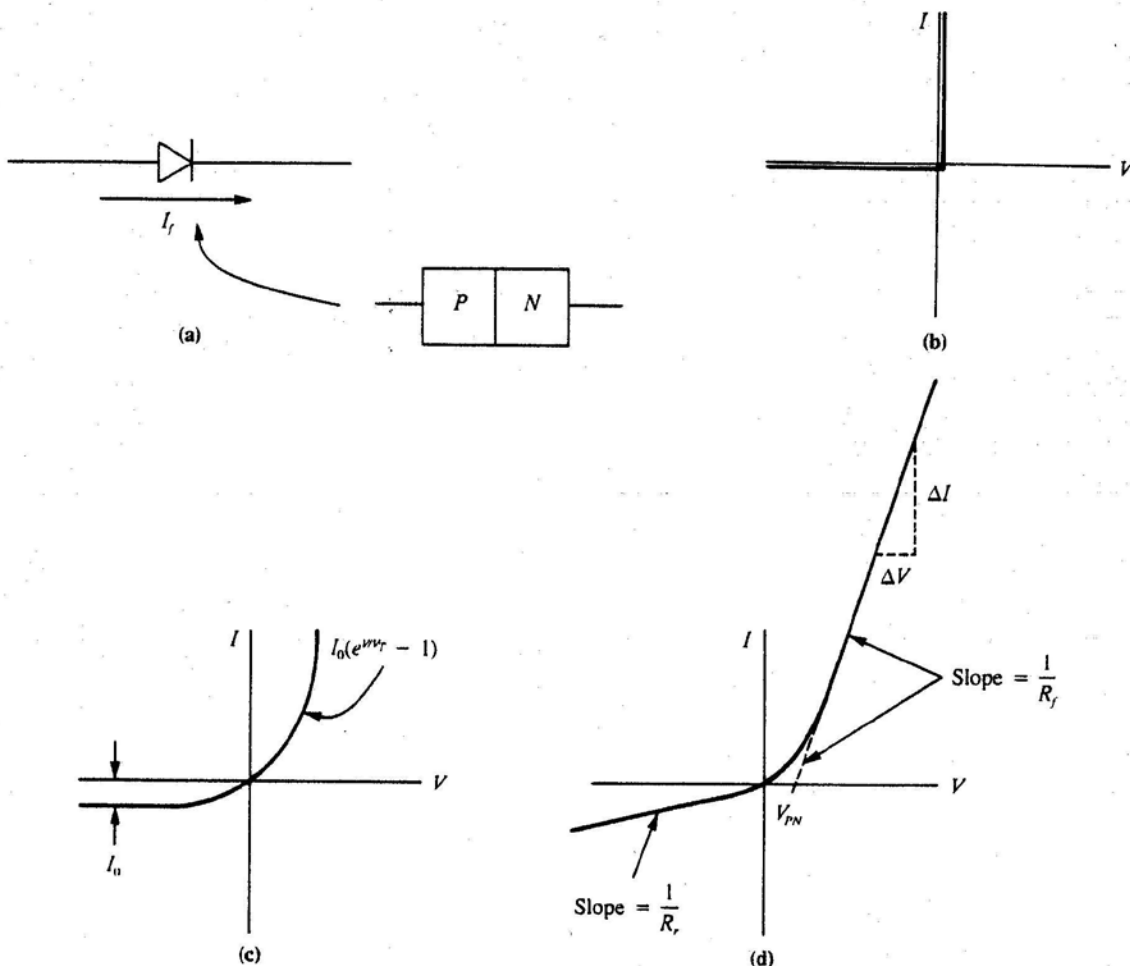


Figure 2: Properties of ideal and real diodes. (a) shows the schematic symbol for a diode, (b) shows the current versus voltage curve for an idealized diode, (c) shows the same for a real diode, and (d) shows how to estimate the threshold voltage V_{PN} from the I-V curve.

