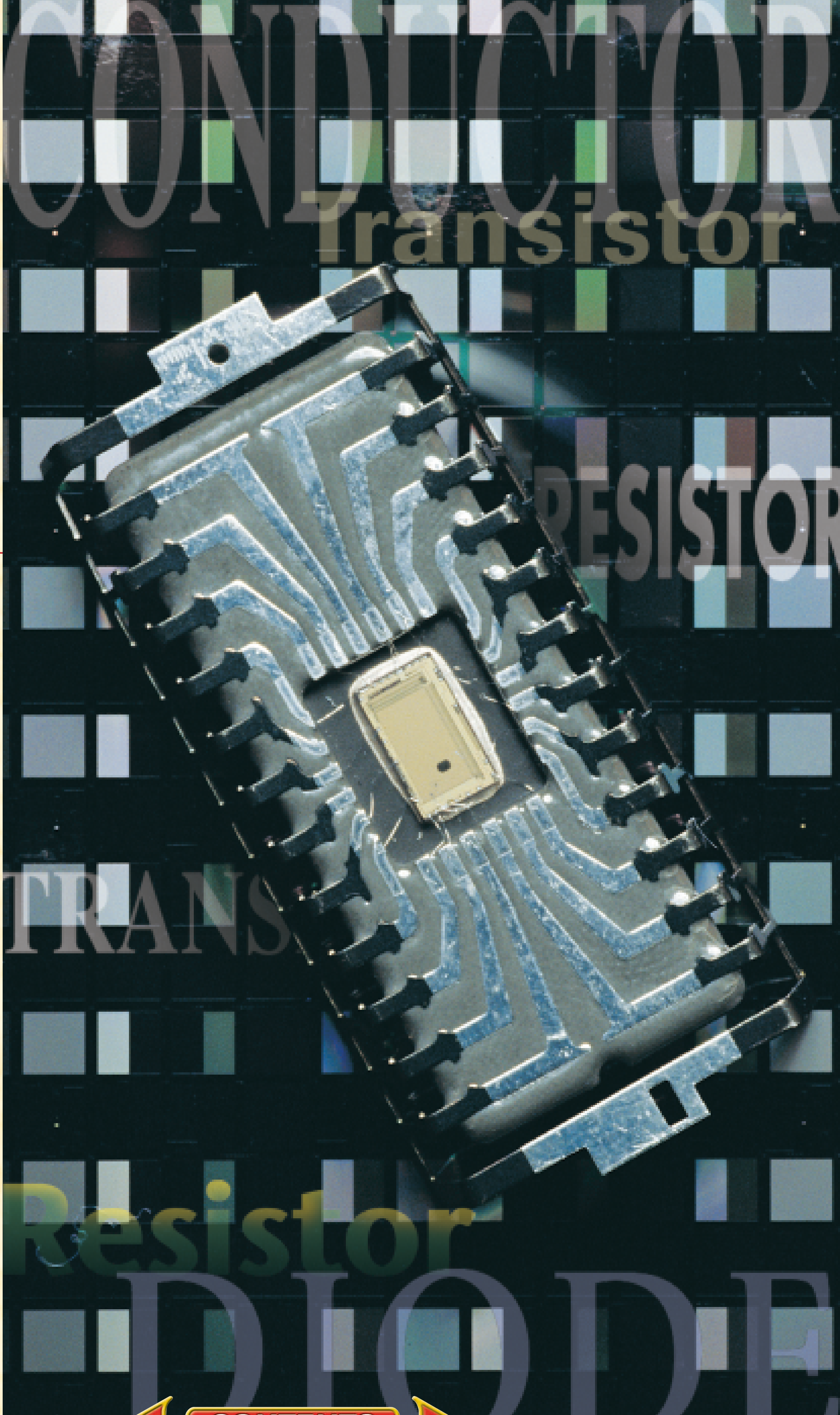
The Inside Dope

How are conductors, resistors, diodes, and transistors, which are an essential part of this microchip, produced from a pure crystal of silicon?

Look at the text on page 685 for the answer.



CHAPTER

29 Solid State Electronics

In our society, people use electronic devices every day. The principles of solid-state physics and electrical engineering surround us in the form of radios, televisions, calculators, CD players, pacemakers, video games, and cell phones, for example.

All of these devices owe their genesis to the vacuum tubes of the early 1900s. Vacuum tubes amplified faint telephone signals, a necessity for a coast-to-coast telephone system. Vacuum tubes also acted as high-speed on-off switches—18 000 of them formed the heart of the first electronic computer. But vacuum tubes are clumsy, big, fragile, take a lot of power, and generate considerable heat. This results in enormous amounts of wasted energy.

In the late 1940s, the transistor was born. Transistors the size of a pencil eraser began to replace the much larger vacuum tubes. Transistors began to be used for many military and industrial applications. The first consumer application was a pocket-sized transistor radio.

By the 1960s, the potential for even smaller transistors spurred researchers. Dozens of individual transistors could be placed on a single crystal of silicon. This integrated circuit, or silicon microchip, shines as the key that unlocked a field of electronics leading to countless technological achievements. Modern circuits containing millions of transistors are about the same size and cost as a single early transistor.

In this chapter, you'll learn how some semiconductors are made, why semiconductors do what they do, and what important functions semiconductors play inside transistors and electronic devices.

WHAT YOU'LL LEARN

- You will be able to distinguish among electric conductors, semiconductors, and insulators.
- You will examine how pure semiconductors are modified to produce desired electrical properties.
- You will compare how diodes and transistors are made and used.

WHY IT'S IMPORTANT

- Semiconductor electronics is used in many aspects of your daily life.

PHYSICS Online

To find out more about solid state electronics, visit the Glencoe Science Web site at **science.glencoe.com**

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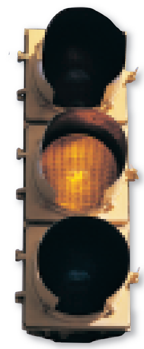
29.1 Conduction in Solids



Electronic devices depend not only on natural conductors and insulators but also on materials that have been designed and produced by many scientists and engineers working together. This brief investigation into electronics begins with a study of how materials conduct electricity.

OBJECTIVES

- **Describe** electron motion in conductors and semiconductors.
- **Compare** and **contrast** *n*-type and *p*-type semiconductors.

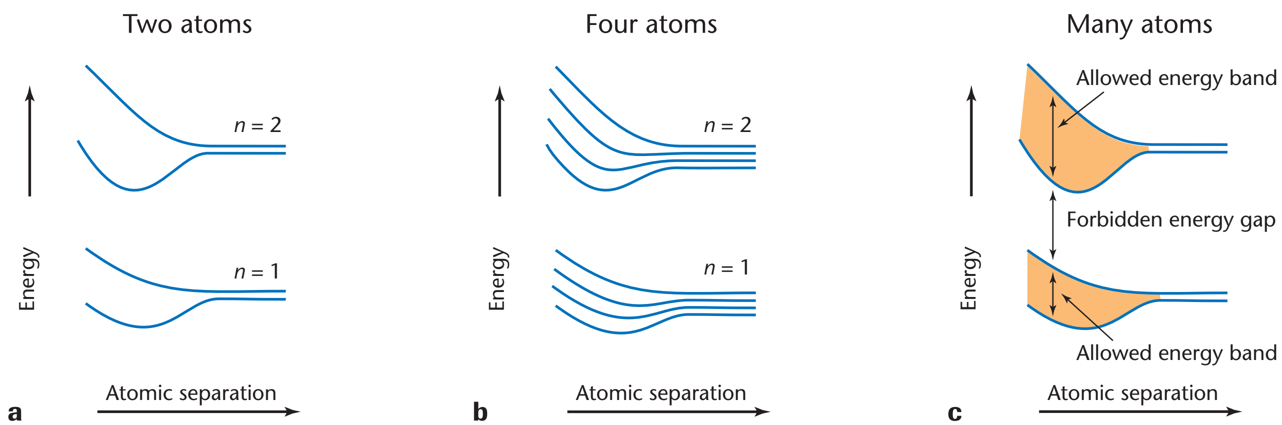
Band Theory of Solids

Recall that materials can be either electrical conductors or insulators. In conductors, electrical charges can move easily, but in insulators, charges are much more difficult to displace. When you examine these two types of materials at the atomic level, the difference in the way they are able to carry charges becomes apparent.

