Semiconductors

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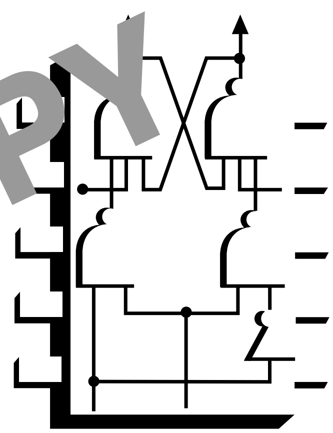
SEMICONDUCTORS

Lesson One

Introduction to Semiconductors



TPC Training Systems

25101

Lesson

1 Introduction to Semiconductors

TOPICS

Electron Flow and Semiconductors
Semiconductor Materials
Structure of Semiconductors
Semiconductor Doping
Conventional vs Electron Flow
Junction Diodes
Diode Characteristic Curves
Diode Specifications
Light-Emitting Diodes
Photoelectric Devices

OBJECTIVES

After studying this Lesson, you should be able to…

- Discuss the basic structure of a semiconductor atom and the movement of free electrons and holes.
- Discuss the purification and doping of semiconductors.
- Describe the *p*-type region, *n*-type region, and junction of a *pn* junction diode.
- Discuss the characteristic curves and specification ratings of a diode.
- Describe the operation of a light-emitting diode, a photoconductive device, and a photovoltaic device.

KEY TECHNICAL TERMS

Semiconductor 1.04 a material that, depending on certain conditions, acts as a conductor or as an insulator
Valence electron 1.09 an electron in the outer shell of an atom
Doping 1.13 adding controlled impurities to a semiconductor material
Diode 1.23 a device that conducts easily in one direction but not the other
Forward bias 1.25, 1.26 a potential applied in the direction that permits a current
Reverse bias 1.27 a potential applied in the direction that blocks current
Zener diode 1.34 a special diode designed to operate in the avalanche region with reverse bias
Light-emitting diode (LED) 1.40 a semiconductor device that converts electrical energy into visible light or invisible infrared radiation

Electronics is concerned primarily with the transfer of information. All electronic information is transferred by signals, generally in the form of frequency, current, or voltage. Electronic signals are used in industry to measure variables and to monitor and control processes and equipment.

This Unit presents the basic building blocks of modern electronics, components that make possible a wide variety of devices ranging from the simple calculator to the complex computer. Lesson One discusses the diode, the simplest of these components.

Electron Flow and Semiconductors

1.01 Electricity is difficult to visualize, but it has many similarities to hydraulics, as in water flow. Even the terminology is similar. Electrical *pressure* (voltage) causes a *current* or *flow* (amperage) of electrons—one amp(ere) = 6.28×10^{18} electrons passing a point in one second. The movement of electrons can be impeded, and such *resistance* is measured in ohms. The volume of electrons delivered, electrical *power*, depends on the combination of pressure, current, and resistance, and is expressed by Ohm's law:

$$E_{\text{volts}} = I_{\text{amps}} \times R_{\text{ohms}} \text{ (for direct current)}$$

For a certain resistance, $E \times I$ defines power, expressed as watts.

1.02 Electrical work of any kind—for example, producing light or heat or making a motor run—is done only when electrons move. Like a water wheel in the old mill stream, if the stream is full of still water, the wheel does not turn. The wheel turns only when the water moves.

1.03 As a water system has pipes, electronic circuits have conductors in the form of wires and printed circuit traces. Water systems have regulators and tanks, and electronic circuits have resistors and capacitors. These discrete components must be used in large numbers and carefully designed combinations to produce working systems. The development of semiconductors has simplified and reduced the size of electronic systems dramatically.

1.04 Normally, a conductor always conducts electron flow at a fixed rate, a carbon or wire-wound resistor always resists electron flow at a fixed value, and a disk or other capacitor always has the capacity to store a fixed quantity of electrons. In contrast, a *semiconductor* sometimes conducts electron flow, sometimes resists electron flow, and sometimes stores electrons. Semiconductors can perform these functions at variable and controllable rates, values, and quantities.

1.05 The operating characteristics of discrete components are described by a few specifications, but a semiconductor requires a large set of specifications to describe its characteristics and to determine its application. In addition, discrete components are fairly rugged in service, but have (relatively) short lives. They have obvious and simple failure modes, and failed components are easily identified and replaced. By comparison, semiconductors are subject to damage from many sources, but have extremely long lives. Failure modes are subtle and complex, difficult to identify, and often cannot be repaired except at high functional levels—that is, at the circuit board level rather than at the chip level.

Semiconductor Materials

1.06 Two elements have been widely used by the manufacturers of semiconductor devices—*germanium* and *silicon*. Germanium (Ge) was the most popular semiconductor material in the 1940s and early 1950s. Silicon (Si) technology was developed in the 1950s. Today silicon is the most widely used semiconductor material.

1.07 Another semiconductor material, *gallium arsenide* (GaAs), also is widely used in the semiconductor industry. Gallium arsenide is expensive and is used primarily in applications in which the ambient temperature is beyond the operating temperatures of germanium and silicon or in which very high speeds are required. Because silicon is the material most often used by today's semiconductor manufacturers, the remainder of this Lesson will focus on silicon.

Structure of Semiconductors

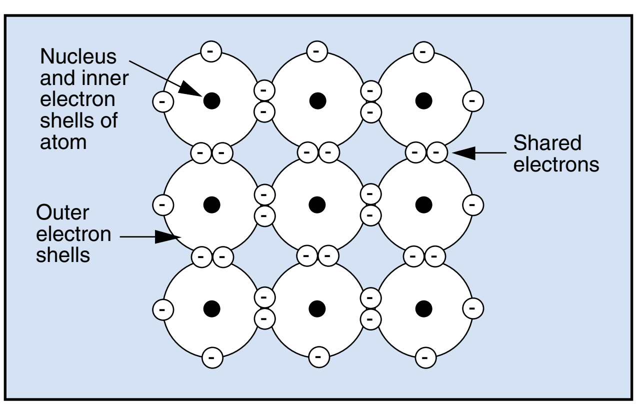
1.08 All semiconductor materials, silicon included, have crystalline structures. These structures, called *crystal lattices*, are three-dimensional and consist of periodically repeated identical cells. The crystal lattice must be as nearly perfect as possible. If it is flawed, the final semiconductor material probably will not perform properly.

