

## Section 9

# HOW DO SEMICONDUCTORS WORK? WHAT IS AC?

## INTRODUCTION

In this section you will investigate the properties of semiconductor devices called “diodes”. You will then learn about alternating current (AC), and how to use a diode and a capacitor to convert it to direct current (DC). Finally, you will use a semiconductor device called a “transistor” as an electronic switch that permits potential differences in the space surrounding charged objects to turn light bulbs on and off.

### 9.1 Commentary: What are semiconductors?

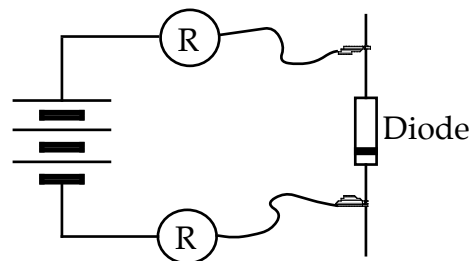
To be a conductor or not to be a conductor — that is the question!

In semiconductors the presence or absence of mobile charge carriers is controllable. In addition, devices made of semiconducting materials behave like valves that can turn the flow of mobile charge on and off. Most of these devices are made of silicon. Pure silicon is an insulator, but with the addition of small and carefully controlled amounts of impurities it becomes a semiconductor.

## INVESTIGATION ONE: HOW ARE DIODES USED IN CIRCUITS?

### 9.2 Activity: Investigating diodes

1. Test a diode using the circuit below to find its conduction properties. Write your observations.



**Figure 9.2**  
**DIODE TESTING**

2. Notice that one end of the diode is marked with a painted band. Is the diode a conductor when it is connected so that the band is placed -

a) away from the positive terminal of the battery? \_\_\_\_\_

b) toward the positive terminal of the battery? \_\_\_\_\_

3. Sketch a picture of the diode, showing the band. Use an arrow to show the direction in which the diode will allow conventional charge flow.

### 9.3 Commentary: The diode symbol

The symbol used to represent a diode in a circuit diagram is shown below. The arrow points in the direction of conventional charge flow. The single vertical line represents the end with the band.



Figure 9.3  
DIODE SYMBOL

### 9.4 Commentary: How does a diode work?

Let's now try to understand why a diode is a conductor in only one direction — a one-way valve. Pure crystals of silicon are insulators because the charge in them is not mobile. Mobile charge is due to impurities; it can be either positive or negative, depending upon the specific kind of impurity added to the silicon. Semiconductors are named by the type of mobile charge present:

**"P-type"** semiconductors have positive mobile charge.

**"N-type"** semiconductors have negative mobile charge.

The negative charge carriers are "electrons" and the positive mobile charge carriers are called "holes". A diode is formed when a "P" region and an "N" region are joined together in the same silicon crystal.

Figure 9.4 shows such a diode in two different circumstances. In both situations the metal electrodes that are bonded to the ends of the silicon are connected through light bulbs to a battery. The two situations differ only in the orientation of the battery, but the consequences are drastically different.

In the situation labeled "forward bias", the pressure difference established in the metal electrodes by battery action pushes the (+) mobile carriers to the right through the boundary and pulls the (-) mobile carriers to the left through the boundary. So both types of charge carrier are flowing through the diode.

In the situation labeled "reverse bias", the (+) carriers in the P-type material are pulled to the left and the (-) carriers in the N-type material are pulled to the right — leaving a zone in the middle of the diode that has been substantially emptied of the charge carriers that are required for conduction. This zone is shown in white in the right hand diagram. The absence of charge carriers makes the zone an insulator which prevents flow in a reverse biased diode.