You learned in Chapter 13 that crystalline solids consist of atoms bound together in regular arrangements. You also know from Chapters 27 and 28 that an atom consists of a dense, positively charged nucleus surrounded by a cloud of negatively charged electrons. These electrons can occupy only certain allowed energy levels. Under most conditions, the electrons in an atom occupy the lowest possible energy levels. This condition is referred to as the ground state. Because the atoms can have only certain energies, any energy changes that occur are quantized; that is, the energy changes occur in specific amounts.

Suppose you could construct a solid by assembling atoms together, one by one. You would start with all the atoms in the ground state. If you brought two atoms close together, the electric field of each atom would affect the other. The energy levels of one atom would be raised slightly, while the energy levels of the other atom would be lowered, as illustrated in **Figure 29–1a.** Note that there are two atoms, and there are two different sets of energy levels.

FIGURE 29–1 Atomic energy levels are split apart when two atoms are brought together **(a)** and when four atoms are brought together **(b).** An energy band is formed when many atoms are brought together **(c).**



Now consider what happens when you bring many atoms close together. The original energy levels in the atoms split into energy levels so close together that they can no longer be easily identified as distinct, as indicated in **Figure 29–1b.** Rather, the levels are spread into broad bands, as shown in **Figure 29–1c.** The bands are separated by values of energy that no electrons possess. These energies are called **forbidden gaps.** Electrical conduction in solids explained in terms of these energy bands and forbidden gaps is called the **band theory** of solids.

Recall that any system will adjust itself until its energy is minimized. Therefore, electrons fill the energy levels of an atom beginning with the level of lowest energy and continuing to the highest; no two electrons can have the same energy at the same time. For atoms in the ground state, the lower energy levels are completely full. The outermost band that contains electrons is called the **valence band.** The lowest band that is not filled to capacity with electrons is called the **conduction band.**

Materials with partially filled bands are conductors, as indicated in **Figure 29–2.** The size of the forbidden gap between the valence band and the conduction band determines whether a solid is an insulator or a semiconductor.

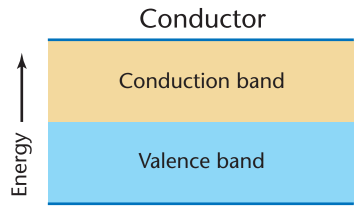


FIGURE 29–2 In a material that is a good conductor, the valence band is partially filled. The blue-shaded area shows energies occupied by electrons.

Conductors

When a potential difference is placed across a material, the resulting electric field exerts a force on the electrons. The electrons accelerate and gain energy; the field does work on them. If there are bands within the material that are only partially filled, then there are energy levels available that are only slightly higher than the electrons' present energy levels. As a result, the electrons that gain energy from the field can move from one atom to the next. Such movement of electrons from one atom to the next is an electric current, and the entire process is known as electrical conduction. Materials with partially filled bands, such as the metals aluminum and copper, conduct electricity easily.

The free electrons in conductors act like atoms in a gas or water molecules in the sea. The electrons move about rapidly in a random way, changing directions only when they collide with the cores of the atoms. However, if an electric field is put across a length of wire, there will be a net force pushing the electrons in one direction. Although their motion is not greatly affected, they have a slow overall movement dictated by the electric field. **Figure 29–3** shows a model of how electrons continue to move rapidly with speeds of 10^6 m/s in random directions, but how they also drift very slowly at speeds of 10^{-5} m/s or slower toward the positive end of the wire. This model of conductors is called the electron gas model. If the temperature is increased, the speeds of the electrons increase, and, consequently, they collide more frequently with atomic cores. Thus, as the temperature rises, the conductivity of metals is reduced. Conductivity is the reciprocal of resistivity. As conductivity is reduced, a material's resistance rises.

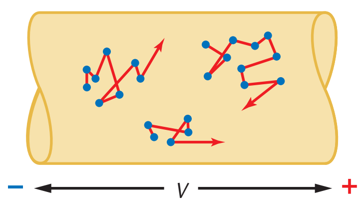


FIGURE 29–3 The electrons move rapidly and randomly in a conductor. If a field is applied across the wire, the electrons drift toward one end.

Example Problem

The Free-Electron Density of a Conductor

How many free electrons exist in a cubic centimeter of copper? Each atom contributes one electron. The density, atomic mass, and number of atoms per mole of copper can be found in Appendix F.

Calculate Your Answer

Known:

For copper: 1 free e^- per atom

$\rho = 8.96\ \text{g/cm}^3$

$M = 63.54\ \text{g/mole}$

$N_A = 6.02 \times 10^{23}\ \text{atoms/mole}$

Unknown:

Free $e^-/\text{cm}^3 = ?$

Strategy:

Use Avogadro's number, the atomic mass (g/mole), and density (g/cm^3) to find atoms/cm^3.

Calculations:

$$\frac{\text{free } e^-}{\text{cm}^3} = \left(\frac{1 \text{ free } e^-}{1 \text{ atom}}\right)\left(\frac{6.02 \times 10^{23} \text{ atoms}}{1 \text{ mole}}\right)\left(\frac{1 \text{ mole}}{63.54 \text{ g}}\right)\left(\frac{8.96 \text{ g}}{1 \text{ cm}^3}\right) = 8.49 \times 10^{22} \frac{\text{free } e^-}{\text{cm}^3 \text{ Cu}}$$

Check Your Answer

- Are the units correct? The number of free electrons per cubic centimeter answers the question.
- Is the magnitude reasonable? Yes, you would expect a large number of electrons in a cubic centimeter.

Practice Problems

1. Zinc, density $7.13\ \text{g/cm}^3$, atomic mass 65.37 g/mole, has two free electrons per atom. How many free electrons are there in each cubic centimeter of zinc?

Insulators

In an insulating material such as sulfur, table salt, or glass, the valence band is filled to capacity and the conduction band is empty. As shown in **Figure 29–4,** the valence band and the conduction band are separated by a forbidden gap. An electron must gain a large amount of energy to go to the next energy level. Recall that an electron volt (eV) is a convenient energy unit for energy changes in atomic systems. In an insulator, the lowest energy level in the conduction band is 5 to 10 eV above the highest energy level in the valence band, as shown in **Figure 29–4a.** There is at least a 5-eV gap of energies that no electrons can possess.

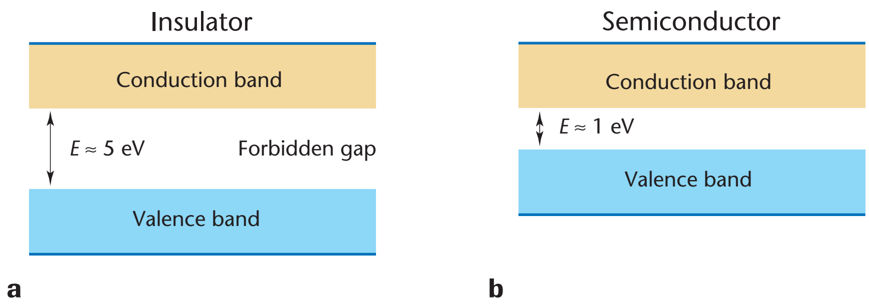


FIGURE 29–4 Compare the valence and conduction bands in an insulator **(a)** and in a semiconductor **(b).** Notice that the forbidden gap is wider in **a** than in **b.** Compare these diagrams with that shown in **Figure 29–2.**

Although electrons have some kinetic energy as a result of their thermal energy, the average kinetic energy of electrons at room temperature is not sufficient for them to jump the forbidden gap. If a small electric field is placed across an insulator, almost no electrons gain enough energy to reach the conduction band, so there is no current. Electrons in an insulator must be given a large amount of energy to be pulled free from one atom and moved to the next. As a result, the electrons in an insulator tend to remain in place, and the material does not conduct electricity.