1.09 Like all matter, silicon is made up of atoms. A silicon atom has 14 orbiting electrons that encircle the nucleus. The nucleus contains neutrons and 14 protons. Electrons are negatively charged, protons are positively charged, and neutrons are electrically neutral. The total atom also is electrically neutral, because the number of electrons equals the number of protons. Of the 14 orbiting electrons, only the outermost electrons are important in understanding semiconductors. The outer orbit contains four electrons called *valence* electrons.

1.10 Notice in the silicon crystal lattice shown in Fig. 1-1 that each neighboring atom shares its four valence electrons with other nearby atoms. This sharing is called *covalent bonding*. Once the bond is broken, the atom loses an electron from its outer shell. The loose electron is called a *free electron*. A *hole* remains where the electron used to be. Free electrons carry a negative charge and holes carry a positive charge. The movement of free electrons and holes enables a material to conduct electricity.

1.11 The number of free electrons is very important. As the number of free electrons and holes increases, the resistance of the material decreases and the material becomes more conductive. The number of free electrons and holes is determined partly by ambient temperature. At absolute zero (-273°C or -460°F), the number of free electrons is zero and the material acts as an insulator. At about room temperature, the material has a very low conductivity. At very high temperatures, the material conducts readily. That is, as temperature increases, conductivity increases and resistivity decreases.

Fig. 1-1. Silicon crystalline structure



1.12 Whenever a potential difference is applied across a semiconductor, heat is produced. This heat increases the temperature of the material and therefore decreases the material's resistivity and increases its conductivity.

Semiconductor Doping

1.13 The resistivity of a material at a specific temperature depends on its purity. Silicon is extracted from sand and made as pure as possible. The purer the silicon, the higher its resistivity. The addition of certain impurities lowers the silicon's resistivity to a value that is specified by the manufacturer. Once the silicon crystal is purified as much as possible, just the right amount and kind of impurities are added to it. The process of adding controlled impurities is called *doping*. Impurities are added to the semiconductor material to increase either the number of electrons or the number of holes in the material.

1.14 Impurities that add electrons are called *donor* materials, because they donate an electron to the silicon crystal. Donor materials have five electrons in the valence orbit, one more than the semiconductor material. Adding impurities that add electrons produces *n*-type material, named for the electrons' negative charge. Figure 1-2 shows atoms of an *n*-type material. Notice the extra free electron present when one atom of the impurity antimony (Sb) is added to silicon atoms. Other common donor materials are arsenic (As) and phosphorus (P).

1.15 Impurities that add holes are called *acceptor* materials, because they accept an electron from the silicon crystal. Acceptor materials have three electrons in the valence orbit, one less than the semiconductor material. The addition of acceptor materials produces *p*-type material, named for the holes' positive charge. Figure 1-3 shows atoms of a *p*-type material. Notice the void (hole) that is present when

Fig. 1-2. *N*-type semiconductor

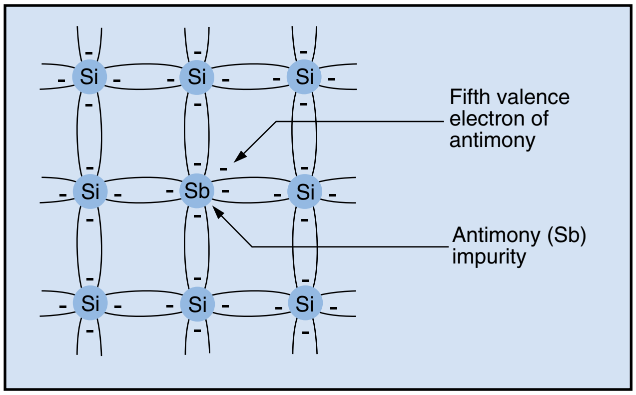
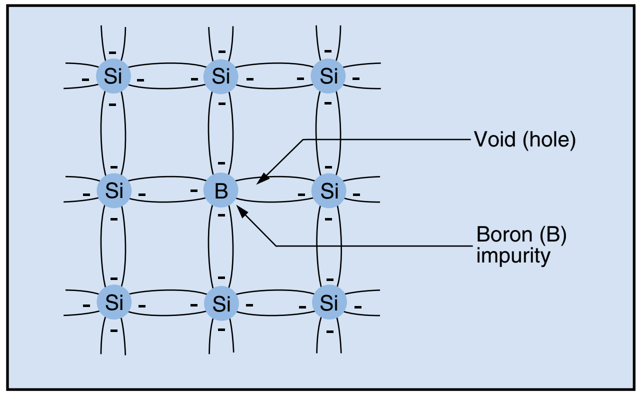


Fig. 1-3. *P*-type semiconductor



one atom of boron (B) is added to the silicon atoms. Other common acceptor materials are aluminum (Al) and gallium (Ga).

1.16 The purification of semiconductor materials is a very precise procedure. A semiconductor is considered sufficiently pure when it contains no more than one impure atom for every billion atoms of semiconductor material. Therefore, the purification process must be performed in the cleanest possible environment under very tightly controlled conditions. Undesired impurities damage silicon for semiconductor purposes.

1.17 The doping of semiconductor materials also must be very carefully controlled, because a relatively small amount of doping material greatly reduces the resistivity of the silicon. For example, the *n*-type material produced when phosphorus is added to pure silicon conducts electricity quite easily, although the doping level is so small (perhaps one part in a million) that the phosphorus atom is completely surrounded by silicon atoms.