The operation of an actual diode near threshold can be summarized by the I-V curve shown in Fig. 2(d). This curve is characterized by two linear regions of constant slope connected by an exponential curve in the region of small forward bias. The PN diode is thus our first example of a nonlinear circuit element: the current through the device is not always proportional to the

voltage across the device. Some circuits make use of the nonlinear region of this curve, but for most applications this region of the curve can be avoided and the device can be modeled as a “piece-wise” linear circuit element.

Figure 2(d) has a linear portion that may be extended to the V-axis to define a “turn on voltage” at V_{PN} . The voltage, V_{PN} , represents the effective voltage drop across a forward-biased PN junction (the turn on voltage) and is represented in the model by a constant voltage source. For a germanium diode, V_{PN} is approximately 0.3 V; for a silicon diode it is close to 0.6 V.

Noting that the slope at any point on this IV curve has the units of inverse resistance, we can assign a "dynamic" resistance to the diode in each of its linear regions: R_f in the forward-biased region and R_r in the reverse-biased region. These resistances are defined by $R_f = \Delta V / \Delta I$ and $R_r = \Delta V / \Delta I$ in their respective regions as shown in Fig. 2(d). Typical signal diodes have a forward resistance of a few Ohms and a reverse resistance around one MegOhm.

Besides turn on voltage, there are other important characteristics that distinguish the thousands of diode types available, e.g., maximum forward current, capacitance, leakage current, and reverse recovery time (see Table 1 for characteristics of some typical diodes). The most important diode feature not included in this model is the switching time between forward current I_f and reverse current I_r . Actual diodes require a time ranging from a picosecond to a microsecond to switch in this direction, even when the applied voltage across the diode is assumed to switch instantly. This represents a significant high-frequency limitation for many diodes.

In the first part of this experiment you will measure the IV characteristic of a typical silicon diode, as well as for a germanium diode, and a light emitting diode (see Fig. 3).

Why are LED light bulbs so energy efficient? The light from a traditional incandescent bulb is an example of *blackbody radiation*, which you will study in your statistical physics class. In a nutshell, it is basically electromagnetic radiation that is converted from thermal energy. All objects emit a spectrum of electromagnetic radiation which is determined by their temperature, for example, the light from the Sun or glowing hot coals on a grill. Because the human body is relatively cool, the radiation it emits is mostly in the infrared and therefore not visible. The filament on a light bulb is a resistor. It resists the flow of current and converts electrical energy into heat. When it heats up, it glows, giving off blackbody radiation. Because blackbody radiation produces a broadband spectrum, only a small fraction of the electromagnetic radiation given off by your light bulb is in the visible frequency range, the rest is in infrared, ultraviolet, etc., which don't contribute to the bulb's function, which is to help you see things. In other words, the energy that is emitted in nonvisible wavelengths is a waste. LEDs on the other hand, emit light when electrons and holes recombine in the semiconductor material, and the photons (light particles) given off are of a precise frequency that is precisely determined by the characteristics of the p-n junction, which can be chosen such that all of the light emitted is visible. Thus, you can replace a 60 W incandescent bulb with an LED bulb of less than 10 watts! See: <http://www.homedepot.com/p/Cree-60W-Equivalent-Soft-White-2700K-A19-Dimmable-LED-Light-Bulb-BA19-08027OMF-12DE26-2U100/204592770?N=5yc1vZbm79>

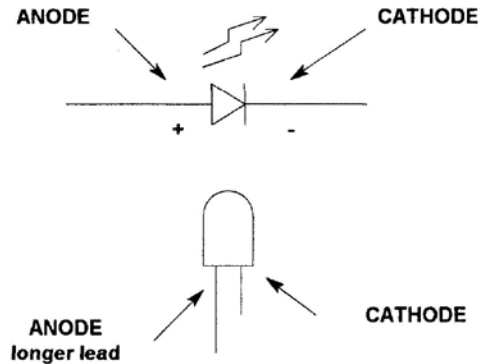


Figure 3: Some important characteristics of light-emitting diodes.