Semiconductors

Electrons can move more freely in semiconductors than in insulators, but not as easily as in conductors, as shown in **Figure 29–4b.** The energy gap between the valence band and the conduction band is 1 eV or less. How does the structure of a semiconductor explain its electronic characteristics? Atoms of the most common semiconductors, silicon (Si) and germanium (Ge), each have four valence electrons. These four electrons are involved in binding the atoms together into the solid crystal. The valence electrons form a filled band, as in an insulator, but the forbidden gap between the valence and conduction bands is much smaller than in an insulator. Not much energy is needed to pull one of the electrons from a silicon atom and put it into the conduction band, as illustrated in **Figure 29–5a.** Indeed, the gap is so small that some electrons reach the conduction band as a result of their thermal kinetic energy alone. That is, the random motion of atoms and electrons gives some electrons enough energy to break free of their home atoms and wander around the silicon crystal. If an electric field is applied to a semiconductor, even more electrons are moved into the conduction band and move through the solid according to the direction of the applied electric field. In contrast to the effect in a metal, the higher the temperature of a semiconductor, the more electrons are able to reach the conduction band, and the higher the conductivity.

An atom from which an electron has broken free is missing an electron and is said to contain a hole. As shown in **Figure 29–5b,** a **hole** is an empty energy level in the valence band. The atom now has a net positive charge. If an electron breaks free from another atom, it can land on the hole and become bound to an atom once again. When a hole and a free electron recombine, their opposite charges cancel each other. The electron, however, has left behind a hole on its previous atom. Thus, as

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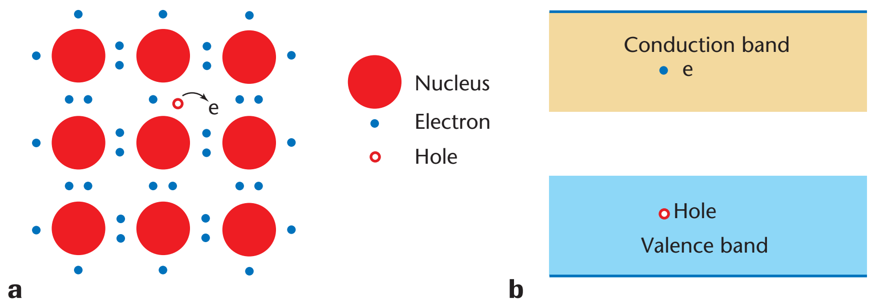


FIGURE 29–5 Some electrons in semiconductors have enough thermal kinetic energy to break free and wander through the crystal, as shown in the crystal structure **(a)** and in the bands **(b).**

in a game of musical chairs, the negatively charged, free electrons move in one direction and the positively charged holes move in the opposite direction. Pure semiconductors that conduct as a result of thermally freed electrons and holes are called **intrinsic semiconductors.** Because so few electrons or holes are available to carry charge, conduction in intrinsic semiconductors is very small; thus, their resistance is very large.

Example Problem

Fraction of Free Electrons in an Intrinsic Semiconductor

Find the number of atoms in silicon that have free electrons. That is, find the ratio of the number of free e^-/cm^3 to the number of atoms/cm^3. Because of the thermal kinetic energy of the solid at room temperature, there are 1×10^{13} free electrons per cm^3.

Calculate Your Answer

Known:

$\rho = 2.33\ g/cm^3$

$M = 28.09$ g/mole

Unknown:

free e^-/ atoms of Si = ?

Strategy:

Use Avogadro's number, the atomic mass (g/mole), and density (g/cm^3) to find atoms/cm^3.

Calculations:

$$\frac{\text{atoms}}{\text{cm}^3} = \left(\frac{2.33\text{ g}}{\text{cm}^3}\right)\left(\frac{1\text{ mole}}{28.09\text{ g}}\right)\left(\frac{6.02 \times 10^{23}\text{ atoms}}{\text{mole}}\right) = 4.99 \times 10^{22}\text{ atoms/cm}^3$$

$$\frac{\text{free e}^-}{\text{atom}} = \left(\frac{1 \times 10^{13}\text{ free e}^-}{\text{cm}^3}\right)\left(\frac{1\text{ cm}^3}{4.99 \times 10^{22}\text{ atoms}}\right) = 2 \times 10^{-10}\text{ free e}^-\text{/atom}$$

or, 1 out of 5 billion Si atoms has a free electron

Check Your Answer

- Using the factor-label method confirms the correct units.
- Is the magnitude reasonable? In an intrinsic semiconductor at room temperature, few atoms have free electrons.

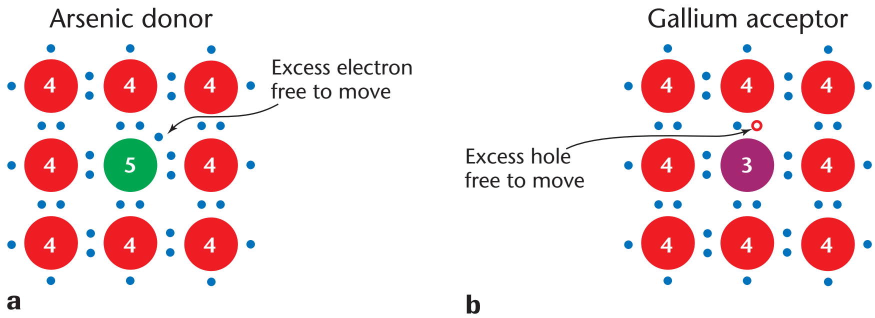


FIGURE 29–6 Donor atoms of arsenic with five valence electrons replace acceptor atoms and provide excess electrons in the silicon crystal **(a).** Acceptor atoms of gallium with three valence electrons create holes in the crystal **(b).**

Practice Problems

2. In pure germanium, density 5.23 g/cm^3, atomic mass 72.6 g/mole, there are 2×10^{16} free electrons/cm^3 at room temperature. How many free electrons are there per atom?

Doped Semiconductors

Although conductivity does not depend only on the number of free electrons, materials with fewer than one free electron per million atoms will not conduct electricity very well. To make a practical device, the conductivity of semiconductors must be increased greatly. This can be done by adding certain other atoms, or impurities, which will create **extrinsic semiconductors.** Impurity atoms, often called **dopants,** increase conductivity by adding either electrons or holes to a semiconductor.

***n*-type semiconductors** There are two kinds of semiconductors: those that conduct by means of electrons, and those that conduct by means of holes. The type of semiconductor that conducts by means of electrons is called an ***n*-type semiconductor** because conduction is by means of negatively charged particles. **Figure 29–6a** shows how a few dopant atoms replace silicon atoms in the crystal. Arsenic (As) atoms that have five valence electrons can be used as a dopant. Four of the five electrons bind to neighboring silicon atoms because silicon needs electrons to fill its valence band. The fifth electron is not needed in bonding and so can move relatively freely. This is called the donor electron. The energy of this donor electron is so close to the conduction band that thermal energy can easily remove it from the impurity atom, putting an electron in the conduction band, as shown in **Figure 29–7a.**

***p*-type semiconductors** The type of semiconductor that conducts by means of holes is called a ***p*-type semiconductor.** What kind of dopant atom can be used to create holes? A gallium (Ga) atom, for example, has only three valence electrons. If a gallium atom replaces a silicon atom, one binding electron is missing, as shown in **Figure 29–6b.** The

Pocket Lab

All Aboard!

