Name ___________________________ Date ____________ Partners_________________________________

SEMICONDUCTORS AND DIODES

OBJECTIVES

- To learn the basic properties of semiconductors and how their properties can be modified.
- To understand the basic principles of a semiconducting diode.
- To understand how the biasing properties of a *p-n* junction diode operate and how a diode might operate in a circuit.
- To measure the *IV* curve of a diode.
- To use the properties of a diode to rectify AC voltage.
- To understand how *LED*s operate.

OVERVIEW

Types of Conducting Materials. The electrical properties of materials can be divided into three broad categories: conductors, insulators, and semiconductors. In addition, a few materials exhibit superconductivity, but we will not address those here. Metals (both pure elements and alloys) are called **conductors**, because they typically conduct electricity. Materials like glass, Teflon, ceramics, and plastics are called **insulators**, because they are poor conductors of electricity. The third category, **semiconductors**, is the subject of this laboratory; their properties lie between conductors and insulators. Semiconductors are interesting, because we can control their electrical properties.

Energy Bands. Let's first examine the band theory of materials. Quantum physics indicates that electrons are placed in certain allowed energy levels in an atom. These are called shells (or orbitals) and subshells. From the Pauli Exclusion Principle, we know how the electrons are placed in the shells and subshells. The properties of the elements are primarily determined by the most loosely bound electrons, which are in the outside shells. Sometimes these outside electrons are tightly bound, and insulators result. If the outside electrons, called valence electrons, are only weakly bound, the electrons are fairly free to move around a solid consisting of many atoms. Thus the material is a conductor.

When atoms come together to form molecules, the atomic energy levels overlap. When many atoms or molecules are placed together to form solids, the atomic energy levels become **energy bands** or just **bands**. The electrical properties of materials become clearer if we look at the energy band structure of the materials as shown in Figure 1. We have only shown the bands adjacent to the band gap between filled and unfilled electron levels.

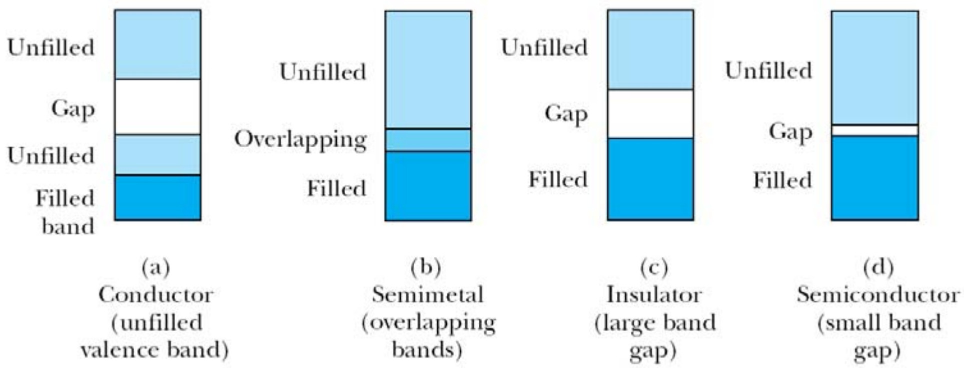


Figure 1. Band structure of materials. Energy is in the vertical direction.
From *Modern Physics,* 3rd ed. by S. T. Thornton and A. Rex (Brooks Cole, 2006).

Electrons in the filled band of conductors can easily move into the unfilled bands under the influence of an external electric field, but electrons in the filled band of insulators have a large energy gap to overcome in order to be free. Semiconductors have a much smaller energy gap between filled and unfilled bands. Heating the material or using a small electric field is normally enough to allow an electron to overcome the small energy gap for semiconductors. An electron in the unfilled band is normally free to move throughout the material; that is, conduct electricity.

The highest filled band for insulators and semiconductors is called the **valence band**. It is separated by the energy gap from the next (unfilled) band, normally referred to as the **conduction band**. Silicon and germanium are special, because their band gaps are only 1.11 eV and 0.66 eV, respectively, at room temperature. Insulators typically have a band gap of about 3 eV, but diamond can have a gap as large as 6 eV.

We can see how semiconductors like silicon and germanium are so useful by examining their intrinsic electron structure. The shell structure for silicon is $1s^2 2s^2 2p^6 3s^2 3p^2$. This means two electrons are in the 1*s* subshell, two electrons are in the 2*s* subshell, six electrons are in the 2*p* subshell, etc. The $1s^2 2s^2 2p^6$ configuration is a particularly tightly bound core. The $3s^2 3p^2$ shell electrons are loosely bound and determine the electronic properties of silicon. In a solid, silicon appears as shown in Figure 2a. Now let's see what happens if we replace one of the silicon atoms with a phosphorus atom that has one more electron in its 3*p* shell ($3p^3$). That electron is able to diffuse throughout the silicon material as seen in Figure 2b. We

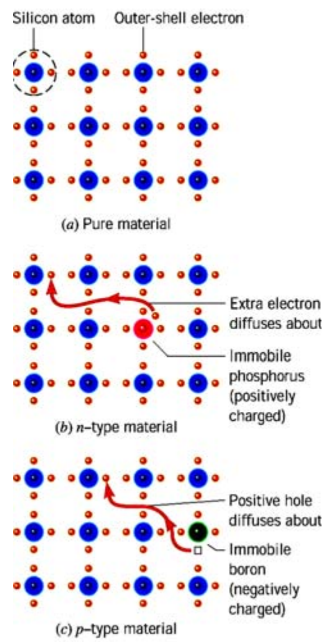


Figure 2. (a) An undoped silicon crystal with its outer shell electrons. (b) When doped with a phosphorus atom, there is an extra electron that is able to diffuse around the crystal. (c) When doped with a boron atom, there is a missing electron or hole, and the hole is able to diffuse. From *Physics*, 7th ed, Cutnell and Johnson (Wiley Publishers, 2007).

say that we have **doped** the *intrinsic* silicon semiconductor, and we call the result an ***n*-type** doped semiconductor. We have produced an *extrinsic* semiconductor that has different electrical properties because of the impure phosphorus atom and its extra electron. Most semiconductors used in electronic circuits are of this extrinsic type.