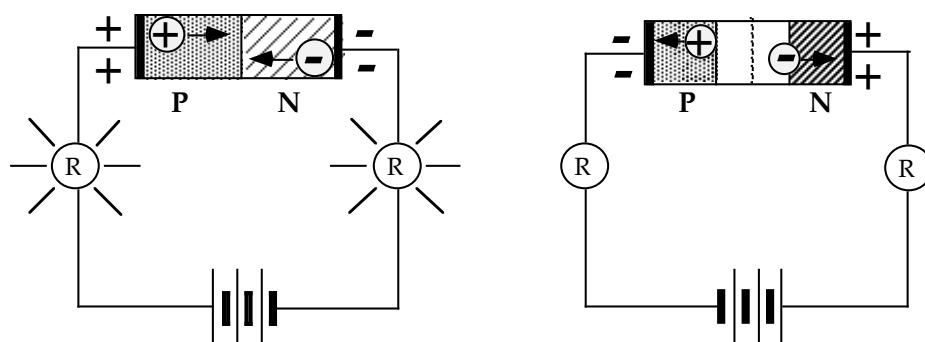
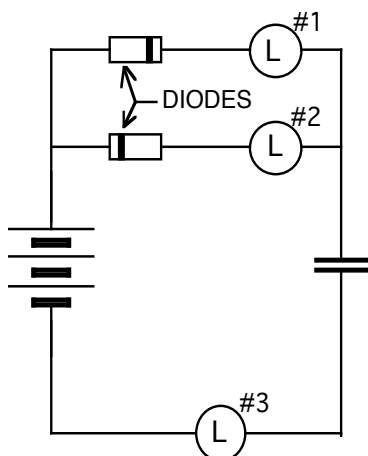


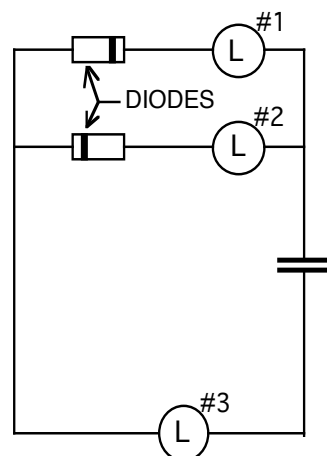
Figure 9.4  
DIODE WITH FORWARD BIAS      DIODE WITH REVERSE BIAS

## 9.5 Activity: Charging the capacitor through diodes and bulbs

A good way to investigate diodes in action is to use two of them in the charging and discharging of a capacitor. What do you think will happen when the circuit below is used for charging and discharging the capacitor? In assembling this circuit, make sure the diodes are connected so that one of them has the painted band at the end near its bulb and the other has the painted band at the end away from its bulb.



**Figure 9.5a**  
**CHARGING THE**  
**CAPACITOR**



**Figure 9.5b**  
**DISCHARGING THE**  
**CAPACITOR**

Charge the 25,000  $\mu\text{f}$  capacitor using the circuit in Figure 9.5a, and then discharge by removing the battery and connecting the free ends of the wires as in Figure 9.5b. Watch carefully how the bulbs light.

1. What happened? Which bulbs lit during each process?
2. How do you think the diodes are affecting the flow of charge in the circuit?
3. A diode sometimes acts as a conductor and sometimes as an insulator. What do you think determines when the diode conducts and when it does not?
4. What does the painted band indicate about charge flow ?

## 9.6 Activity: How diodes are used to convert AC to DC

Batteries produce a constant pressure difference which causes charge to flow in one direction. We call this flow **DIRECT CURRENT** — or often just **DC**. Power companies have found that it is easier and cheaper to generate and transmit **ALTERNATING CURRENT** — often just called **AC**. The direction of charge flow in an AC circuit is continually reversing — caused by a continually reversing potential difference at the terminals of the AC generator. North America uses “60 cycle” AC generators, which means that the flow is driven forward 60 times and backward 60 times each second. A Genecon can be used to drive alternating current, but at a much lower frequency.

Connect the two-color light emitting diode (LED) to the Genecon as shown in Figure 9.6a below. Turn the handle back and forth about 90° once each second. Be gentle so that you do not damage the plastic gears.

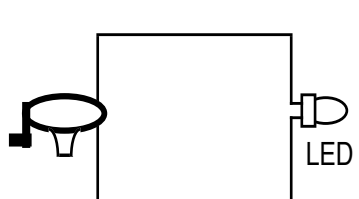


Figure 9.6a  
GENECON WITH LED

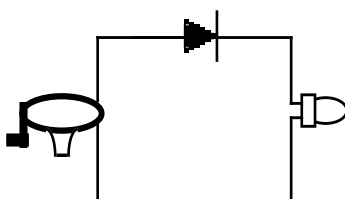


Figure 9.6b  
WITH DIODE ADDED

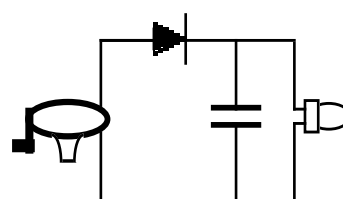


Figure 9.6c  
WITH CAPACITOR ADDED

1. Observe the LED as the handle is turned back and forth. Record your observations.
2. Add the diode as shown in Figure 9.6b, and observe the LED as the handle moves in both directions.
3. Connect the 25,000  $\mu\text{f}$  capacitor as shown in Figure 9.6c and record your observations.