Metals become better conductors when they are cooled. Semiconductors become better conductors when they are heated. Does a thermistor act like a metal or a semiconductor?

Make a series circuit with a low-voltage DC power supply, a thermistor, and an ammeter (0–100 mA scale). Slowly turn up the power supply until the needle is in the middle of the scale (50 mA). The voltage will be about 0.6 V. Watch what happens to the current when you hold the thermistor between your fingers. Describe the results.

Comparing and Contrasting List several possible advantages of thermistors over standard thermometers.

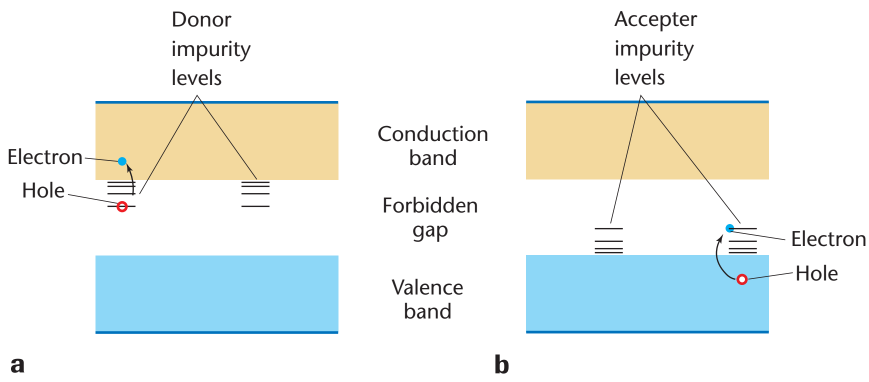


FIGURE 29–7 In an *n*-type semiconductor, donor energy levels place electrons in the conduction band **(a).** In a *p*-type semiconductor, acceptor energy levels result in holes in the valence band **(b).**

gallium atom is called an electron acceptor. That is, the gallium atom creates a hole in the silicon semiconductor. Only thermal energy is needed to excite electrons from the valence band into this hole creating a hole on a silicon atom that is free to move through the crystal. Conduction is the result of the motion of positively charged holes in the valence band, as shown in **Figure 29–7b.** Both *p*-type and *n*-type semiconductors are electrically neutral. Adding dopant atoms of either type does not add any net charge to a semiconductor. If there are free electrons, then there are the same number of positively charged atoms. When a semiconductor conducts electricity by means of holes, there is a corresponding number of negatively charged atoms.

Silicon is doped by putting a silicon crystal in a vacuum with a sample of the impurity material. The impurity material is heated until it is vaporized, and the atoms condense on the cold silicon. When the silicon is warmed gently, the impurities diffuse into the material. Only a few impurity atoms per million silicon atoms are needed to increase the conductivity of the semiconductor by a factor of 1000 or more. Thus, the electrical properties of a semiconductor can be determined by controlling the number of impurity atoms doped into it. Finally, a thin layer of aluminum or gold is evaporated on the crystal, and a wire is welded to the conductor. The wire allows the user to put current into and bring it out of the doped silicon.

F.Y.I.

Silicon circuits are now being built on a layer of sapphire crystal. Unlike semiconductor bases that allow some current to pass through, the sapphire layer is nonconductive. Engineers may now be able to put several integrated chips for a cellular phone on a single chip.

Thermistors The electrical conductivity of intrinsic and extrinsic semiconductors is sensitive to both temperature and light. Unlike metals in which conductivity is reduced when the temperature rises, an increase in temperature of a semiconductor allows more electrons to reach the conduction band. Thus, conductivity increases and resistance decreases. One semiconductor device, the thermistor, is designed so that its resistance depends very strongly on temperature. Thus, the thermistor can be used as a sensitive thermometer and to compensate for temperature variations of other components in an electrical circuit. Thermistors can also be used to measure the power of radio-frequency, infrared, and visible light sources.

Example Problem

The Conductivity of Doped Silicon

Silicon is doped with arsenic so that one in every million Si atoms is replaced by an arsenic atom. Each As atom donates one electron to the conduction band.

a. What is the density of free electrons?

b. By what ratio is this density greater than that of intrinsic silicon with 1×10^{13} free e^-/cm^3?

c. Is conduction mainly by the electrons of the silicon or the arsenic?

Calculate Your Answer

Known:

1 As atom/10^6 Si atoms

1 free e^-/As atom

4.99×10^{22} Si atoms/cm^3

1×10^{13} free e^-/cm^3 in intrinsic Si

Unknown:

a. free e^-/cm^3 donated by As

b. ratio of As-donated free e^- to intrinsic free e^-

Strategy:

From the density of Si atoms, find the density of As atoms. Because each As atom donates one e^-, this number is the density of free electrons.

Calculations:

a. $$\frac{\text{free } e^-}{cm^3} = \left(\frac{1 \text{ free } e^-}{1 \text{ As atom}}\right)\left(\frac{1 \text{ As atom}}{1 \times 10^6 \text{ Si atoms}}\right)\left(\frac{4.99 \times 10^{22} \text{ Si atoms}}{cm^3}\right) = 4.99 \times 10^{16} \text{ free } e^-/cm^3$$

b. Ratio is $$\frac{4.99 \times 10^{16} \text{ free } e^-/cm^3 \text{ in doped Si}}{1 \times 10^{13} \text{ free } e^-/cm^3 \text{ in intrinsic Si}} = 4.99 \times 10^3$$

c. Because there are 5000 arsenic-donated electrons for every intrinsic electron, conduction is mainly by the arsenic-donated electrons.

Check Your Answer

- Are the units correct? Using the factor-label method confirms the correct units.
- Is the magnitude reasonable? The ratio is large enough so that intrinsic electrons make almost no contribution to conductivity.

Practice Problems

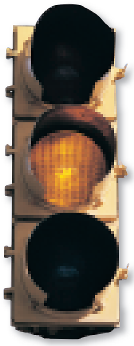
3. If you wanted to have 5×10^3 as many electrons from As doping as thermally free electrons in the germanium semiconductor described in Practice Problem 2, how many As atoms should there be per Ge atom?

Light meters Other useful applications of semiconductors depend on their light sensitivity. When light falls on a semiconductor, the light can excite electrons from the valence band to the conduction band, in the same way that light excites atoms. Thus, the resistance decreases as the light intensity increases. Materials such as silicon and cadmium sulfide are used as light-dependent resistors in light meters used by astronomers to measure the brightness of stars; by lighting engineers to design the illumination of stores, offices, and homes; and by photographers to capture the best image, as shown in **Figure 29–8.**

FIGURE 29–8 Photographers sometimes use a light meter to measure the intensity of incident light on an object. The meter converts the measurement into a unit that tells the photographer what exposure to set on the camera.

29.1 Section Review

1. In which type of material, a conductor, a semiconductor, or an insulator, are electrons most likely to remain with the same atom?
2. Magnesium oxide has a forbidden gap of 8 eV. Is this material a conductor, an insulator, or a semiconductor?
3. You are designing an integrated circuit using a single crystal of silicon. You want to have a region with relatively good insulating properties. Should you dope this region or leave it as an intrinsic semiconductor?
4. Evaluate the impact of semiconductor research on society.
5. **Critical Thinking** If the temperature increases, the number of free electrons in an intrinsic semiconductor increases. For example, raising the temperature by 10°C doubles the number of free electrons. Is it more likely that an intrinsic semiconductor or a doped semiconductor will have a conductivity that depends on temperature? Explain.