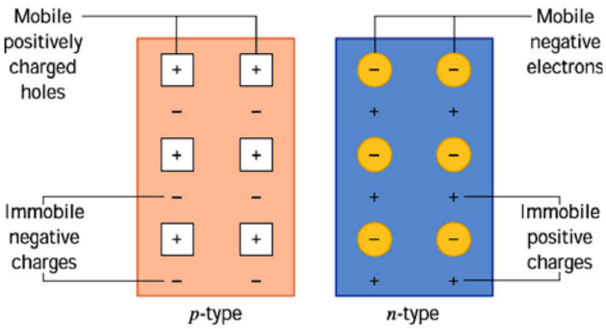


Figure 3 A schematic diagram of *p*-type and *n*-type semiconductors indicating the mobile holes and electrons. From *Physics*, 7th ed, Cutnell and Johnson (Wiley Publishers, 2007).

Boron has one less electron than silicon, and if we dope the pure silicon material with boron, we have a vacant electron position, which is called a **hole**. This hole is positive, and it permeates throughout the material with unique electrical properties as shown in Figure 2c. Such a doped semiconductor is called ***p*-type.** If we add many doping atoms we produce *p*-type and *n*-type semiconductors with many mobile positive holes and negative electrons as shown in Figure 3.

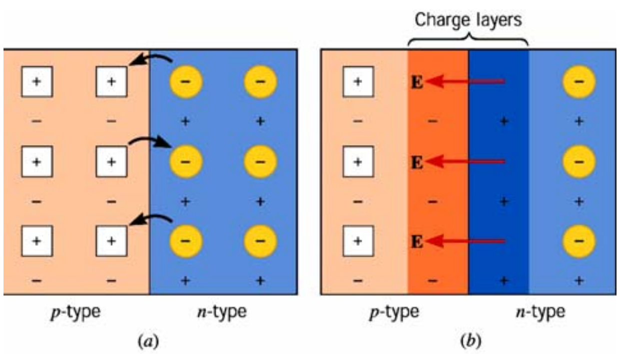


Figure 4. (a) The mobile holes and electrons are free to neutralize each other leaving in (b) an internal electric field **E** at the junction. From *Physics*, 7th ed., Cutnell and Johnson (Wiley Publishers, 2007).

If one *dopes* the two halves of a single piece of a semiconductor, for example silicon, so that they become, respectively, *p*-type and *n*-type material, one creates at the interface between the two halves a ***p-n* junction**. As shown in Figure 4, at the junction the mobile holes and electrons are free to combine and neutralize each other. What is left (Figure 4b) are the immobile ions, which create an internal electric field **E**.

Such a *p*-*n* junction has the remarkable property that it does not obey Ohm's law: If the polarity of the applied voltage is as shown in Figure 5a, the junction is said to be **forward biased** and a current flows. If a voltage is applied to the junction as shown in Figure 5b, no current will flow and the junction is said to be **reverse biased**.

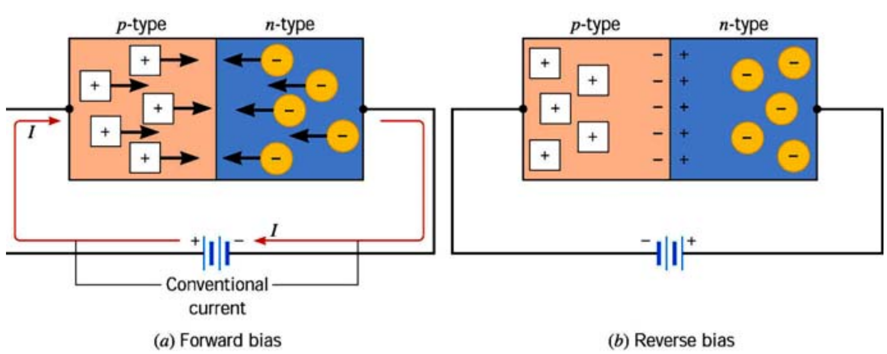


Figure 5. (a) When the junction diode is voltage biased in the forward direction, current flows, but (b) when a reverse voltage bias is applied, no current flows. From *Physics*, 7th ed., Cutnell and Johnson (Wiley Publishers, 2007).

It is useful to look at the doping of a semiconductor from the energy standpoint, particularly to show the energy levels. At low temperatures, the electrons are in their lowest energy states in the valence band. The energy gap for Silicon is 1.1 eV, and no electrons are allowed in the gap. The conduction band is above the energy gap as shown in Figure 6. Any electron in the conduction band can be easily accelerated by an electric field.

If the silicon crystal is doped as *n*-type, there are extra valence electrons that occupy localized impurity donor energy levels just below the conduction band as shown in Figure 7. Electrons can be excited from these levels into the conduction band by thermal excitation or electric fields (for example from a voltage difference). These so-called donor levels donate electrons to the conduction band without leaving mobile holes in the valence band. Such a semiconductor is called *n*-type because the majority carriers are negative electrons.