## 9.7 Exercise: Graphing AC line voltage

Figure 9.7a below shows how the voltage supplied by the power company's AC generator varies with time, reversing direction (forward and backward) to produce 60 complete cycles or waves each second.

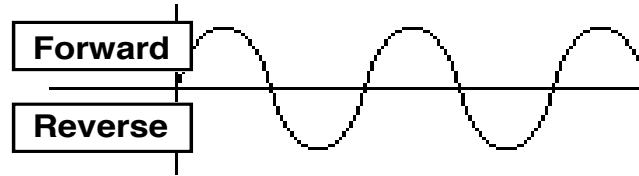


Figure 9.7a  
AC LINE VOLTAGE

1. In Figure 9.7b, sketch over the dotted lines for AC line voltage to describe the voltage across the LED for a rectifier circuit like that shown in Figure 9.6b with one diode and no capacitor.
2. In Figure 9.7c, sketch the voltage across the LED for a rectifier circuit like that shown in Figure 9.6c with a diode and a capacitor added to “fill in the gaps”.

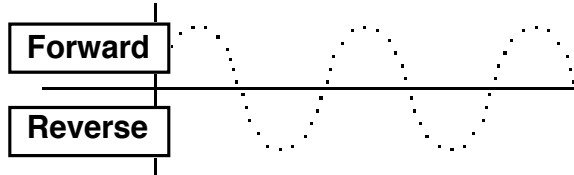


Figure 9.7b

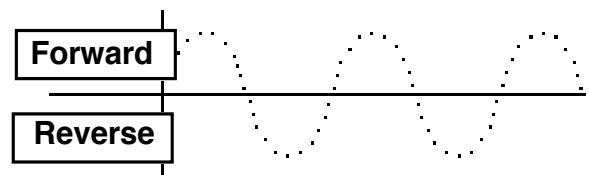


Figure 9.7c

Many types of electronic equipment – from radios to computers – require direct current to operate correctly. With 60 cycle current the gaps are very short, and the charging and discharging of the capacitor can fill the gaps to give very smooth DC current — which allows the equipment to be run from the AC power. This avoids the need for expensive batteries as a DC source.

## INVESTIGATION TWO: HOW ARE TRANSISTORS USED IN CIRCUITS?

### 9.8 Commentary: What are transistors?

In the world of electricity where wires act like pipes, batteries are pumps and capacitors are tanks, semiconductors act like a valve. A diode is a one-way valve that allows charge to flow one way but not the other; in effect it is either 'on' or 'off'. A more complicated semiconductor device called a "transistor" is a valve that can be controlled gradually like a kitchen faucet. It is this faucet-valve action that makes semiconductors so important to electronic devices.

Transistors are semiconductor devices that have three terminals. Two of the terminals are just entrance and exit ports for a stream of charge carriers moving in an electric circuit. The third terminal is like the faucet handle that turns the stream on/off by means of HIGH/LOW electric pressure due to some kind of activity in a separate circuit. The terminal that brings conventional charge flow into a field effect transistor is called the DRAIN. The outflow terminal is called the SOURCE. (If it seems like the names DRAIN and SOURCE are backwards, you are right! They were named in reference to electron flow. Remember that any circuit can be analyzed in terms of either conventional flow or electron flow, but the results will be the same in either case.



### 9.9 Activity: The metal-oxide-semiconductor field effect transistor (MOSFET)

WARNING!!! A field effect transistor (FET) of the metal-oxide-semiconductor (MOS) variety used in this activity is easily damaged by static electricity. It is packed with a piece of conducting foam placed over the leads to protect the device by keeping all three terminals at the same electric pressure. A few extra precautions will help protect the device during this activity:

1. Do not touch the Gate unless you are also touching some other part of the circuit.
2. Connect the Gate to the Source when it is not in use. (Use a wire to do this.)
3. Place the conducting foam back over the leads after the activity is finished.