Electronic Devices

29.2

Today's electronic instruments, such as radios, televisions, CD players, and microcomputers, often use semiconductor devices that are combined on chips of semiconducting silicon a few millimeters wide. The chips contain not only regions of doped silicon that act as wires or resistors, but also areas where two or three differently doped regions are in contact. In these devices, current and voltage vary in more complex ways than are described by Ohm's law. Because the variation is not linear, the devices can change current from AC to DC and amplify voltages.

OBJECTIVES:

- **Describe** how diodes limit current to motion in only one direction.
- **Explain** how a transistor can amplify or increase voltage changes.

Diodes

The simplest semiconductor device is the **diode.** A diode consists of joined regions of *p*-type and *n*-type semiconductors. Rather than two separate pieces of doped silicon being joined, a single sample of intrinsic silicon is treated first with a *p*-dopant, then with an *n*-dopant. Metal contacts are coated on each region so that wires can be attached, as shown in **Figure 29–9.** The boundary between the *p*-type and *n*-type regions is called the junction. The resulting device therefore is called a ***pn*-junction diode.**

The holes and electrons in the *p*- and *n*-regions are affected by the junction. There are forces on the free-charge carriers in the two regions near the junction. The free electrons on the *n*-side are attracted to the positive holes on the *p*-side. The electrons readily move into the *p*-side and recombine with the holes. Holes from the *p*-side similarly move into the *n*-side, where they recombine with electrons. As a result of this flow, the *n*-side has a net positive charge, and the *p*-side has a net negative charge. These charges produce forces in the opposite direction that stop further movement of charge carriers. The region around the junction is left with neither holes nor free electrons. This region, depleted of charge carriers, is called the **depletion layer.** Because it has no charge carriers, it is a poor conductor of electricity. Thus, a junction diode consists of relatively good conductors at the ends that surround a poor conductor.

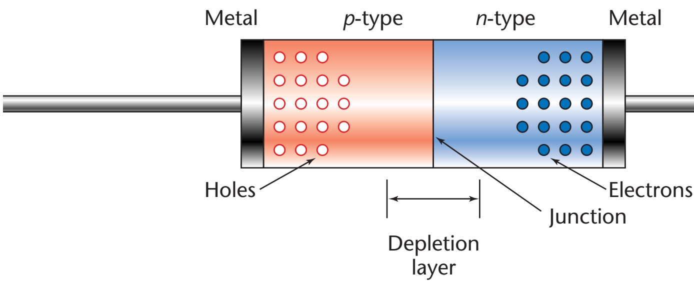


FIGURE 29–9 A diagram of the *pn* junction diode shows the depletion layer, where there are no charge carriers.

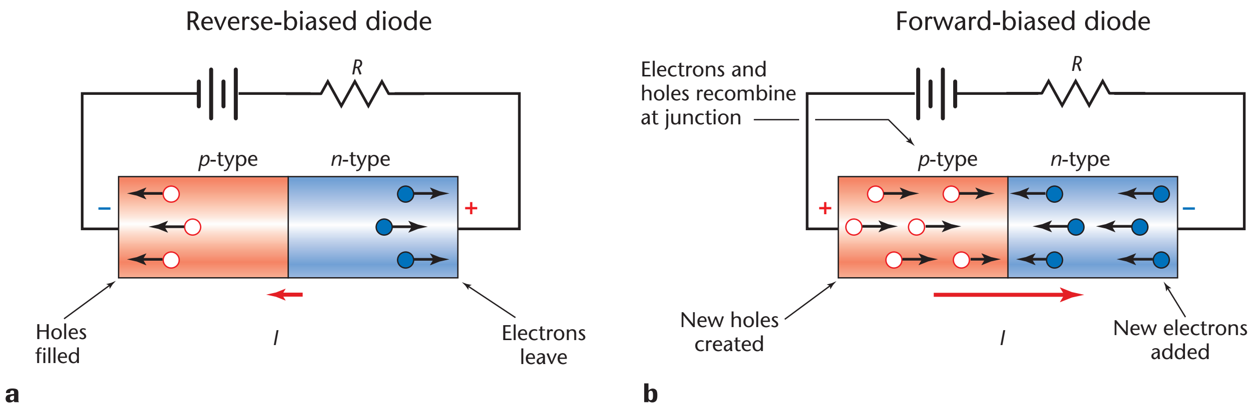


FIGURE 29–10 Compare the direction of current in a reverse-biased diode **(a)** and a forward-biased diode **(b).**

When a diode is connected into a circuit in the way shown in **Figure 29–10a,** both the free electrons in the *n*-type semiconductor and the holes in the *p*-type semiconductor are attracted toward the battery. The width of the depletion layer is increased, and no charge carriers meet. Almost no current flows through the diode: it acts like a very large resistor, almost an insulator. A diode oriented in this manner is a reverse-biased diode.

If the battery is connected in the opposite direction, as shown in **Figure 29–10b,** charge carriers are pushed toward the junction. If the voltage of the battery is large enough, 0.6 V for a silicon diode, electrons reach the *p*-end and fill the holes. The depletion layer is eliminated, and a current flows. The battery continues to supply electrons for the *n*-end. It removes electrons from the *p*-end, which is the same as supplying holes. With further increases in voltage from the battery, the current increases. A diode in this kind of circuit is a forward-biased diode.

The graph shown in **Figure 29–11** indicates the current through a silicon diode as a function of voltage across it. If the applied voltage is negative, the reverse-biased diode acts like a very high resistor; only a tiny current flows (about 10^{-11} A for a silicon diode). If the voltage is positive, the diode is forward-biased and acts like a small resistor, but not, however, one that obeys Ohm's law. One major use of a diode is to convert AC voltage to a voltage that has only one polarity. When a diode is used in a circuit such as that illustrated in **Figure 29–12,** it is called a rectifier. The arrow in the symbol for the diode shows the direction of conventional current.

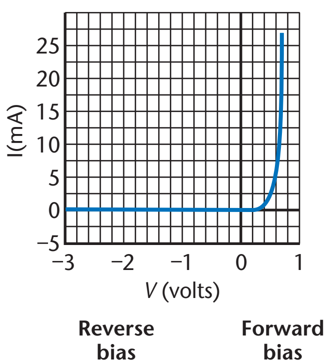


FIGURE 29–11 The graph indicates current-voltage characteristics for a silicon junction diode.

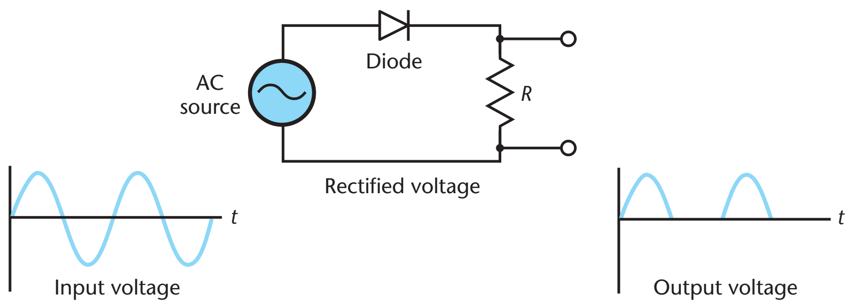


FIGURE 29–12 A diode can be used as a rectifier in a circuit.

Example Problem

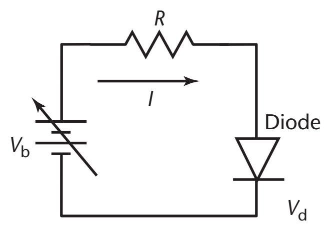
A Diode in a Simple Circuit

A silicon diode, with I/V characteristics like those shown in **Figure 29–11,** is connected to a power supply through a 470-Ω resistor. The power supply forward-biases the diode, and its voltage is adjusted until the diode current is 12 mA. What is the battery voltage?

Sketch the Problem

- Draw a circuit diagram indicating the direction of current.