If the silicon crystal is doped as *p*-type, empty impurity energy levels are created just above the valence band as shown in Figure 8. Electrons can be easily excited from the valence band into these localized states, called acceptor levels, leaving mobile holes in the valence band.

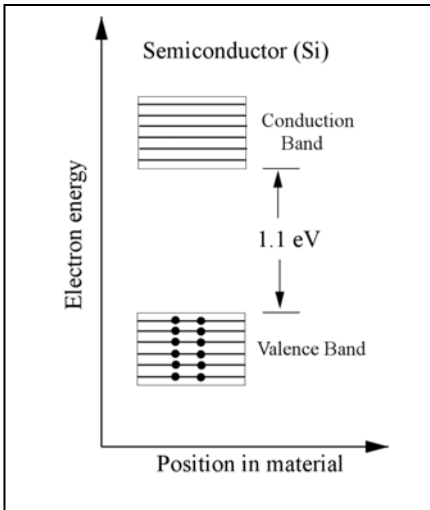


Figure 6

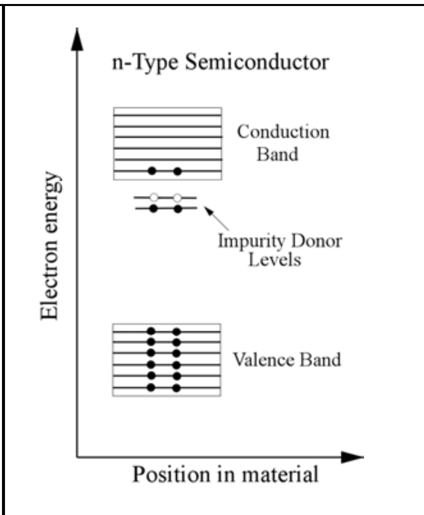


Figure 7

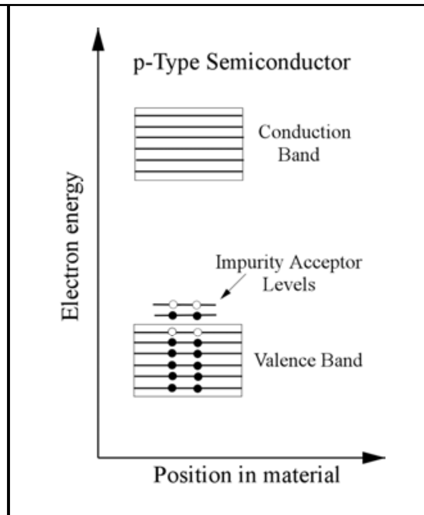


Figure 8

Devices that consist of a *p-n* junction with leads attached to the *n*-side and the *p*-side, respectively, are known as *semiconductor diodes* or simply **diodes** because they have two electrodes. (In Greek, the prefix *di-* signifies *two-* or *twice-*). Diodes act as **rectifiers,** i.e. they allow a current to pass through in one direction but not in the other. They are represented by the various symbols shown in Figure 9.

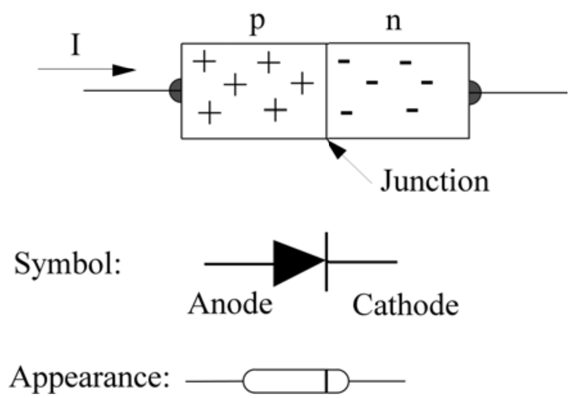


Figure 9. Various symbols for junction diodes.

If we place a voltage across a diode and measure the current passing through the diode in a circuit similar to Figure 5a, we determine a characteristic *I-V* curve as shown in Figure 10. A diode passes current when under a forward bias, but not under a reverse bias. There are several important uses for diodes, the most important one may be in its use in rectification of AC voltage into DC voltage as we will explore in this lab.

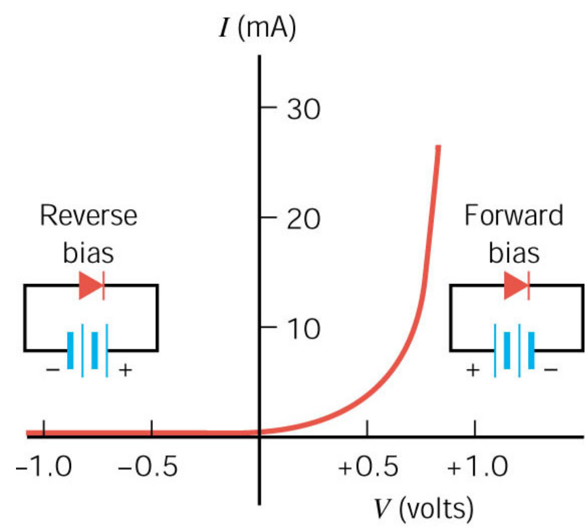


Figure 10. A current-voltage (*IV*) curve for a junction diode. Current is passed with a positive forward bias, but not with a negative reverse bias.