A. Rectification

A rectifier changes alternating current (ac) to direct current (dc); this is one of the simplest and most important applications of diodes (diodes are sometimes called rectifiers). The simplest circuit is shown in Figure 4(a). The "ac" symbol represents a source of ac voltage; in electronic circuits it is usually provided by a transformer, powered from the ac power line. In our lab, it can be the function generator. For a sine-wave input that is much larger than the forward drop (about 0.6V for silicon diodes, the usual type), the output will look like that in Fig. 4(b). If you think of the diode as a one-way conductor you won't have any trouble understanding how the circuit works. This circuit is called a *halfwave rectifier*, because only half of the input waveform is delivered to the load resistor.

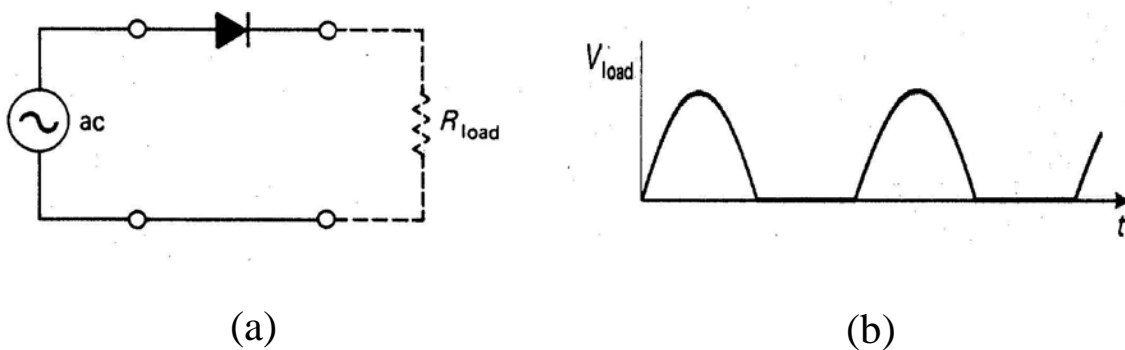


Figure 4: A Half-Wave Rectifier. (a) Circuit diagram. (b) Voltage drop on load resistor as a function of time.

Figure 5(a) shows another rectifier circuit, a full-wave bridge. Figure 5(b) shows the voltage across the load resistor R_{load} as a function of time for which the whole input waveform is used.

The gaps at zero voltage occur because of the diodes' forward voltage drop. The rectified waveforms shown in Fig 5(b) are not good for much as they stand. They are dc only in the sense that they do not change polarity. But they still have a lot of "ripple" (periodic variations in voltage about the steady value) that has to be smoothed out in order to generate genuine dc. This we do by adding a low-pass filter (Fig. 6), which we will learn about when we study capacitors. (*Something to look forward to!*)

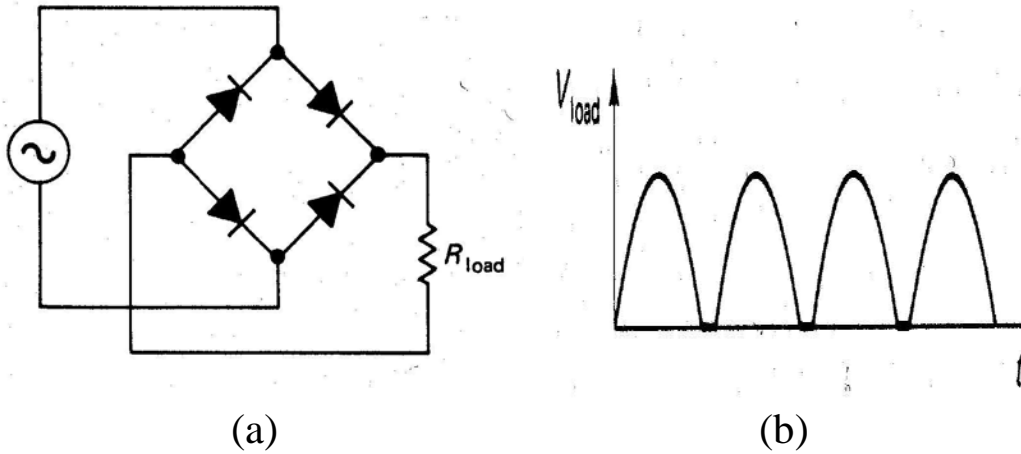


Figure 5: Full-wave bridge rectifier.