Calculate Your Answer



Known:

$I = 0.012$ A

$V_d = 0.7$ V

$R = 470$ Ω

Unknown:

$V_b = ?$

Strategy:

The voltage drop across the resistor is known from $V = IR$, and this is the difference between the battery voltage and the diode voltage drop.

Calculations:

$$V_b = IR + V_d$$

$$V_b = (0.012 \text{ A})(470\ \Omega) + 0.7 \text{ V}$$

$$= 6.3 \text{ V}$$

Check Your Answer

- Are the units correct? The battery's potential difference is in volts.
- Is the magnitude reasonable? Yes, it is larger than the diode voltage drop, but less than 12 V, which is typical of batteries.

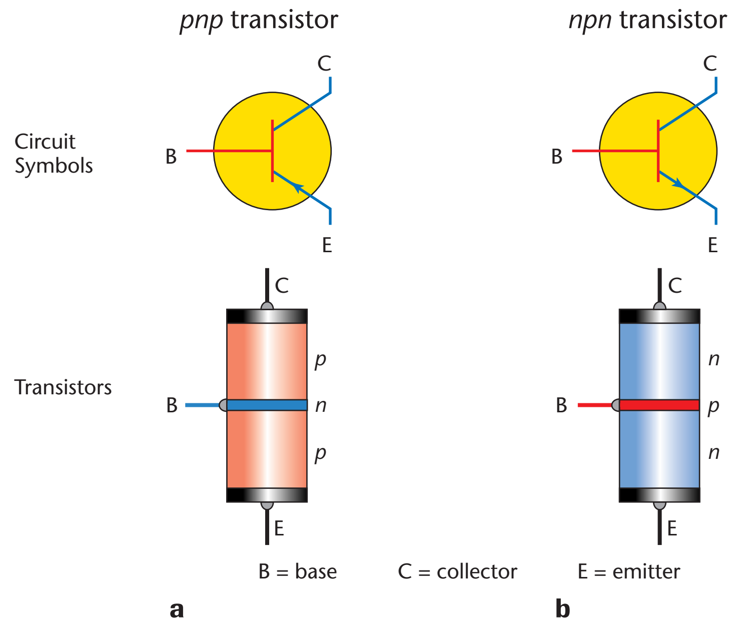
Practice Problems

4. What battery voltage would be needed to produce a current of 2.5 mA in the diode in the preceding Example Problem?

5. A Ge diode has a voltage drop of 0.4 V when 12 mA flow through it. If the same 470-Ω resistor is used, what battery voltage is needed?

Diodes can do more than provide one-way paths for current. Diodes made from combinations of gallium and aluminum with arsenic and phosphorus emit light when they are forward-biased. When electrons reach the holes in the junction, they recombine and release the excess energy at the wavelengths of light. These diodes are called light-emitting diodes, or LEDs. Certain semiconductor crystals can be cut with parallel faces so that the light waves reflect back and forth in the crystal. The

FIGURE 29–13 Compare the circuit symbols used to represent a *pnp* transistor **(a)** and an *npn* transistor **(b).**



Pocket Lab

Red Light

Make a series circuit with a power supply, a 470-Ω resistor, and a red LED. Connect the short lead of the LED to the negative side of the power supply. Attach the other lead to the resistor. Hook the remaining resistor lead to the positive side of the power supply. Slowly increase the voltage until the LED glows. Note the voltage setting on the power supply.

Hypothesize What will happen if you reverse the direction of current? Why? Try it and explain what happens.

result is a diode laser that emits a narrow beam of coherent, monochromatic light, or infrared radiation. Diode lasers are used in CD players and supermarket bar-code scanners. They are compact, powerful light sources.

Both CD players and supermarket scanners must detect the laser light reflected from the CD or bar code. Diodes can detect light as well as emit it. A reverse-biased *pn*-junction diode is usually used as a light detector. Light falling on the junction creates pairs of electrons and holes. These are pulled toward the ends of the diode, resulting in a current that depends on the light intensity.

Transistors and Integrated Circuits

A **transistor** is a simple device made of doped semiconducting material that is used in most electronic circuits. One example of a transistor consists of a region of one type of doped semiconductor sandwiched between layers of the opposite type. An *npn* transistor consists of *n*-type semiconductors surrounding a thin *p*-type layer. If the center is an *n*-type region, then the device is called a *pnp* transistor. In either case, the central layer is called the base. The two surrounding regions are the emitter and the collector. The schematic symbols for the two transistor types are shown in **Figure 29–13.** The arrow is on the emitter and shows the direction of conventional current.

The operation of an *npn* transistor is illustrated in **Figure 29–14.** The *pn*-junctions in the transistor can be thought of as two back-to-back diodes. The battery on the right keeps the potential difference between collector and emitter, V_{CE}, positive. The base-collector diode is reverse-biased, so there is no current. The battery on the left is connected so that the base is more positive than the emitter. That is, the base-emitter diode is forward-biased.

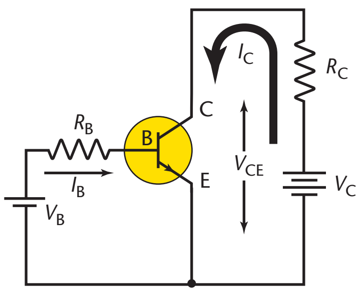


FIGURE 29–14 The circuit of an *npn* transistor demonstrates how voltage can be amplified.

Physics & Society

A Revolution in Robots

As our knowledge of solid state electronics advances, so does our ability to create smaller, more powerful computers called robots. The essential characteristics of a robot include the ability to be programmed to carry out a sequence of actions and to repeat those actions over and over again, as instructed.

Robots for hazardous tasks

Robots were first used for monotonous assembly-line tasks such as bolting together engine parts and handling molten metal. Now, they are used for work in hazardous or unusual environments. A robot rover called Pioneer, developed during the 1990s to clean toxic-waste storage tanks, helped decontaminate the damaged Chernobyl nuclear reactor in Russia by locating radioactive hot spots and providing details of structural damage.

Robots as explorers

Unlike humans, robots require no life-support systems, so they are less expensive to send on interplanetary expeditions. The *Mars Sojourner* rover was equipped with solar panels for power, wheels for travel, sensors and analyzers for examining rocks and soil, and communications equipment for receiving instructions from and sending data back to human operators on Earth.

Microrobots

Engineers have discovered that tiny robots are better than larger ones at handling tiny components, such as those used in the manufacture of electronic circuits. Microrobots have also become very important in medicine. Because tiny instruments can be inserted into the body through small incisions, they reduce the pain and trauma of surgery. A surgeon, viewing the body's interior with a remote camera, can control the robot to remove a gall bladder or repair knee ligaments. Some medical equipment is so precise that it can more accurately manipulate tissues than the larger hand of a skilled human surgeon.

Robots even smaller than those currently in use are in the works. Microtechnologists have created a working helicopter the size of a peanut. Some of its parts are a hundred times smaller than the diameter of a human hair. Medical technologists and computer makers are among those keeping a close watch on the microtechnology industry—an industry that develops the microscopic structures used in microdevices.

Investigating the Issue

1. **Using the Internet** Search for information about recent advances in artificial intelligence, then prepare to discuss the following questions. Has anyone invented a robot that can make human decisions? Do you think robots will ever be capable of human thought and emotions?
2. **Thinking Critically** Some researchers are trying to develop robots that look and act like humans. Would you prefer to work alongside a robot that looks like a machine or one that looks like a person? Why?

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To find out more about robots, visit the Glencoe Science Web site at **science.glencoe.com**

The Stoplight

Problem

How can you design a circuit so that changing the direction of the current changes the LED that lights up?