1.18 It is possible for valence electrons to absorb enough energy from natural sources—for example, light and heat—to break the bonding of the atoms. Thus, a few holes also are present in *n*-type material. However, the number of free electrons is always greater than the number of holes in *n*-type material. For this reason, the free electrons in *n*-type material are called *majority carriers* and the holes are called *minority carriers*.

1.19 *P*-type materials also can be created by adding only a small amount of impurities—boron, for example. The doping level is so small that the boron atom is completely surrounded by silicon atoms. Because the boron atom has only three electrons, it captures an electron from the silicon crystal and thus leaves a hole in the crystal.

1.20 A few free electrons are present in *p*-type material. However, the number of holes is always greater than the number of free electrons in *p*-type material. Therefore, in *p*-type material, the holes are the majority carriers and the free electrons are the minority carriers, just the opposite of *n*-type material.

The Programmed Exercises on the next page will tell you how well you understand the material you have just read. Before starting the exercises, remove the REVEAL KEY from the back of the book. Read the instructions printed on the Reveal Key. Follow these instructions as you work through the Programmed Exercises.

1-1. Substances that conduct electricity depending on certain conditions are called ________.	1-1. SEMICONDUCTORS Ref: 1.04
1-2. The protons in an atom are positively charged and the ________ are negatively charged.	1-2. ELECTRONS Ref: 1.09
1-3. If an atom loses an electron from its outer shell, it leaves a(n) ________.	1-3. HOLE Ref: 1.10
1-4. As the temperature of a semiconductor increases, its resistivity ________.	1-4. DECREASES Ref: 1.11
1-5. The purer the silicon, the ________ its resistivity.	1-5. HIGHER Ref: 1.13
1-6. Doping means adding controlled ________ to a purified semiconductor.	1-6. IMPURITIES Ref: 1.13
1-7. There are more free electrons than holes in ________ material.	1-7. *n*-TYPE or DONOR Ref: 1.14
1-8. In *p*-type material, holes are the ________ carriers and free electrons are the ________ carriers.	1-8. MAJORITY; MINORITY Ref: 1.20

Conventional vs Electron Flow

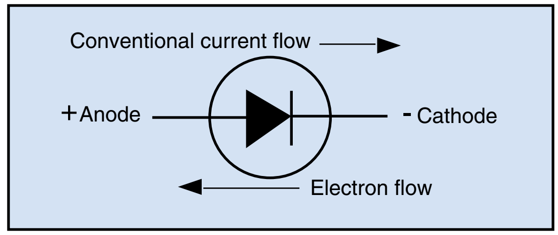
1.21 To understand the movement of charges and current inside a semiconductor, you need to understand the difference between conventional flow and electron flow. The two concepts of electrical flow are illustrated in Fig. 1-4. In 1750, Benjamin Franklin developed a theory of electrical flow. He thought of electricity as an invisible fluid that was part of any material. Franklin believed that a material with more fluid than normal had a positive charge and one with less fluid than normal had a negative charge. He said that electrons moved from positive (excess) to negative (shortage). Franklin's theory is now known as *conventional flow* or *conventional current*.

1.22 Scientists later discovered that electrons actually move from negative to positive, while holes move from positive to negative. At the atomic level, only electron flow presents the correct picture. Otherwise, either conventional flow or electron flow is valid in that both approaches produce the same answers mathematically. Much of today's engineering literature still uses conventional flow. However, this text uses electron flow because it describes current more accurately.

Junction Diodes

1.23 Semiconductor crystals can be produced with both a *p* region and an *n* region. The boundary where the two regions meet is called a *junction*. A device with a *pn* junction is called a *pn diode* or a *junction diode*. A *diode* is a device that uses *p*-type and *n*-type material to conduct current in one direction and to block current in the other direction. This one-way electron flow is described as *unidirectional*. The symbol for a diode is shown in Fig. 1-5. The arrow points in the direction of conventional flow (positive to negative), but the electrons actually flow from negative to positive.

Fig. 1-5. Diode symbol



1.24 Figure 1-6 on the following page shows the structure of a *pn* junction diode. The two regions of the diode are not connected together mechanically. Rather, it is the behavior of the electrons and holes near the junction that allows current in only one direction.

1.25 Figure 1-7 on the following page shows a *pn* junction diode connected to a DC source. The negative terminal is connected to the *n* region, and the positive terminal is connected to the *p* region. A diode that is connected in this way—with negative to negative and positive to positive—is said to be *forward-biased*. Additional bias can be applied from an external voltage source to provide control capability.

1.26 Like charges repel and unlike charges attract. For this reason, both the negatively charged electrons in the *n* region and the positively charged holes in the *p* region move toward the junction. The electrons fall

Fig. 1-4. Two directions of electric current

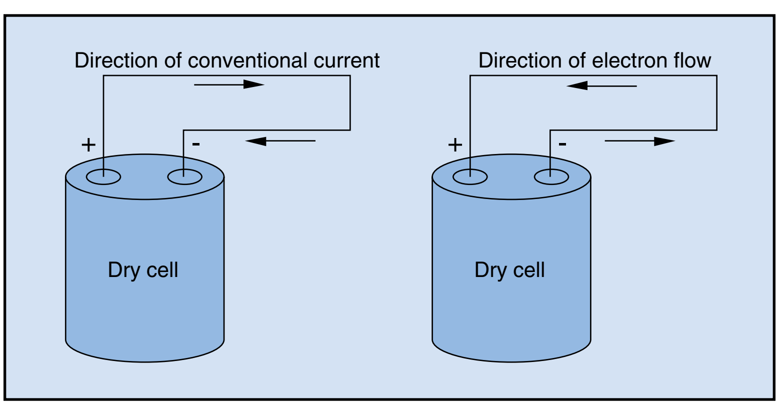
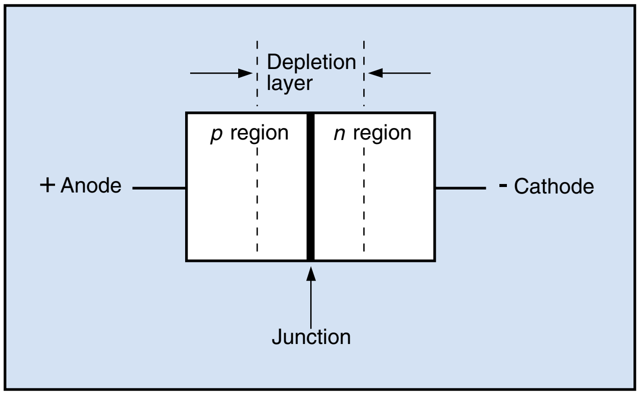