A simplified physical model for the current in the diode gives

$$I = I_o\left[\exp\left(eV/nkT\right)\text{-}1\right] \tag{1}$$

where I_o is the maximum reverse current occurring for large negative V, e is the electron charge, k is the Boltzmann constant, T is the absolute temperature in Kelvin, and n is a constant that has values between 1 and 2, depending on the type of material (Ge, Si, GaAs) and the current range. For Si diodes over the range where we will be using them, $n = 2$ gives a reasonable fit. At room temperature $kT/e \approx 26$ mV. I_0 is very small, but strongly temperature dependent. For large positive voltage, the exponential is very large, so to a good approximation

$$I = I_o \exp\left(eV/nkT\right) \tag{2}$$

We will be investigating Equation 2 in this laboratory.

INVESTIGATION 1: DIODE PROPERTIES

In this investigation you will be given a diode and asked to determine its properties. Which way is voltage applied for the forward bias? How can you tell the *p*- type end of a diode from the *n*-type end? And finally you will measure the voltage-current (the so-called *IV* curve) of a diode to show that it does not have ohmic characteristics, that is, it does not follow ohm's law.

In order to do this you will need the following items:

- a 1N914 diode
- Wavetek 27XT multimeter
- D-cell battery and holder
- several wires with alligator clips
- 1000 Ω resistor

Activity 1-1: Diode Direction

1. Use the material listed above to determine the correct direction that current will flow through the diode. Use the black circle around the diode to define the orientation of the diode.

Remember that ammeters have small internal resistances that are not equal on different current scales. Voltmeters have large internal resistances. You may want to consider this while doing this experiment.

2. Discuss the method by which you made your determination. Use simple drawings if necessary.

Question 1-1: Which end of the diode is the *p*-type and *n*-type? Use the black circle around the diode as a reference. Discuss how you know this.

> In electronics we normally refer to the + voltage side as the *anode* and the – voltage side as the *cathode*. When using cables we sometimes use red cables for +voltage and black cables for – voltage or *ground*.

Question 1-2: Is the black circle end of the diode the anode or cathode end when positive voltage allows current to pass through? Explain how you determined this?

Activity 1-2: *IV* Curve

In this activity you will determine the current-voltage (*IV*) curve for a junction diode. Remember to not exceed a few mA (certainly no more than 20 mA) through the silicon diode.

In addition to the material used in the previous activity, you will need the following:

- Op amp designer board
- Several connecting wires to use with the board
- *Data Studio* computer system

> **Never exceed 8.0 volts across the diode! If you destroy a diode, points will be deducted from your lab grade. It is actually the current through the diode that is crucial. Don't exceed 20 mA.**

1. We will use the op-amp designer board in this experiment so that we can more easily hook up the wires. Note in Figure 11 which holes or sockets are connected together underneath the board. We will use the voltage source at the top of the board, but remember to not use a voltage much higher than 8.0 V or you may destroy the diode.