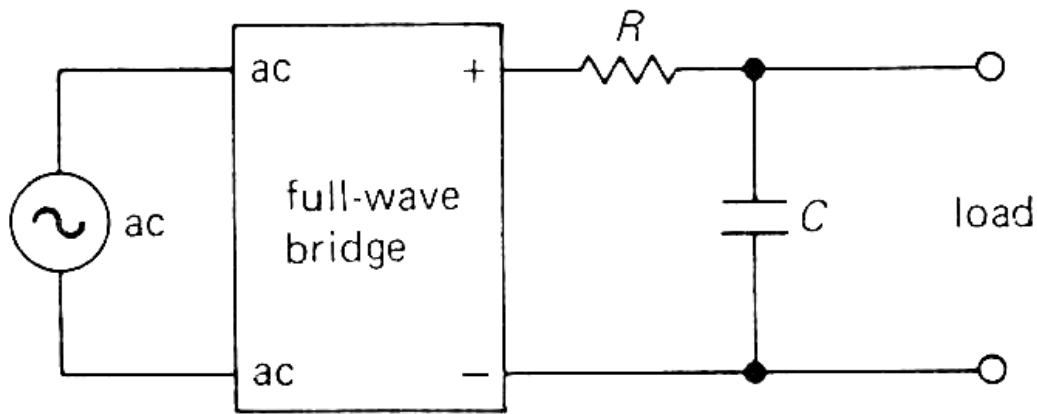


Figure 6: Circuit for building a dc power supply. A low-pass filter is added to the rectifier circuit to deliver genuine dc to the load.

B. The Signal Rectifier and AM Radio

There are other occasions when you use diodes to make a waveform of one polarity only. The example we will be concentrating on is AM radio. In AM radio, the signal (sound) that you wish to transmit is superimposed on a much higher frequency (500-1600 kHz) electromagnetic wave by modulating the amplitude of the carrier wave with the envelope of the sound wave, as shown in Figure 7.