Fig. 1-6. Junction diode structure



into the holes at the junction and keep moving to the left by means of holes that are moving to the right. At the left, the electrons leave the crystal and flow toward the positive terminal of the battery. At the right side of the crystal, electrons are constantly being pulled in. Thus, the movement of the electrons from negative to positive and the movement of the holes from positive to negative causes the diode to conduct.

1.27 If the battery terminals are reversed, as shown in Fig. 1-8, the electrons move toward the positive terminal and away from the junction, and the holes move toward the negative terminal and away from the junction. A diode that is connected in this way—with negative to positive and positive to negative—is said to be *reverse-biased*. Because holes and electrons flow away from the junction, very few meet and there is very little current. The area near the junction is called the *depletion layer*.

1.28 A diode that is reverse-biased does permit a small amount of current. The reason is that thermal (heat) energy continuously dislodges a very small number of electrons and holes near the junction, creating pairs of free electrons and holes in the depletion layer. Again, external bias can be applied.

1.29 The depletion layer forces a free electron to the right, in turn forcing an electron from the end of the crystal. At the same time, the depletion layer forces a hole to the left and this extra hole allows an electron to enter the left end of the crystal. Thus, the diode carries a small current, even if it is reverse-biased. However, the important point is that current is *approximately* zero in a reverse-biased diode.

1.30 A diode acts somewhat like a mechanical switch in that it permits a current in one direction and prevents it in the other. However, diodes have two definite advantages over mechanical switches:

- Diodes can operate much faster, because they are controlled by electric polarity.

- Diodes generally last much longer, because the only moving parts are the electrons.

Diode Characteristic Curves

1.31 The curve in Fig. 1-9 shows the forward- and reverse-bias characteristics of a junction diode. Characteristic curves like this one can be seen on the screen of a special oscilloscope (called a curve tracer) when the scope is connected to a diode. The current

Fig. 1-7. Forward-biased diode

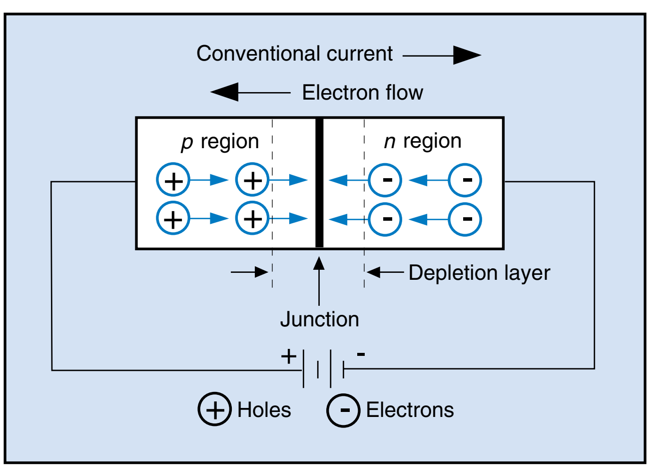
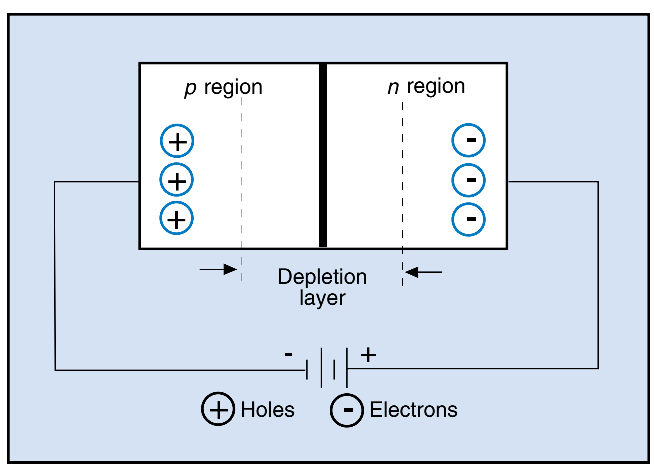


Fig. 1-8. Reverse-biased diode



through the diode, measured in milliamps, is plotted along the vertical line. The potential difference across the diode, measured in volts, is plotted along the horizontal line. Notice that when the diode is forward-biased and a small voltage is applied, the current is quite large.

1.32 What happens when a diode is forward-biased? There is an electric field at the junction. The strength of the field increases as electrons move from the depletion layer to the *n* region. At equilibrium, the electric field is equivalent to a potential difference called the *barrier potential*.

1.33 When the applied potential is greater than the barrier potential, larger numbers of free electrons cross the junction, and the current increases rapidly. The potential difference at which this happens is sometimes called *knee voltage* because the curve resembles a bent knee. The barrier potential, or knee voltage, at 25°C is about 0.7 V for silicon diodes and about 0.3 V for germanium diodes. For both materials, the barrier potential decreases 2 mV for each °C increase.

Application 1-1

A control systems technician for a company that manufactures conveyor belts needed to solve a problem for a customer with a variable speed conveyor. At the maximum dial setting of 10, the conveyor was operating too fast, causing some of the material to fall onto the floor. The customer asked how to limit the speed setting to 8.