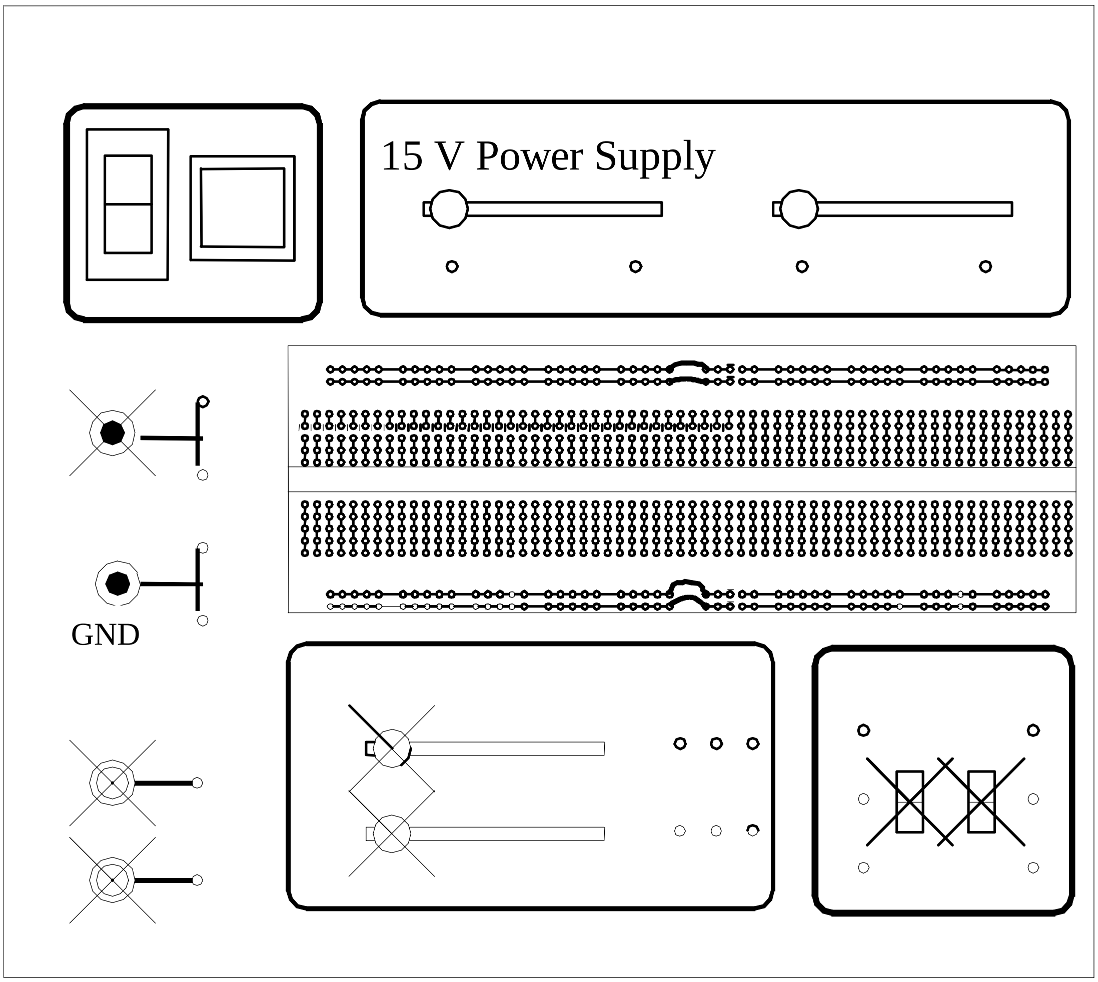


Fig. 11. Op-amp designer board. The small circles represent sockets that components can be plugged into. The lines show which of the sockets are interconnected underneath the board. The two upper slide resistors are connected to two independent power supplies whose output voltages, variable between 0 - 15 V, are present at the pin connectors beneath. The components marked with a cross are not used in this experiment. The horizontal rows of sockets should be interconnected in the middle with jumper wires as shown.

2. Assemble the circuit shown in Figure 12. Connect the negative terminal of the power supply (one of the 0 – 15 V supplies at the top of the board) to the ground terminal to reduce noise. The ground is the black connector on the left of the board.
3. Note that the voltage read at input B is proportional to the current through the diode ($I = V/R$) and is numerically the value of the current in mA, because we are reading the voltage across a 1.0 kΩ resistor.

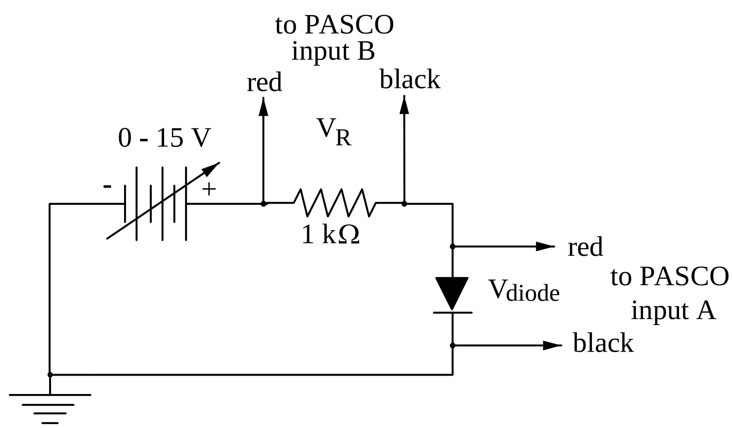


Figure 12. Circuit to produce *IV* curve for diode.

4. Open the experiment file **Diode IV** in *Data Studio*.

5. The computer will record 20 samples per second of the voltages at A and B and list them in the two tables. A graph of B input (proportional to current) will be plotted versus the A input (voltage across the diode).

6. Start recording data and *slowly* slide the voltage knob and increase the voltage from 0 to about 8 volts. You will feel a click in the slider as you reach this voltage. Stop recording. You have obtained data for the positive voltages. Do not erase the data.

7. Determine the value of voltage at which the graph is going almost straight up. You will probably find it is 0.6 – 0.7 V.

   Voltage: _____________

8. Now you need to make a similar plot but using negative voltages. You can do this by reversing the two leads on the power supply, setting the supply to –8V, start recording, sweep up to 0 V. This will be a new run, but the data will be plotted on the same graph as the positive voltages (but in a different color on the screen).

Question 1-3: Does the graph have the qualitative shape you expect from the previous discussion? Discuss.

Question 1-4: What threshold voltage did you find for silicon? Is this about what you expected? Discuss.

Question 1-5: Did you detect any current passing through the diode when the bias voltage was negative (reverse bias)? If so, what was it?

Current ______________________

How can you explain the existence of this current?

9. Print out a copy of your graph for your group report. You do not need to print out the data tables. Do not erase your data!

Activity 1-3: Determination of *n* in Equation 2

We now want to compare your data for positive voltages with Equation 2. You should be able to do this by using the fit data routines of *Data Studio*, which you have done previously.

1. Arrange for your graph to show only the positive voltage data.

2. Now figure out a way to fit these data with an exponential. Describe here how you did this and list the best value of the exponential term e/nkT.

Best fit value of e/nkT with uncertainty ________________

Question 1-6: Did the visual fit of your data lead you to believe that Equation 2 describes the diode's behavior? Discuss.

3. Use the known values of e and k and the room temperature T and determine the value of n.

   n: __________

Question 1-7: Is this value of n consistent with what you expected? Discuss.

4. Ask your Instructor if time is available to repeat this activity for a germanium diode (Sylvania #ECG109). If time is available, give the values for germanium below:

   Threshold voltage: ______________

   n: __________

Question 1-8: Are these values consistent with what you expect for germanium? Discuss.

Activity 1-4: Diode Test Function on Wavetek Multimeter

Many good multimeters have a test function to determine the forward bias voltage of a given diode. Our Wavetek model 27XT has such a function.

1. Turn the switch on the Wavetek to the —▷|— symbol. Connect the red test lead to the V-Ω input and the black test lead to the COM input.

2. Connect the probe tip of the red test lead to the anode and the black test lead to the cathode of the diode.

3. The meter applies just enough voltage to allow current to pass. The meter's display indicates the forward voltage drop.

4. Reverse the test leads on the diode to perform a reverse bias test. An overload signal (*OL*) indicates a good diode.

> An overload condition for both reverse and forward bias tests indicates an open diode, which means the diode is bad. A low voltage reading for both bias tests indicates a shorted diode.