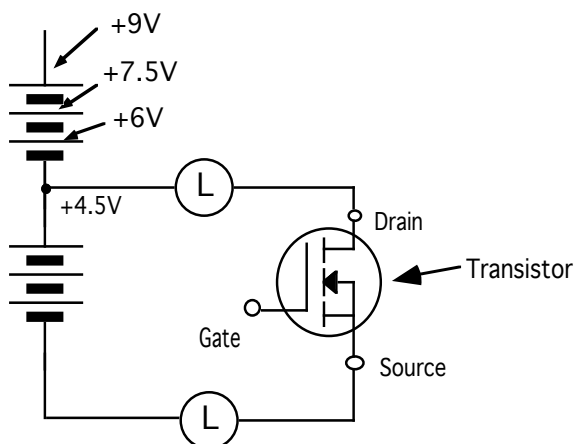


Connect the circuit as shown in Figure 9.9. Check the diagram on the package to be sure that the wires are connected to the correct terminals of the transistor.

Remember to keep the Gate connected to the Source until the entire circuit is wired.

Remove the protective connecting wire only when you are ready to experiment. At the moment you remove this wire, the electric pressure in the Gate will be the same as in the Source.

The light bulbs should be off, showing that the transistor is preventing flow from the Drain to the Source. Now let's see if we can turn the flow on. With one hand holding the +9 volt point on the second battery, touch a finger of your other hand to the Gate terminal of the transistor. A 9 volt pressure difference will then drive a small amount of extra charge through your body and into the Gate. (You have become part of the separate circuit controlling the Gate.) Somehow, the presence of this extra charge in the Gate turns on the flow from the Drain to the Source.



**Figure 9.9**  
**TRANSISTOR CIRCUIT**

1. What is the evidence that flow is now taking place from the Drain to the Source?
2. What is the evidence that extra charge in the Gate made this happen?
3. Does the extra charge stay in the Gate when you remove your finger? What's the evidence?
4. Can you devise a way to turn the bulbs off? Why do you think this works?
5. A faucet can be opened part way. Can the transistor Gate turn the Drain-to-Source flow part-way on? Try doing this by connecting the Gate to the 4.5-volt point, then the 6.0 and then the 7.5-volt points in the second battery and observing the brightness of the light bulbs. A paper clip can be used as a probe to reach into the contact points in the second battery holder; hold the paper clip in one hand and touch the Gate with the other. What do you observe?
6. Does the experiment you have just performed reveal a limit to how bright the lamps can become as the Gate is raised to higher electric pressure relative to the Source? What is the evidence? Explain your result.

## 9.10 Commentary: What is going on inside the MOSFET?

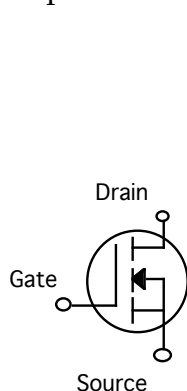
How does the presence of extra charge in the transistor Gate make Drain-to-Source flow possible? To find the answer, we must know something about the architecture of the transistor.

The use of metal-oxide-semiconductor (MOS) technology to make a field effect transistor (FET) begins with a small slab of P-type silicon. As illustrated in the diagram in Figure 9.10b, two puddles of N-type material are diffused onto the left side of the slab to form the “Drain” and “Source” terminals. A very thin insulating layer of silicon dioxide (shown in white) is formed over these terminals, and a conducting layer (shown in black) is added by layering aluminum over the silicon dioxide. The aluminum layer is the “Gate” that turns the flow from Drain to Source on and off.

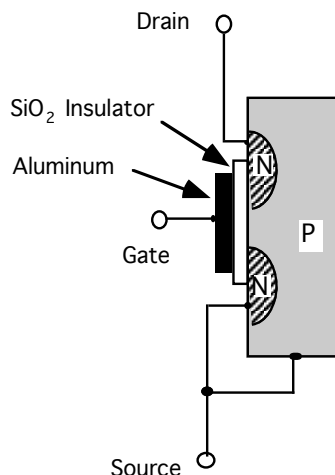


Remember from our investigation of diodes that charge cannot flow from N-type into P-type material. So there is no flow from the Drain to the Source as long as the N-type Drain and Source areas are separated by the P-type slab.