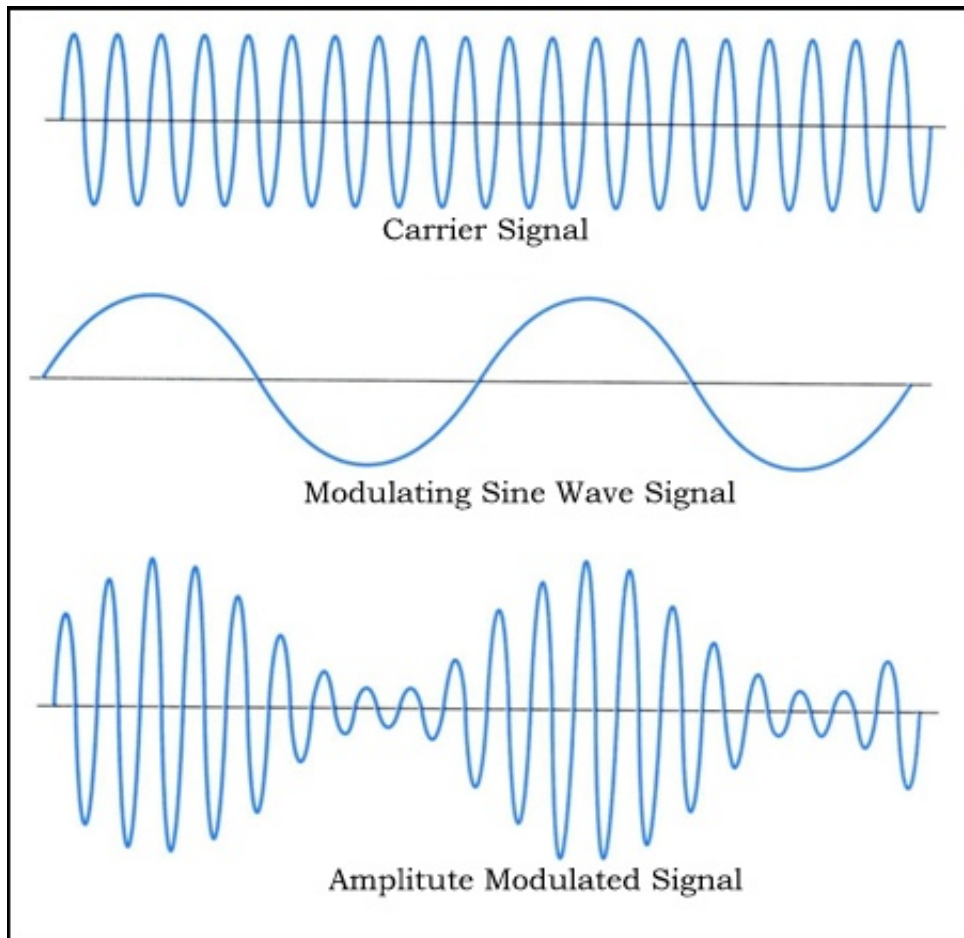


Figure 7: The figure shows a schematic of speech or other sound to be transmitted (middle panel). The carrier wave, or the electromagnetic wave responsible for delivering the sound is shown in the top panel. When the envelope of the sound wave is superimposed on the carrier wave, (the amplitude of the carrier wave varies with the same frequency of the sound) you get the amplitude modulated wave in the lower panel.

The carrier wave contains no information, and is only used as a means of transmitting the sound wave information from the transmission point to the audience. Note that the amplitude modulated signal is double sided, unlike the original sound wave. For this reason, it could not be heard if we plugged it directly into a speaker, because the peaks and the troughs would cancel each other out. The average power is zero. We are really only interested in the envelope of one side of this transmitted wave. How do we recover a one sided wave? Use a diode as shown in Figure 8.

Note that just rectifying the signal does not restore the original sound wave. We still have the artifacts of the radio frequency wave in the rectified signal. In practice, those high frequency peaks are, in many cases, too fast for your speaker to reproduce. Later, when we introduce capacitors, we will learn how to use a capacitor as a **low pass filter** to smooth out all of those fast oscillations, recovering the wave on the right of Figure 8.

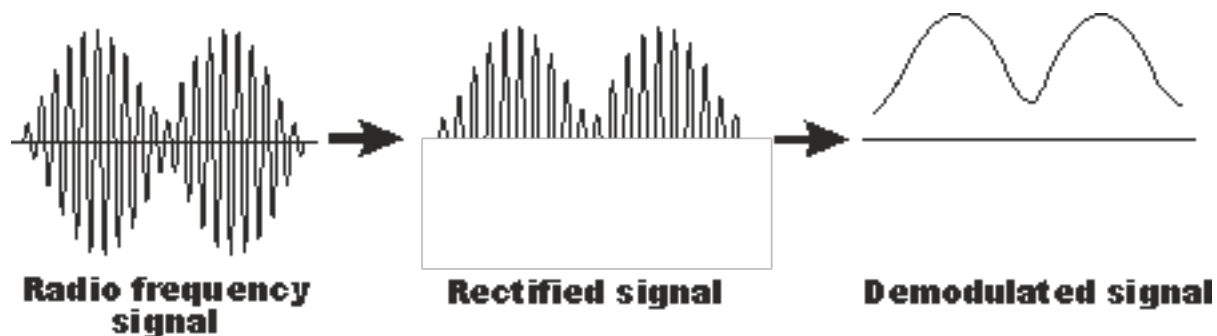


Figure 8: Rectifying an am signal. The diode removes the negative side of the wave.

Always keep in mind the forward voltage drop of the diode. This circuit, for instance, a silicon diode would give no output for square waves smaller than 0.6 Volts peak-to-peak. We will have to judiciously choose the diode to use as our AM rectifier.