5. Perform the forward and reverse bias tests for both a silicon and germanium diode. List your results below:

   Silicon bias voltage: ______________________

   Germanium bias voltage: __________________

INVESTIGATION 2: RECTIFICATION OF AC VOLTAGE

In this investigation you will investigate the use of diodes in rectifying AC voltage, for example from AC to DC. The uses of rectifiers are too numerous to mention, but the electrical generator of your automobile most likely produces AC voltage that must be rectified to DC for your car's electrical system. Calculators and computers also use rectifiers.

In addition to the material used in the previous activity, you will need the following:

- Digital function generator amplifier (PI-9587C), sometimes called simply a *signal generator*.
- Total of four Si diodes 1N914

Activity 2-1: Half-Wave Rectifiers

1. Hook up the circuit shown below in Figure 13. You must pay careful attention to this circuit. The positive signal (red cable) of the signal generator is the Hi Ω output, and the negative end is the ground output.

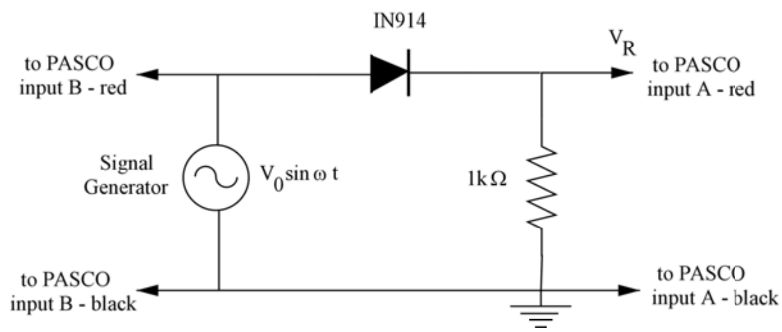


Figure 13. Half-wave rectifier circuit diagram.

2. Set the signal generator to produce a 100 Hz sine wave. Start with the amplitude knob about half maximum.

Prediction 2-1: Draw in the graph below the voltage across the 1000 Ω resistor (output current) if the sine curve shown is the input voltage from the signal generator.

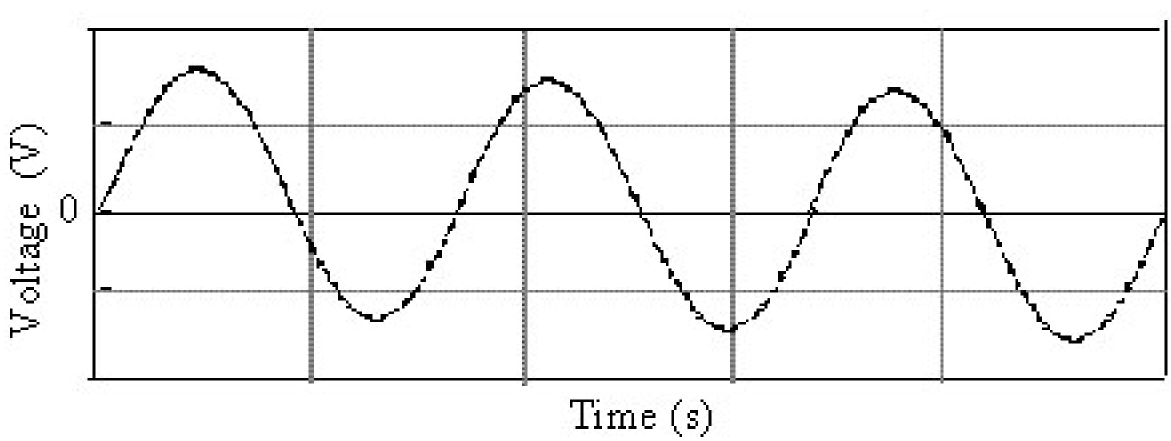


Figure 14. Graph of input voltage and output voltage (*IR* through resistor).

3. In *Data Studio* open the experiment file called **Rectifier**. *Data Studio* will be in the oscilloscope mode, and you will be observing the input signal generator voltage in Channel B and the current through the diode (actually the voltage across the 1000 Ω resistor) in channel A.

4. Start recording data. You should be triggering with channel B, the signal generator. Make sure channel B is highlighted with the box around it in the upper right of the computer screen (click on it to make it happen). You will notice a green triangle on the left side of the screen that denotes the triggering level (only voltage signals above the trigger level pass through). Move the trigger level to see what happens.

5. You can set the amplitude of the input voltage by changing the amplitude knob on the signal generator. Set the voltage to 4.0 V. You probably should have *Data Studio* set at 1 V/div on the vertical screen and 2 ms/div on the horizontal. Change those values to see what happens.

6. Use the Smart Tool in *Data Studio* to determine the maximum voltage for the two cases.

   Maximum input voltage ____________________________

   Maximum output voltage (actually *IR*) ________________

7. Print out the data for your group report.

Question 2-1: Compare your data with your prediction. Discuss the agreement and explain any disagreement.

Question 2-2: Note in step 6 that the maximum output voltage was less than the input voltage. Explain why.

Question 2-3: Note that there is a time delay between the time the input voltage rises above zero and the time the output voltage rises above zero. Explain why this occurs.