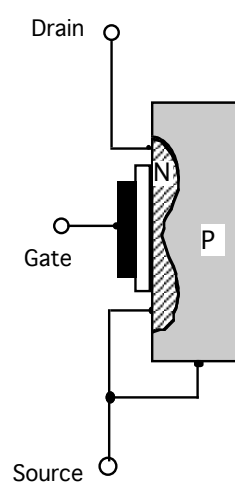
Flow will occur, however, if the extra charge in the Gate creates an N-type channel through the P-type slab — a channel that extends from the Drain to the Source as shown in Figure 9.10c. That is exactly what happens if there is sufficient positive charge on the Gate to give it a HIGH electric pressure.



**Figure 9.10a**  
**MOSFET SYMBOL**



**Figure 9.10b**  
**NONCONDUCTING**



**Figure 9.10c**  
**CONDUCTING**

When extra positive charge is present in the aluminum layer that forms the Gate, that layer will be surrounded by a halo of high electric pressure (electric potential). This halo will increase the actual pressure in the portion of the P-type slab situated just the other side of the insulating layer — because that part of the slab now finds itself inside the potential halo. The positive charge carriers that normally inhabit the P-region will then be pushed away from the Gate, and negative carriers will be pulled in from the two N-regions. These shifts of mobile charge will expand the two N-regions and make their edges move closer to each other.



When the edges meet, a thin channel of N-type material is opened next to the insulating layer of silicon dioxide as shown in Figure 9.10c. Charge can now flow through this channel from the Drain to the Source without crossing a boundary between N-type and P-type material. Just as the handle of a kitchen faucet controls the rate of flow of water by changing the size of the channel through which the water flows, so the potential halo surrounding the transistor Gate controls the rate of flow of charge by changing the size of the N-type channel through which the charge flows.



Since the Gate is insulated from the rest of the transistor, no current flows from the Gate lead once it is charged. MOSFET functioning depends crucially on this insulating layer being very thin, so that the potential pressure halo around the Gate can strongly influence the semiconductor on the other side of the insulator. But that makes the insulating layer easily damaged by the static electricity which creates very large potential differences as a person walks across a rug or slides on a plastic chair. When you touch the Gate lead without grounding yourself you may cause a spark to jump through this layer and form a conducting path through it. In electronics factories, workers who handle MOSFETs are required to wear a grounding strap on their wrist.

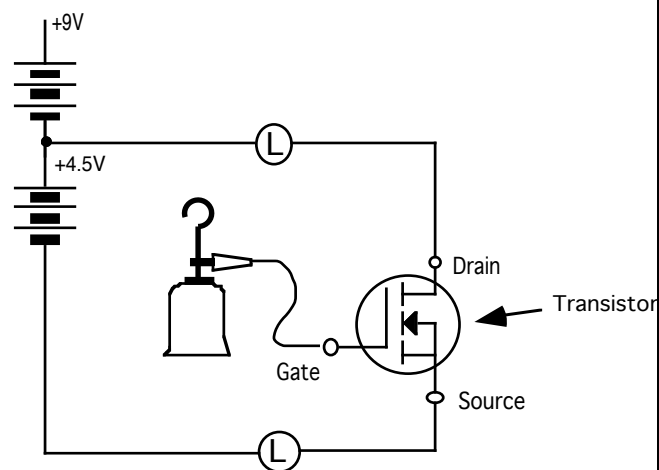
### 9.11 Exercise: Analyzing the MOSFET

1. Look at Figures 9.10b and 9.10c. Based on these illustrations, why does extra charge sent into the Gate stay there until something is done from the outside to get it out?
2. Again, study Figures 9.10b and 9.10c. Does the extra charge in the Gate influence the Drain-to-Source region directly or indirectly?