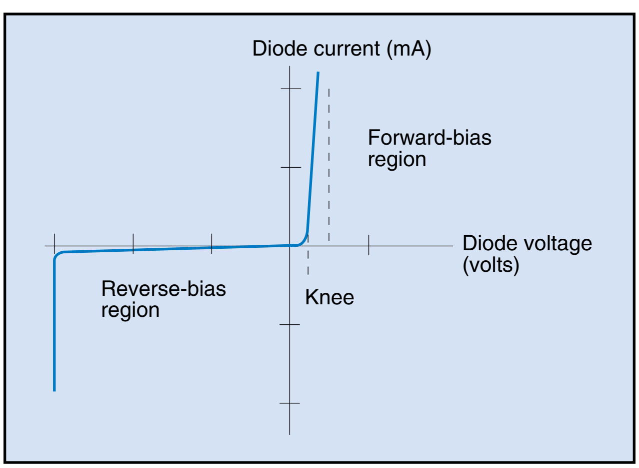
The input to the control system was a linear DC voltage ranging from 0 V (off) to 10 V (maximum speed setting of 10). The speed setting of 8 corresponded to a nominal 8-V output from the potentiometer dial as an input to the control system.

The technician's solution was to install a simple circuit between the potentiometer and the control system input that would limit the input voltage to a nominal 8 V. This circuit, sometimes called a clipper circuit, consists of a diode and a reference voltage (V_R). The diode is used as a switch that does or does not permit current, depending on the voltage. For this application, the reference voltage is 7.3 V (8 V minus 0.7 V barrier potential):

- If the input voltage is less than or equal to 7.3 V, the current is zero. With no current, the output is equal to the input voltage.
- If the input voltage is greater than 7.3 V, the output voltage remains at 7.3 V.

This means that for dial settings of up to 8, the nominal voltage (and thus the conveyor speed) corresponds to the setting. For dial settings of 9 or 10, the circuit clips the voltage (and the conveyor speed) to 8. Even if an operator accidentally selects the maximum dial speed, the conveyor actually operates at the speed setting of 8. The customer's problem was solved.

Fig. 1-9. Characteristic curve of a *pn* diode

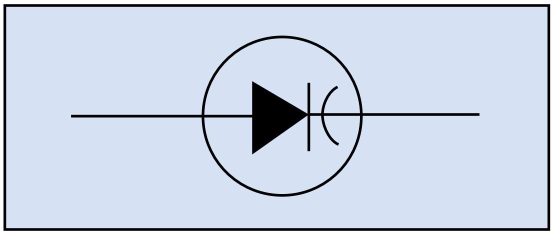


1.34 *Zener diodes* are designed to operate with reverse bias. Diodes that are heavily doped have a narrow depletion layer with a very strong electric field. Diodes exhibiting the *zener effect* have an electric field that is strong enough to create free electrons by forcing valence electrons out of their orbits. At the breakdown voltage, a zener diode has a sharply bent knee and an almost vertical increase in current, which indicates an almost constant voltage.

1.35 Because zener diodes are designed for use in the avalanche region, which was formerly called the *breakdown region*, zener diodes sometimes are referred to as *breakdown diodes*. Sometimes they also are called *voltage-regulator* diodes, because that is their main use.

1.36 When the diode is reverse-biased, at first there is no significant amount of current. However,

Fig. 1-10. Varactor diode symbol



when the *avalanche voltage* is reached—the voltage at which the diode ceases to block current—the current increases very quickly in the negative direction. If the diode's avalanche voltage is exceeded, the diode usually is damaged or destroyed. The avalanche voltage depends on the kind of diode and how heavily it is doped.

1.37 Reverse-biased diodes act as capacitors and can store energy when they are not conducting. Their *capacitance* (amount of stored energy) varies with the bias voltage. These characteristics can be used to create tunable (adjustable) *varactor* diodes, which can replace conventional multicomponent tunable capacitors in many applications. Solid-state varactors are simpler, smaller, and more stable than conventional capacitors, and they also last longer. The varactor diode symbol is shown in Fig. 1-10.

Diode Specifications

1.38 Manufacturers provide diode specifications to help in the selection of correct diodes for particular applications. Different ratings are given for different kinds of diodes. However, there are several ratings that are important to all diodes:

- Forward current (I_F) is the maximum current that a diode can carry without being destroyed by heat. When forward-biased, the diode generates power (and resulting heat) equal to the current times the voltage. The diode must be able to *dissipate* (get rid of) the heat safely.

- Forward voltage (V_F) is the voltage required at the desired forward current. It is greater than 0.7 V for silicon diodes.

- Reverse current (I_R) is the current that passes through a reverse-biased diode. It is less than 1 μA for silicon diodes.

- Reverse avalanche voltage (sometimes still called reverse breakdown voltage, or V_{BR}) is the reverse-bias voltage that causes the diode current to increase suddenly in the negative direction.

- Reverse recovery time (t_{rr}) is the time that it takes the diode to switch from forward to reverse bias—that is, the time needed to turn off the diode.

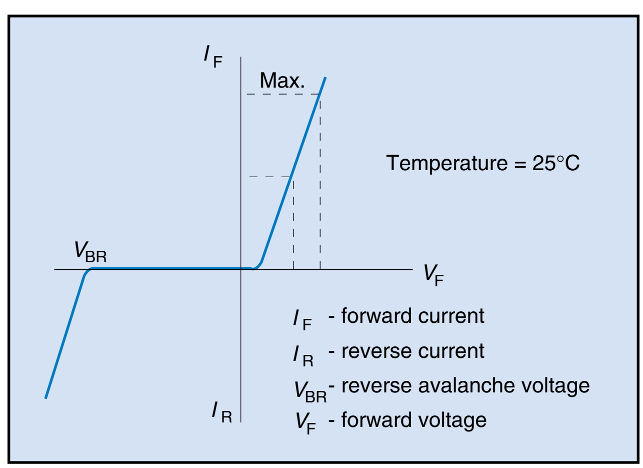
1.39 Figure 1-11 shows a characteristic curve that illustrates each of these specifications except t_{rr}. All of these diode specifications are rated at 25°C. Note that changes in temperature change the values of these specifications.