Activity 2-2: Full-Wave Rectifiers

1. Hook up the circuit shown below in Figure 15.

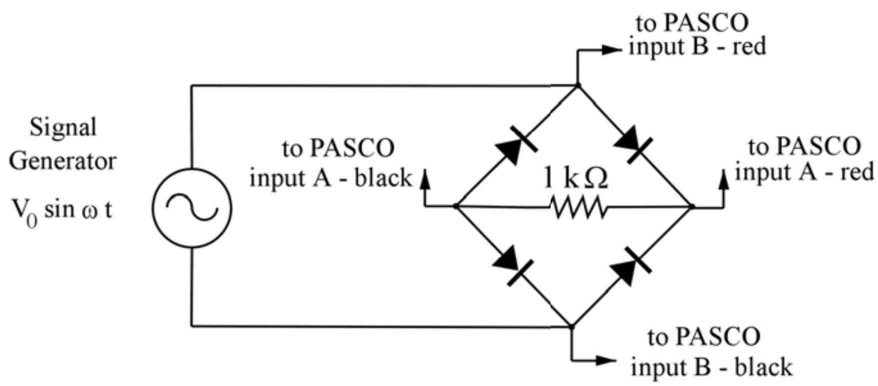


Figure 15. Full wave rectifier circuit

2. You will follow the same steps 2-7 that you did in the last activity. Use the same experiment file **Rectifier**. Fill out the predictions for the output voltage and fill in the maximum values for the voltages.

Prediction 2-2: Draw in the graph below the voltage across the 1000 Ω resistor (output current) if the sine curve shown is the input voltage from the signal generator.

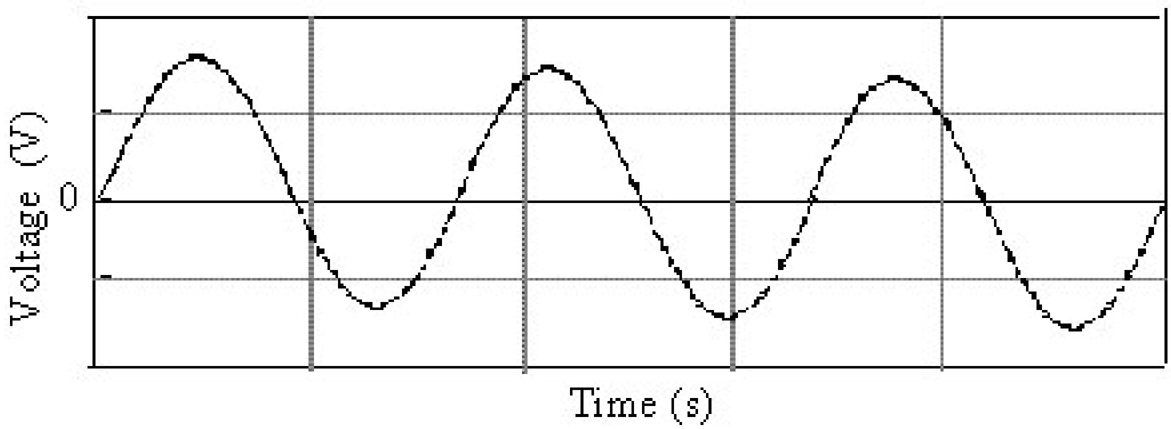


Figure 16. Graph of input voltage and output voltage (*IR* through resistor).

Maximum input voltage ___________________________

Maximum output voltage (actually *IR*) _______________

Question 2-4: Compare your data with your prediction. Discuss the agreement and explain any disagreement.

Question 2-5: Note that the difference between the maximum output voltage and the input voltage is even greater than for the half-wave rectifier. Explain why.

Question 2-6: Compare the time delay between the time the input voltage rises above zero and the time the output voltage rises above zero with the half-wave rectifier. If there is a difference, explain why this occurs.

3. On the circuit diagram in Figure 15, draw the path that the current takes through the rectifier circuit when the input voltage is positive. Use a dashed line to draw the path that the current takes through the rectifier circuit when the input voltage is negative. Make sure your paths are clear and well marked.

Question 2-7: Explain why the output voltage across the 1000 Ω resistor is always positive for the full wave rectifier.

INVESTIGATION 3: LIGHT EMITTING DIODES (LED)

Light emitting diodes are used in numerous applications including small store-front signs, digital clocks, remote controls for TVs and other electronic devices, indication of electronic instruments and appliances being on, road construction barrier lights, traffic signal illumination, motorcycle/bicycle warning lights, spoiler and car decorative lights, etc. You may even have one of the newer type flashlights that uses LEDs or drive a car that uses LEDs for the turn or brake signals. Their advantages are they don't have a filament that burns out, they don't get very hot, and they last longer than incandescent bulbs.

As free electrons pass across the junction in a diode, they fall into empty holes in the *p*-type material. When doing so, the electrons fall into a lower energy level, and light in the form of electromagnetic radiation called photons is released. In the case of the silicon and germanium crystals we have been studying up to now, those photons are in the infrared spectrum, and they are not visible to the human eye. However, if the electron flow occurs in a junction diode with a larger energy band gap, then the photons will be in the visible region. It is the energy difference that the electron experiences as it travels across the junction that determines the photon frequency. The equation is

$$E = hf \tag{3}$$

where f is the photon frequency, and h is Planck's constant (value h = 6.6261×10^{-34} J s).