Materials

0- to 12-V variable power supply
red LED
green LED
bicolored LED
wires
470-Ω resistor
voltmeter

Procedure

1. Connect a series circuit with the power supply, the resistor, and the red and green LEDs to light them both. Do not bypass or omit the resistor with an LED. Always have the resistor between an LED and one side of the power supply.
2. Reverse the direction of the current in the circuit and note the result. Measure the voltage across an LED.
3. Design a circuit so that changing the direction of the current will change the color that lights up.
4. Test your circuit.
5. When you have completed the lab, dispose of or recycle appropriate materials. Put away materials that can be reused.

Data and Observations

1. What voltage was needed to light the LEDs?
2. Describe what happened when the current was reversed.

Analyze and Conclude

1. **Diagramming a Circuit** Make a drawing to show your stoplight circuit (red on, green off; then green on, red off).
2. **Explaining Results** Why does your stoplight circuit work?
3. **Analyzing Results** Is your circuit a series or parallel circuit?
4. **Making Predictions** What change would you observe if you replaced the resistor with a 330-Ω resistor?
5. **Forming a Hypothesis** If the voltage across the LED was increased, what would happen to the current?
6. **Thinking Critically** What must be true for the graph of current vs. voltage to be a straight line?

Apply

1. Design and conduct experiments to discover what type of LED the bicolored LED is. Remember to leave the resistor connected to the power supply.
2. How does an LED differ from a 60-W lightbulb?

There is conventional current in the direction of the arrow from the base into the emitter. Thus, electrons flow from the emitter into the base. But the base layer is very thin, often less than 10^{-6} m wide. As a result, most of the electrons pass through the base to the collector. The current through the collector, I_C, is much larger than the current through the base, I_B. The collector current causes a voltage drop across resistor R_C. Small changes in the voltage on the base produce large changes in the collector current, and thus changes in the voltage drop across R_C. As a result, the transistor amplifies small voltage changes into much larger changes. A *pnp* transistor works the same way, except that the potentials of both batteries are reversed, and holes carry the current in the transistor. The energy for amplification comes from the battery.

In a tape player, the small voltage variations from the voltage induced in a coil by magnetized regions on the tape are amplified to move the speaker coil. In computers, small currents in the base-emitter circuits can turn on or turn off large currents in the collector-emitter circuits. In addition, several transistors can be connected together to perform logic operations or to add numbers together. In this case, they act as fast switches rather than as amplifiers.

Microchips An integrated circuit, or a microchip, consists of thousands of transistors, diodes, resistors, and conductors, each no more than a few micrometers across. All these components can be made by doping silicon, as shown in **Figure 29–15.** A microchip begins as an extremely pure single crystal of silicon, 10–20 cm in diameter and 1/2 m long. The silicon is sliced by a diamond-coated saw into wafers less than 1 mm thick. The circuit is then built layer by layer on the surface of this wafer.

F.Y.I.

Materials using microelectromechanical systems are almost sentient. They can "sense" changes in temperature, pressure, and motion. They are able to actuate control mechanisms and communicate. Researchers foresee clouds of these tiny machines monitoring hurricanes, performing medical procedures, and controlling machine parts.

The Inside Dope

Answers question from page 668.

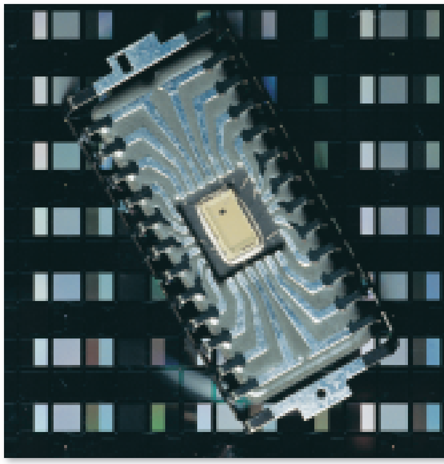


FIGURE 29–15 A piece of ultrapure silicon forms the basis for an integrated circuit chip.

By a photographic process, most of the wafer's surface is covered by a protective layer, with a pattern of selected areas left uncovered so that it can be doped appropriately. The wafer is then placed in a vacuum chamber. Vapors of a dopant such as arsenic enter the machine, doping the wafer in the unprotected regions. By controlling the amount of exposure, the engineer can control the conductivity of the exposed regions of the chip. This process creates resistors, as well as one of the two layers of a diode or one of the three layers of a transistor. The protective layer is removed, and another one with a different pattern of exposed areas is applied. Then the wafer is exposed to another dopant, often gallium, producing *pn* junctions. If a third layer is added, *npn* transistors are formed. The wafer also may be exposed to oxygen to produce areas of silicon dioxide insulation. A layer exposed to aluminum vapors can produce a pattern of thin conducting pathways among the resistors, diodes, and transistors.

Hundreds of identical circuits, usually called chips, are produced at one time on a single wafer with a 10– to 20–cm diameter. The chips are then sliced apart and tested, attached to wires, and mounted in a plastic protective body. The tiny size of integrated circuits allows the placement of complicated circuits in a small space. Because electronic signals need to travel tiny distances, this miniaturization has increased the speed of computers.

Semiconductor electronics requires that physicists, chemists, and engineers work together. Physicists contribute their understanding of the motion of electrons and holes in semiconductors. Physicists and chemists together add precisely controlled amounts of impurities to extremely pure silicon. Engineers develop the means of mass-producing chips containing thousands of miniaturized diodes and transistors. Together, their efforts have brought our world into this electronic age.

29.2 Section Review

1. Compare the resistance of a *pn*-junction diode when it is forward-biased and reverse-biased.
2. In a light-emitting diode, which terminal should be connected to the *p*-end to make the diode light?
3. If the diode shown in **Figure 29–11** is forward-biased by a battery and a series resistor so that there is more than 10 mA of current, the voltage drop is always about 0.7 V. Assume that the battery voltage is increased by 1 V.
   a. By how much does the voltage across the diode or the voltage across the resistor increase?
   b. By how much does the current through the resistor increase?
4. **Critical Thinking** Could you replace an *npn* transistor with two separate diodes connected by their *p*-terminals? Explain.

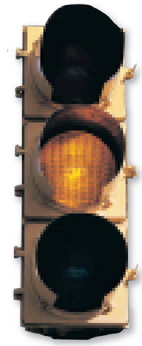
CHAPTER 29 REVIEW

Key Terms

29.1
- forbidden gap
- band theory
- valence band
- conduction band
- hole
- intrinsic semiconductor
- extrinsic semiconductor
- dopant
- *n*-type semiconductor
- *p*-type semiconductor

29.2
- diode
- *pn*-junction diode
- depletion layer
- transistor

Summary



29.1 Conduction in Solids

- Electrical conduction may be explained by the band theory of solids.
- In solids, the allowed energy levels are spread into broad bands. The bands are separated by regions called the forbidden gaps, that is, by values of energies that electrons may not possess.
- In conductors, electrons can move because the valence band is only partially filled.
- Electrons in metals have a very fast random motion. A potential difference across the metal causes a very slow drift of the electrons.
- In insulators, more energy is needed to move electrons than is generally available.
- Conduction in semiconductors is usually the result of doping pure crystals with impurity atoms.
- *n*-type semiconductors conduct by means of free electrons, and *p*-type semiconductors conduct by means of holes.

29.2 Electronic Devices

- Diodes conduct charges in one direction only and can be used to produce current in one direction only.
- A transistor has alternate layers of *n*-type and *p*-type semiconductors and can amplify voltage changes.

Reviewing Concepts

Section 29.1

1. How do the energy levels in a crystal of an element differ from the energy levels in a single atom of that element?
2. Why does heating a semiconductor increase its conductivity?
3. What is the main current carrier in a *p*-type semiconductor?