Application 1-2

A repair technician who worked in her company's calibration department was given a benchtop DC power supply that another repair tech had just repaired. When the power supply was connected and turned on, the fuse blew. One of the diodes in the bridge rectifier was shorted.

The voltage rating on the diode was 300 V in a 120-V AC circuit. The 300-V diode should have been able to handle 170 V, because the peak voltage in a 120-V circuit is about 170 V. The current rating on the diode was 1.0 A. The power supply output was only 240 mA, so the diode also should have been able to handle the current.

Fig. 1-11. Diode characteristic curve and data points



What was wrong? The technician checked the circuit schematic diagram to see which way the diode should be connected. She knew that a replacement diode always must be connected in the same direction as the original diode. She rechecked the circuit and found that the diode had been connected backwards. The backward diode meant that all of the other diodes in the bridge had carried too much current before the fuse blew. Because the other diodes also might have been damaged, she replaced all of the diodes in the circuit, making sure to connect them correctly. Then she turned on the power, and the power supply worked just as it should.

Light-Emitting Diodes

1.40 The *light-emitting diode* (*LED*) is a special kind of diode that looks like a tiny light bulb. The difference between an LED and a regular light bulb is the way the light is produced. In a regular light bulb, the filament is heated by a current until the filament glows brightly. An LED produces radiation by allowing a forward current to pass through it in such a way that the electrons and holes in the semiconductor combine to produce visible light or radiation that is invisible to the human eye (*infrared* light). An LED produces light only when it is forward-biased.

1.41 The brightness of the light depends on the current through the LED. The greater the current, the brighter the light. Most LEDs have a maximum forward voltage rating of about 1 or 2 V and a maximum forward-bias current rating of about 50 mA.

1.42 Figure 1-12 shows the construction of an LED. At the junction, the electrons in the *n* region combine with the holes in the *p* region, emitting photons (radiated energy). The metal comb anode is designed in such a way that light passes through the top surface.

1.43 LEDs produce different colors of light—red, green, blue, yellow, or orange—depending on the semiconductor materials. The color characteristic makes the LED especially useful in electronic circuits. A green LED often indicates that power to the equipment is turned on and is operating correctly. Red and yellow LEDs often indicate warnings of a specific condition—for example, a process variable that has reached an upper limit.

1.44 The symbol for an LED is shown in Fig. 1-13 on the following page. As with other diodes, the arrow in the LED symbol points in the direction of conventional current rather than electron flow.

Photoelectric Devices

1.45 Some semiconductor materials are used to produce photoelectric devices. These materials respond to light in one of two ways:

- *Photoconductive* devices conduct current in the presence of light and block current in darkness.
- *Photovoltaic* devices generate voltage in the presence of light.

Fig. 1-12. Construction of a light-emitting diode (LED)

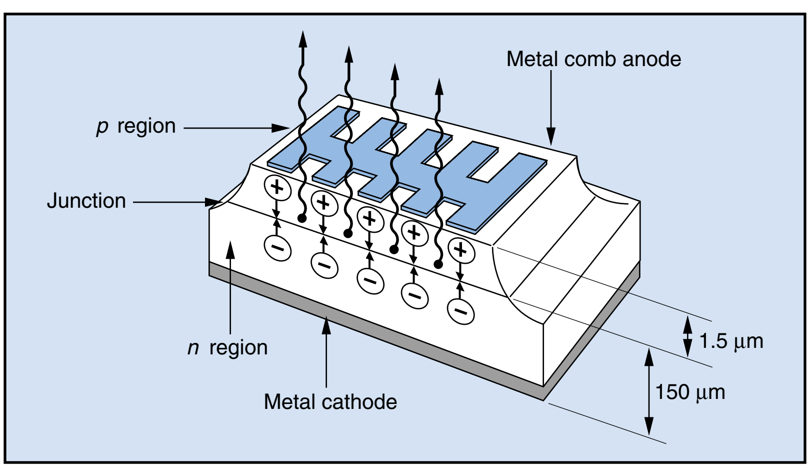
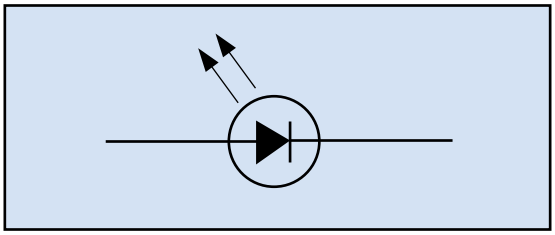


Fig. 1-13. LED symbol

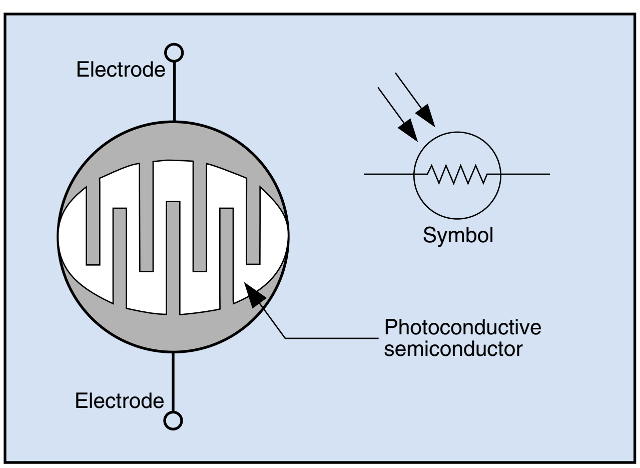


1.46 **Photoconductive devices.** The conductivity of a photoconductive device increases when light shines on it. As the intensity of the light increases, the device increases in conductivity and decreases in resistance. For example, under dim light—about 0.1 lumen per square foot (lm/ft^2)—the resistance of the device is about 50 kΩ. Under very bright light (about 100 lm/ft^2), the resistance decreases to about 5 kΩ.