In principle, with the diode and the earpiece, we now have our simplest AM radio already! See Fig. 9. In practice, it won't work very well, if at all, because the signal would be too weak, and we would hear all stations at once since we haven't yet built a **tuner**...but we will...

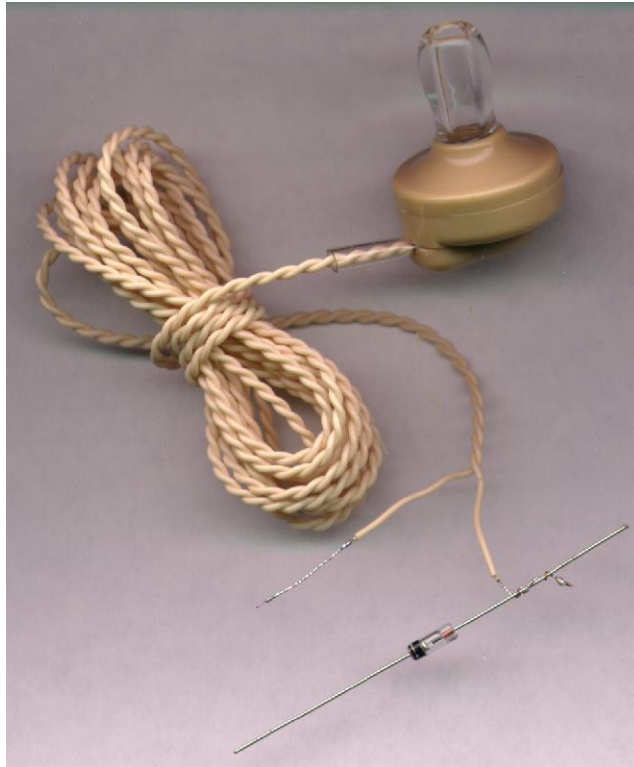


Figure 9: The most primitive AM radio.

IV. EXPERIMENTS

Experiment Part 1 - Measurement of the IV Characteristic of a diode

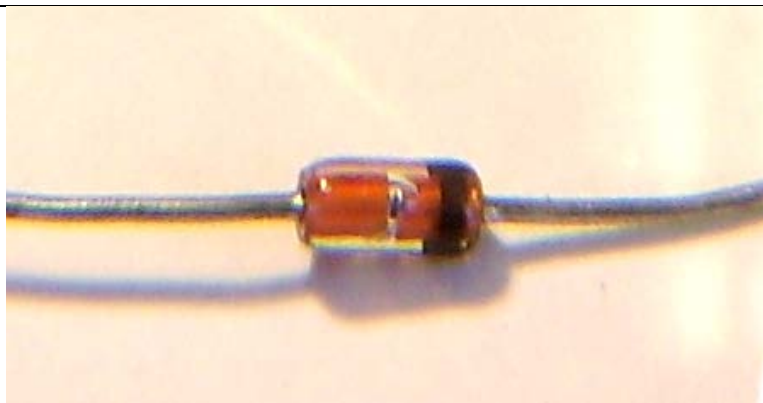


Figure 10: Photograph of a 1N914 Silicon Switching Diode

Table 1 Electrical characteristics of the 1N914 Silicon diode.

Peak Reverse Voltage	75 V
Average Forward Rectified Current	75 mA
Peak Surge Current, 1 Second	500 mA
Continuous Power Dissipation at 25°C	250 mW
Operating Temperature Range	-65 to 175°C
Reverse Breakdown Voltage	100 V
Static Reverse Current	25 nA
Static Forward Voltage	1 V at 10 mA
Capacitance	4 pF

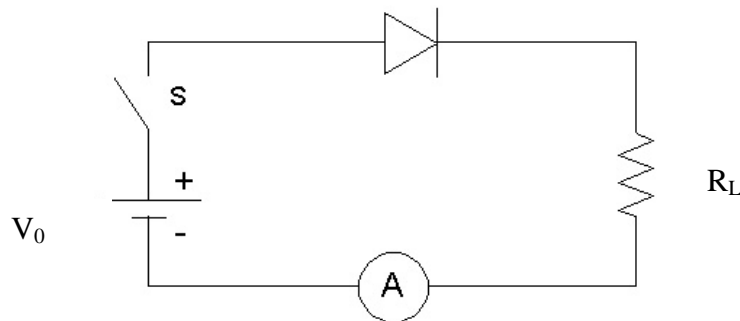


Figure 11: Circuit for first part of the experiment.