Section 29.2

4. An ohmmeter is an instrument that places a potential difference across a device to be tested, measures the current, and displays the resistance of the device. If you connect an ohmmeter across a diode, will the current you measure depend on which end of the diode was connected to the positive terminal of the ohmmeter? Explain.
5. What is the significance of the arrowhead at the emitter in a transistor circuit symbol?
6. Redraw **Figure 29–14** as a *pnp* transistor.

Applying Concepts

7. The resistance of graphite decreases as temperature rises. Does graphite conduct electricity like copper or like silicon?
8. Which of the following materials would make a better insulator: one with a forbidden gap 8 eV wide, one with a forbidden gap 3 eV wide, or one with no forbidden gap?
9. Consider atoms of the three materials in question 8. From which material would it be most difficult to remove an electron?
10. How does the size of the gap between the conduction band and the valence band differ in semiconductors and insulators?
11. Which would make a better insulator, an extrinsic or an intrinsic semiconductor? Explain.
12. Silicon is doped with phosphorus. Will the dopant atoms be donors or acceptors? Will the semiconductor conduct with holes or electrons?

13. Doping silicon with gallium produces a *p*-type semiconductor. Why are the holes mainly on the silicon atoms rather than on the gallium atoms that caused the holes to be produced?

14. You use an ohmmeter to measure the resistance of a *pn*-junction diode. Would the meter show a higher resistance when the diode is forward-biased or reverse-biased?

15. If the ohmmeter in problem 14 shows the lower resistance, is the ohmmeter lead connected to the arrow side of the diode at a higher or lower potential than the lead connected to the other side?

16. If you dope pure germanium with gallium alone, do you produce a resistor, a diode, or a transistor?

Problems

Section 29.1

17. The forbidden gap in silicon is 1.1 eV. Electromagnetic waves striking the silicon cause electrons to move from the valence band to the conduction band. What is the longest wavelength of radiation that could excite an electron in this way? Recall that

$$E = \frac{1240\ \text{eV}\cdot\text{nm}}{\lambda}$$

18. A light-emitting diode (LED) produces green light with a wavelength of 550 nm when an electron moves from the conduction band to the valence band. Find the width of the forbidden gap in eV in this diode.

19. How many free electrons exist in a cubic centimeter of sodium? Its density is 0.971 g/cm^3, its atomic mass is 22.99 g/mole, and there is one free electron per atom.

20. At a temperature of 0°C, thermal energy frees 1.1×10^{12} e$^-$/cm^3 in pure silicon. The density of silicon is 2.33 g/cm^3, and the atomic mass of silicon is 28.09 g/mole. What is the fraction of atoms that have free electrons?

21. Use the periodic table to determine which of the following elements could be added to germanium to make a *p*-type semiconductor: B, C, N, P, Si, Al, Ge, Ga, As, In, Sn, and Sb.

22. Which of the elements listed in problem 21 would produce an *n*-type semiconductor?

Section 29.2

23. The potential drop across a glowing LED is about 1.2 V. In **Figure 29–16,** the potential drop across the resistor is the difference between the battery voltage and the LED's potential drop, 6.0 V − 1.2 V = 4.8 V. What is the current through

a. the LED?

b. the resistor?

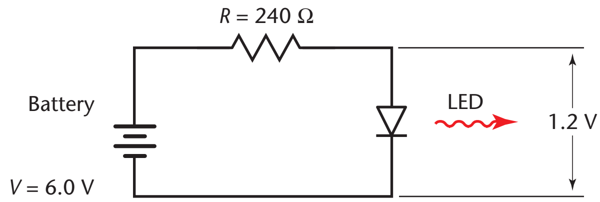


FIGURE 29–16

24. Jon wanted to raise the current through the LED in problem 23 up to 30 mA so that it would glow brighter. Assume that the potential drop across the LED is still 1.2 V. What resistor should be used?

25. **Figure 29–17** shows a battery, diode, and bulb connected in series so that the bulb lights. Note that the diode is forward-biased. State whether the bulb in each of the pictured circuits, 1, 2, and 3, is lighted.

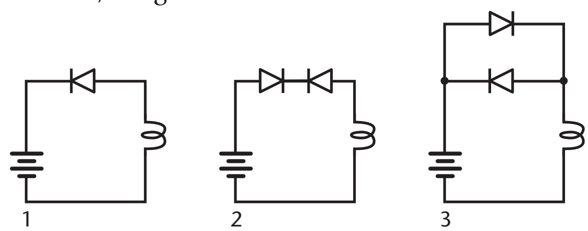


FIGURE 29–17

26. In the circuit shown in **Figure 29–18,** tell whether lamp L_1, lamp L_2, both, or neither is lighted.

27. A silicon diode whose *I*/*V* characteristics are shown in **Figure 29–11** is connected to a battery through a 270-Ω resistor. The battery forward-biases the diode, and its voltage is adjusted until the diode current is 15 mA. What is the battery voltage?

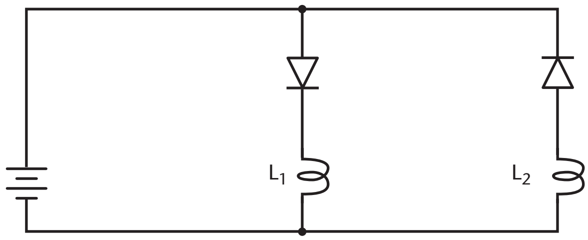


FIGURE 29–18

28. What bulbs are lighted in the circuit shown in **Figure 29–19** when
a. switch 1 is closed and switch 2 is open?
b. switch 2 is closed and switch 1 is open?

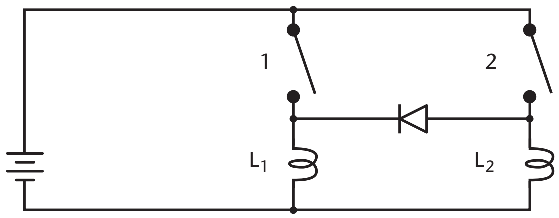


FIGURE 29–19

29. Which element or elements could be used as the second dopant used to make a diode, if the first dopant were boron?

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

30. The I/V characteristics of two LEDs that glow with different colors are shown in **Figure 29–20.** Each is to be connected through a resistor to a 9.0-V battery. If each is to be run at a current of 0.040 A, what resistors should be chosen for each?

31. Suppose that the two LEDs in problem 30 are now connected in series. If the same battery is to be used and a current of 0.035 A is desired, what resistor should be used?

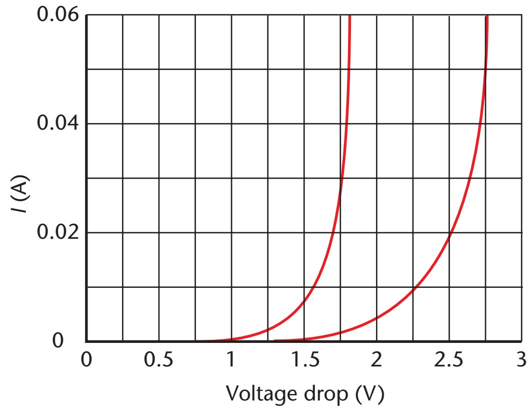


FIGURE 29–20

Going Further

Graphing Data Planck's constant can be estimated from an experiment with LEDs. To a good approximation, the voltage drop, V, across an LED depends on the frequency of light emission, f, according to $V = hf/e$, where h is Planck's constant and e is the elementary charge. As shown in **Figure 29–11,** however, the voltage drop depends on current. To estimate Planck's constant, you have to measure the voltage when the current is very small, approximately 60 μA. Obtain a collection of different-colored LEDs, from blue or green to infrared. Either measure the wavelength of the light that they emit with a diffraction grating or prism spectrometer, or obtain the wavelength from the manufacturer's data tables. Compute the light frequency. Measure and plot the voltage drop as a function of frequency. The slope of the line is h/e. Estimate Planck's constant from the slope.

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