1.47 Figure 1-14 shows a photoconductive cell and its symbol. The zigzag arrangement of the semiconductor material increases the device's sensitivity to light, an important feature. For example, some photoconductive devices—especially those made of cadmium sulfide (CdS)—are used to adjust a camera lens opening according to the amount of light.

1.48 Some semiconductor materials—for example, cadmium selenide (CdSe)—respond to infrared light rather than to visible light. Photoconductive devices made of these materials are often used in security systems. As an intruder's arm or leg passes between the infrared light and the photoconductive device, the device responds by sending an alarm to the security system. Intruders are not aware that the system is in operation, because they cannot see the infrared light.

Fig. 1-14. Photoconductive cell and symbol



1.49 Figure 1-15 compares the response to light of cadmium sulfide, cadmium selenide, and the human eye. Notice that the eye responds to different wavelengths of light somewhat like the cadmium sulfide semiconductor that is used in cameras.

1.50 **Photovoltaic devices.** A photovoltaic device, or *cell*, produces a potential difference between two layers when it is exposed to light. One kind of photovoltaic cell, called a *solar cell*, generates electric power when exposed to radiation from the sun. In recent years, the solar cell has been used as a source of electric power in remote areas of the world.

1.51 Figure 1-16 shows the construction of a photovoltaic cell and its symbol. Light passes through a glass window to the junction between the *p*-type semiconductor and the *n*-type semiconductor. The *p*-type material must be very thin so that as much light as possible reaches the junction. If enough light strikes a valence electron, the electron will break away from the atom and leave a hole in its place. This process produces a small potential difference.

1.52 The amount of current produced by a photovoltaic cell depends on the intensity of the light. Even with a very strong light, the voltage and current rating of a single photovoltaic cell is small. However, a great many cells connected in series and in parallel can generate voltages of up to 120 V DC and currents of several hundred amps. Photovoltaic cells are used in a wide variety of applications. For example, small photovoltaic cells power handheld calculators, and large panels of several hundred cells produce electricity for satellites orbiting in space.

Application 1-3

The owner of a small watch repair shop often works in a back room. He needed a security system that would ring a bell in the back room whenever a customer came through the front door.

The security systems company designed a simple, low-cost system that worked with a photovoltaic cell. A special light is mounted on one side of the doorway and a cell is mounted on the other side of the door,

Fig. 1-15. Comparison of responses to light

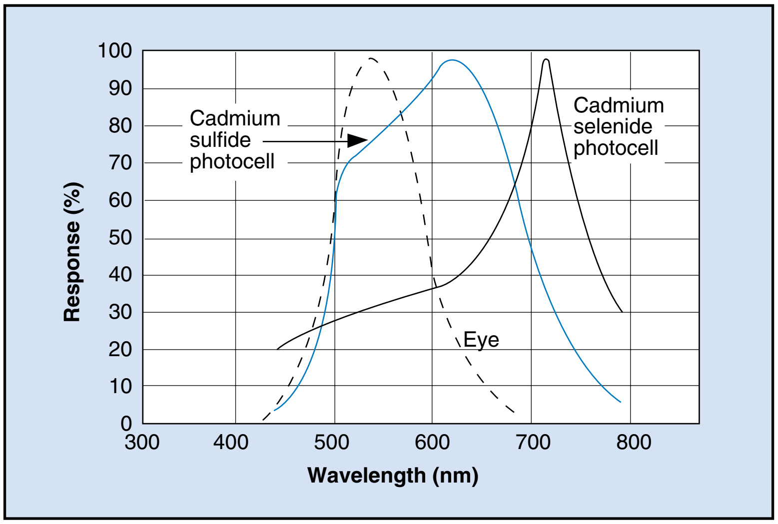
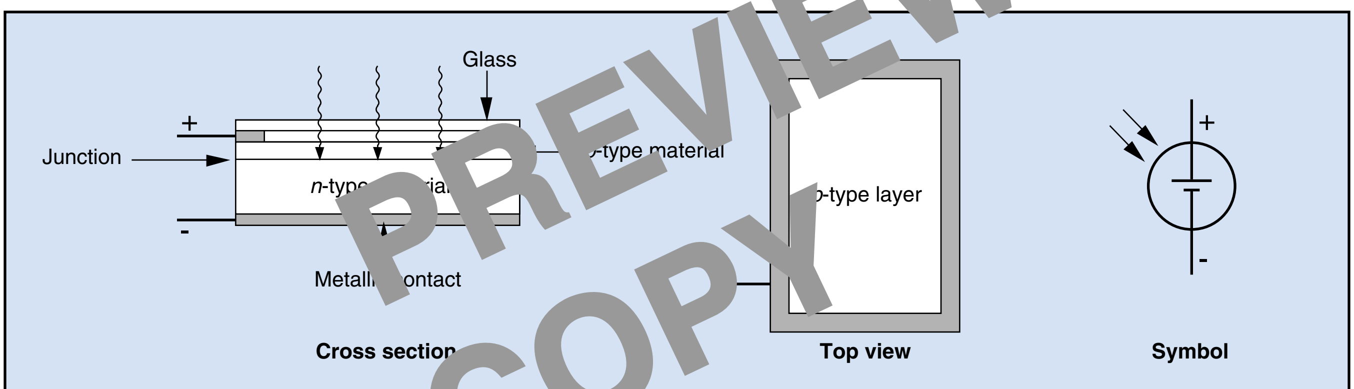


Fig. 1-16. Solar cell and symbol



directly across from the light. The output of the cell is connected to a diode that is biased to hold open a relay circuit whenever the cell senses the special light. When the light is blocked—as when a customer enters the shop—the diode shuts off and the relay circuit rings a bell in the back room.