Shown in figure 10 is a photograph of a 1N914, a type of silicon diode we are using for this part and Table 1 shows its specifications. You are also provided with two additional diodes, a 1N34A germanium diode, and an LED. How do you know the specifications for the last two diodes? Try typing 1N34A into a web browser, and look for the specification sheet. We will be doing this for many of our components.

1. Set up the circuit shown in figure 11. The “load resistor”, R_L , is used to limit the total amount of current flowing through the diode so that it is not damaged; use a 51Ω resistor for R_L . V_0 is the power supply and A is the multimeter used as an ammeter (remember to use the ‘DC’ setting, and plug in to the appropriate terminals).
2. Now measure the voltage across the load resistor, the voltage across the diode, the voltage across the ammeter, and the input voltage when the input voltage is approximately 5 volts. Verify that the sum of the voltages around the loop is consistent with zero **within errors** (Kirchoff’s law).

For parts 3,4,5, consider only statistical uncertainties due to the precision of your multimeter.

3. Measure the voltage across the diode versus current for 20 different values of the voltage across the diode. Set up a plot so that, as you add data, the plot automatically updates and you can see that the data is looking good. (this diagnostic plot does not need error bars) **Show your instructor that you can do this.** Be sure to include measurements at both positive and negative voltages. Take more data for positive voltages between 0.5 and 0.8 volts than in the other regions. (You may wish to discuss why with your instructor. If you understand why, you will do a better job of choosing your voltage values and get a better result without having to take more data once the purpose is understood.) Be sure to use the “mA” setting on the dial when using the 400 mA terminal, and the “A” setting when using the 10A terminal. Switch terminals when necessary to get the most accurate measurement. Plot your data.
4. Perform a linear fit of the I-V curve in the conductive forward-biased region and find the V-intercept, V_{PN} (with an uncertainty). Also, use the slope to extract the effective (dynamic) resistance of the diode, with an uncertainty.
5. Repeat steps 3 and 4 for the other two diodes. Think, before you begin, what you need to do in order to take your data quickly and efficiently.
6. Include a paragraph of discussion in your spreadsheet on how the diodes were similar, and how they differ. Do their V_{PN} values differ, considering uncertainties? (if you are not absolutely sure what V_{PN} is, ask your instructor!!) Which would be best for our radio and why? Discuss with your classmates and instructor.

Experiment Part 2 - Rectifiers and Measurements with a sine wave input

A. Full Wave Rectifier

Do not do error analysis for this section.

NOTE: The sine waves from the generator should be symmetric about zero; use the Offset knob to achieve this. Also check that the instrumentation (differential) amplifier does not have a dc offset.

1. Set up the full wave bridge circuit shown in Fig. 5 using a 1 k Ω load resistor and a 1 kHz sine wave input from the signal generator. Look at the signal both with your scope and send it to the circuit by utilizing a “T” at the function generator output.
2. Identify any points on the circuit that are at ground. Discuss what you find with your instructor. Discuss the “differential preamp” with your instructor.
3. Connect the oscilloscope to V_{load} **using the differential preamp.** (Why?)
4. Note that the generator can add a dc offset to the output voltage. While looking at V_{load} on the oscilloscope, adjust the dc offset to zero to make the all of the rectified peaks of uniform height. Use the knob labeled “Offset” and adjust it after pulling it out.

5. Using the measure functions on the oscilloscope, measure the peak-peak, mean, and rms of both the input voltage and the voltage across the load. Do these measurements for 6 different values of V_{gen} and plot load versus input for each measured quantity. Be sure to include one where the input voltage is smaller than 0.5 V. Also, transfer plots of the generator voltage and the load voltage to your computer for typical conditions and include in your report.