Scientists have developed such crystals to use as LEDs with compounds (using especially gallium) that produce visible light, such as

- aluminum gallium arsenide (AlGaAs) - red

- aluminum gallium phosphide (AlGaP) - green
- aluminum gallium indium phosphide (AlGaInP) - orange, yellow, and green
- gallium arsenide phosphide (GaAsP) - red, orange, and yellow
- gallium phosphide (GaP) - red, yellow and green

There is a huge advantage in efficiency by using LEDs compared with incandescent bulbs where the filament must be very hot. LEDs do not produce much heat. A much larger percentage of the electrical power goes to produce light for LEDs as compared with incandescent bulbs. The problem, until recently, has been the cost of producing LEDs. LEDs have become so inexpensive and reliable that they are taking over many of the applications previously dominated by incandescent and fluorescent bulbs. LEDs can last tens of thousands of hours and tend to be immune to heat, cold, shock, and vibration. They do not have the annoying flicker like from fluorescents, and scientists are still developing nice, warm feeling white light that people prefer. The white LEDs now available tend to have a little blue color in them. No breakable glass is used in LEDs, and they can be waterproofed for marine use.

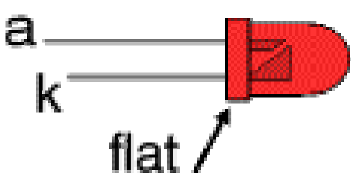
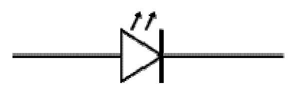


Figure 17. Diagram of a LED showing the anode and cathode (K) leads.

The circuit symbol for LEDs is 

The long lead wire is labeled anode for +. The short lead wire is labeled k for cathode (after the German spelling kathode) and is negative. There may be a slight flat on the body of round LEDs on the cathode side. Most LEDs have colored bodies to enhance the color, but we are using clear ones so we can more easily see the color of the light produced.

Never connect a battery or power supply directly across a LED. The diode may be destroyed because of excessive current. LEDs must always be placed in series with a resistor to limit the current. It is usually safe to place a 1 kΩ resistor in series.

Figure 18 shows a circuit in which the function of the LED can be tested. V_S is the supply voltage, R is the resistor in series, and V_L is the voltage across the LED. If I is the current through the circuit, we can write Ohm's law across the resistor as

$$V_R = \text{voltage across resistor}$$

$$V_R = IR = V_S - V_L \qquad \text{or}$$

$$R = \frac{V_S - V_L}{I} \tag{4}$$

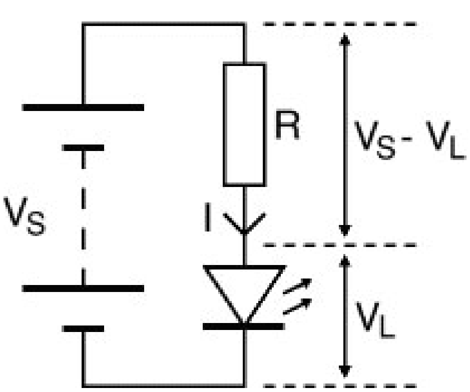


Figure 18. Always place a resistor in series with a LED before placing a voltage across it.

Generally data sheets for LEDs tell us what maximum current should pass through the LED. The range of voltages V_L that trigger the LED we are using is about 2.0 volts. They can go up to 4 V for blue or white LEDs.

You may need the following material:

- Digital function generator amplifier (PI-9587C), sometimes called simply a *signal generator*.
- Op amp designer board
- Red, green, and yellow LEDs
- Three 1000 Ω resistors
- Several connecting wires to use with the board

Activity 3-1: LED Operation

Most LEDs come in colored covers to help enhance the color produced, but we are using clear cover LEDs so we can tell what color light is produced.

Prediction 3-1: If our power supply has a maximum of 15 V, and the forward maximum voltages are about 2.5 V, calculate the value of the resistor we should use for a limiting current of 20 mA.

Question 3-1: Will we be safe by using a 1 kΩ resistor in series with our LEDs? Explain your answer.

Question 3-2: We want to test red, yellow, and green LEDs in one circuit, but the voltages at which they pass current will probably be different. Do we want to place the three LEDs in series or parallel in order to measure the voltages at which the LEDs pass current? Explain.

1. We want to determine the *IV* curves for the three LEDs. You might want to refer to Activity 1-2 and Figure 12. Draw the circuit below you plan to use to test the LEDs. Before actually hooking up the LEDs in your circuit, check with your instructor. Remember that a 1 kΩ resistor must be in series.

2. Use the op amp designer board to hook up your circuit after your instructor has approved your design. Use the 15 V sliding power supply on the board.

3. Open the *Data Studio* experiment file **DIODE IV** that you used previously in Activity 1-2. We want to determine the *IV* curve for each LED in turn. When you are sure your circuit will not destroy the LED, start data collection and turn up the voltage steadily until you reach 5 mA. You should see the diode light up. It is probably best to stop the data collection before turning the voltage down, because the data will retrace itself making it look messy. Do it again until you have clean data. Find the voltage at which you first have 1 mA and also 2 mA and put your results in Table 1.

	Voltage (V)	
Color	1 mA	2 mA
Red		
Green		
Yellow		

4. Repeat step 3 for the other two LEDs.

Question 3-3: From the energy relation, $E = hf$, does the order of voltage make sense? Which color has the largest frequency? Which color has the largest energy band gap?

Activity 3-2: LED Oscillating Operation

Your assignment is to design and produce a circuit that shows a green and red oscillating LED for which you can adjust the frequency of it going on and off. The green and red LEDs must each be on about half the time, but not at the same time. You can use any of the equipment you have available.

1. Draw the circuit below.

2. Remember that points will be deducted from everyone in your group if you destroy a LED. Work together and make sure everyone agrees about your circuit.

3. Show your instructor that your circuit works.

Question 3-4: What key operation did you have to do in order to have the green and red LED oscillate out of phase?