Instead, the company could have installed a photoconductive device whose light is in the infrared region of the spectrum. However, this kind of system costs much more and its advantage of being invisible to the customer is not important to the watch repairer.

1-9. Actual electron flow is from ________ to ________, the opposite of conventional current.	1-9. NEGATIVE; POSITIVE Ref: 1.22
1-10. If a diode is forward-biased, ________ in the *n*-region and ________ in the *p*-region all move toward the junction.	1-10. FREE ELECTRONS; HOLES Ref: 1.26
1-11. A diode readily conducts electricity if it is ________-biased.	1-11. FORWARD Ref: 1.26
1-12. A plot of diode characteristics on a curve tracer shows ________ on the horizontal axis and ________ on the vertical axis.	1-12. VOLTAGE; CURRENT Ref: 1.31
1-13. If a diode's maximum forward current is exceeded, the diode will ________ and stop functioning.	1-13. OVERHEAT Ref: 1.38
1-14. A diode that converts current to light (radiation) is called a(n) ________.	1-14. LIGHT-EMITTING DIODE (LED) Ref: 1.40
1-15. Some photoconductive devices respond to ________ rather than visible light.	1-15. INFRARED Ref: 1.48
1-16. The solar cell, one kind of ________ device, generates electric power in response to radiation from the sun.	1-16. PHOTOVOLTAIC Ref: 1.50

Answer the following questions by marking an "X" in the box next to the best answer.

1-1. Silicon is most conductive at

- ☐ a. absolute zero
- ☐ b. very low temperatures
- ☐ c. about room temperature
- ☐ d. very high temperatures

1-2. Controlled impurities are added to pure silicon to

- ☐ a. balance the number of holes and electrons
- ☐ b. decrease its resistivity
- ☐ c. increase its resistivity
- ☐ d. increase the number of neutrons in the atom

1-3. Holes move in the same direction as

- ☐ a. atom flow
- ☐ b. conventional current
- ☐ c. electron flow
- ☐ d. ion flow

1-4. A junction diode consists of _______ semiconductor material.

- ☐ a. only *n*-type
- ☐ b. only *p*-type
- ☐ c. *n*-type and *p*-type
- ☐ d. *n*-type, *p*-type, and *j*-type

1-5. A forward-biased diode

- ☐ a. blocks electricity
- ☐ b. conducts electricity
- ☐ c. has bilateral flow
- ☐ d. has no *n* region

1-6. If the positive terminal of a voltage source is connected to the *n* section of a junction diode,

- ☐ a. free electrons in the *n* section move away from the junction
- ☐ b. free electrons in the *n* section move toward the junction
- ☐ c. holes in the *p* section move toward the junction
- ☐ d. the circuit has maximum conductivity

1-7. The depletion layer in a junction diode has

- ☐ a. free electrons as majority carriers
- ☐ b. free electrons as minority carriers
- ☐ c. holes as majority carriers
- ☐ d. very few electron-hole pairs

1-8. The avalanche voltage for a junction diode is the

- ☐ a. forward-bias voltage at which current increases suddenly
- ☐ b. maximum forward voltage of the diode
- ☐ c. reverse-bias voltage at which current increases suddenly
- ☐ d. voltage at which current is blocked

1-9. The LED

- ☐ a. emits light
- ☐ b. is the basic kind of junction diode
- ☐ c. produces a voltage
- ☐ d. responds to light

1-10. Solar cells are used to _______ when exposed to radiation from the sun.

- ☐ a. carry a current
- ☐ b. emit light
- ☐ c. generate electric power
- ☐ d. produce a magnetic field

SUMMARY

A semiconductor sometimes permits electron flow, sometimes resists electron flow, and sometimes stores electrons. Today silicon is the most widely used semiconductor material, replacing the previously popular germanium. Gallium arsenide is used in special applications. All semiconductor materials have crystalline structures. The outer orbit of a silicon atom contains four valence electrons shared in covalent bonding. A hole remains where an electron breaks its bond. Free electrons carry a negative charge and holes carry a positive charge. As temperature increases, the number of free electrons and holes increases, conductivity increases, and resistivity decreases.

Semiconductor material is either *n*-type or *p*-type, depending on what kind of controlled impurities are added. Donor materials have five electrons in the valence orbit and add electrons, creating *n*-type material. Acceptor materials have three electrons in the valence orbit and add holes, creating *p*-type material. In *n*-type material, free electrons are majority carriers and holes are minority carriers. In *p*-type material, the opposite is true.

A diode is a device that contains an *n*-type region, a *p*-type region, and a junction where the two regions meet. A forward-biased diode conducts, but a reverse-biased diode is prevented from conducting. The diode is "switched" between forward and reverse bias by electrical polarity rather than by moving parts. The diode is the basic building block of all electronic semi-conducting devices. A light-emitting diode (LED) is a special kind of diode that produces either visible light or invisible infrared radiation. LEDs produce red, green, blue, yellow, or orange visible light and are commonly used in electronic equipment to indicate certain conditions.

Photoelectric devices use semiconductor material to respond to light. Photoconductive devices carry a current in response to light and block current when dark. Photovoltaic devices generate a potential difference in response to light. The solar cell is a kind of photovoltaic device.

Answers to Self-Check Quiz

1-1. d. Very high temperatures. Ref: 1.11

1-2. b. Decrease its resistivity. Ref: 1.13

1-3. b. Conventional current. Ref: 1.22

1-4. c. *n*-type and *p*-type. Ref: 1.23

1-5. b. Conducts electricity. Ref: 1.25, 1.26

1-6. a. Free electrons in the *n* section move away from the junction. Ref: 1.27

1-7. d. Very few electron-hole pairs. Ref: 1.27

1-8. c. Reverse-bias voltage at which current increases suddenly. Ref: 1.36

1-9. a. Emits light. Ref: 1.40

1-10. c. Generate electric power. Ref: 1.50