## 9.12 Activity: The magic wand

Your “magic wand” in this Activity will be an acrylic plate that has been charged (+) by rubbing it on a foam plate. You can turn the light bulbs on or off by waving this wand toward or away from the metal “detector” to which the Gate will be connected. You can make the performance more dramatic by saying a few magic words like “VOLTS! COULOMBS! AMPERES!” as you wave the wand.

Connect a large piece of metal to the Gate of your FET circuit — a soft drink can or a weight-hanger — to serve as a reservoir of mobile charge that can be driven into the Gate. Remember to discharge any static electricity from the reservoir before connecting it to the Gate of the transistor. This reservoir will be the detector (antenna) when you wave the wand. It must be carefully insulated from the rest of the circuit. A good way to do that is to place it on a glass beaker. Figure 9.12 shows a weight-hanger detector on top of an inverted glass beaker. (If you use a soda can as the detector/antenna, clip the lead from the Gate to the pop-top.)



**Figure 9.12**  
**MAGIC WAND CIRCUIT AND DETECTOR**

Check that the light bulbs can still be turned on by touching the 9-volt terminal of the second battery pack with one hand and touching the weight hanger with the other; and that it can be turned off by contacting the 4.5-volt terminal or the Source.

1. Turn the light bulbs on. What do you know about the charge on the gate and the condition of the internal P-type and N-type semiconductors?

If an object with negative charge is brought near the weight hanger, it will attract the positive charge away from the Gate, reducing the electric potential halo around the Gate, and the lights will go out. We found in Section 9 that rubbing an acrylic plate on a foam plate leaves the acrylic with excess positive charge and the foam with excess negative charge.

2. Rub an acrylic plate and foam plate together vigorously. What is the effect on the light bulbs as you move the foam plate toward the detector?

3. Note that the electric pressure in the antenna is lowered just because there is a negative charge in the nearby space. This is occurring without touching. How far away can you make this action-at-a-distance work?

4. Try other charged 'magic wands'. Rub other substances together to charge them, such as silk, acrylic, glass, plastic wrap, and overhead transparency. Or comb your hair vigorously to charge the comb. Then use the magic wand circuit to determine what charge is on each object.

Once you have demonstrated that negatively charged objects can be used to turn the light bulbs off, you should experiment with positively charged objects to turn them on. First turn the bulbs off by touching the 4.5-volt terminal and the weight-hanger detector at the same time. (Be careful that all charged objects are a long way away.) Now any nearby object that is positively charged will increase the electric pressure in the weight hanger and drive positive charge into the gate of the transistor. The potential halo of the extra charge in the gate will then open a conducting channel from the Drain to the Source — and turn the lamps on.

### 9.13 Activity: The potential halo of two objects

1. Touch the 4.5-volt point and the Gate to turn the bulbs off. Rub the foam and acrylic plates to charge them. Bring the positive acrylic close to the detector until the lamps are nearly full brightness. Speculate what will happen if you hold the acrylic in place and bring the foam plate up from the other side of the circuit — so that its LOW potential halo is added to the HIGH potential halo of the acrylic? What do the bulbs do when you try this?

2. Hold the charged foam and acrylic plates about 40 cm apart and parallel to each other — like the plates of a large charged capacitor — with the detector between them. Move them left and right, together as a unit, and observe how the potential varies in the space between the plates according to how the bulbs change brightness. Based on your observations, which plate is positive?

### **SUMMARY EXERCISE**

1. How does a diode control charge flow in a circuit?
  
  
  
  
  
  
  
  
  
  
2. Explain these useful applications of diodes:
  - a) How can diodes be used to convert AC to DC?
  
  
  
  
  
  
  
  
  
  
  - b) How can a capacitor be used to smooth pulsating DC from the diode in an AC circuit?
  
  
  
  
  
  
  
  
  
  
3. Consider the role of electric potential in the operation of a field effect transistor:
  - a) Explain the operation of an N-channel FET in terms of the electric potential caused by charge on the Gate terminal.
  
  
  
  
  
  
  
  
  
  
  - b) How would a P-channel FET work?
  
  
  
  
  
  
  
  
  
  
4. How may a MOSFET be used to detect potential differences in the space outside charged objects?

5. A diode only allows current to flow through in one direction.

a. In a diode, does charge flow as conventional current, as electron flow, or some other current? Explain carefully.

b. Why can't current flow through in the opposite direction in a diode?