chapter 2

Semiconductors

To understand how diodes, transistors, and integrated circuits work, you first have to study semiconductors: materials that are neither conductors nor insulators. Semiconductors contain some free electrons, but what makes them unusual is the presence of holes. In this chapter, you will learn about semiconductors, holes, and other related topics.

Objectives

After studying this chapter, you should be able to:

- Recognize, at the atomic level, the characteristics of good conductors and semiconductors.
- Describe the structure of a silicon crystal.
- List the two types of carriers and name the type of impurity that causes each to be a majority carrier.
- Explain the conditions that exist at the *pn* junction of an unbiased diode, a forward-biased diode, and a reverse-biased diode.
- Describe the types of breakdown current caused by excessive reverse voltage across a diode.

Chapter Outline

Vocabulary

ambient temperature
avalanche effect
barrier potential
breakdown voltage
conduction band
covalent bond
depletion layer
diode
doping
extrinsic semiconductor
forward bias
free electron
hole
intrinsic semiconductor
junction diode
junction temperature
majority carriers
minority carriers
n-type semiconductor
p-type semiconductor
pn junction
recombination
reverse bias
saturation current
semiconductor
silicon
surface-leakage current
thermal energy

2-1 Conductors

Copper is a good conductor. The reason is clear when we look at its atomic structure (Fig. 2-1). The nucleus of the atom contains 29 protons (positive charges). When a copper atom has a neutral charge, 29 electrons (negative charges) circle the nucleus like planets around the sun. The electrons travel in distinct *orbits* (also called *shells*). There are 2 electrons in the first orbit, 8 electrons in the second, 18 in the third, and 1 in the outer orbit.

Stable Orbits

The positive nucleus of Fig. 2-1 attracts the planetary electrons. The reason why these electrons are not pulled into the nucleus is the centrifugal (outward) force created by their circular motion. This centrifugal force is exactly equal to the inward pull of the nucleus, so the orbit is stable. The idea is similar to a satellite that orbits the earth. At the right speed and height, a satellite can remain in a stable orbit above the earth.

The larger the orbit of an electron, the smaller the attraction of the nucleus. In a larger orbit, an electron travels more slowly, producing less centrifugal force. The outermost electron in Fig. 2-1 travels slowly and feels almost no attraction to the nucleus.

The Core

In electronics, all that matters is the outer orbit. It is called the *valence orbit.* This orbit controls the electrical properties of the atom. To emphasize the importance of the valence orbit, we define the *core* of an atom as the nucleus and all the inner orbits. For a copper atom, the core is the nucleus (+29), and the first three orbits (−28).

The core of a copper atom has a net charge of +1 because it contains 29 protons and 28 inner electrons. Figure 2-2 can help in visualizing the core and the valence orbit. The valence electron is in a large orbit around a core that has a net charge of only +1. Because of this, the inward pull felt by the valence electron is very small.

Figure 2-1 Copper atom.

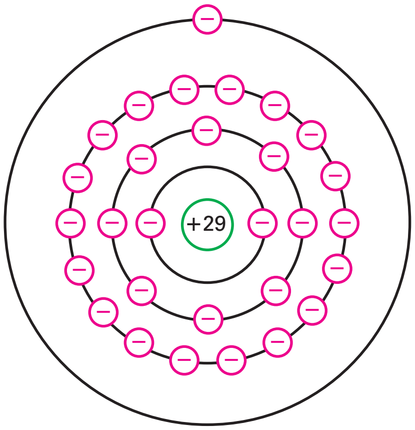
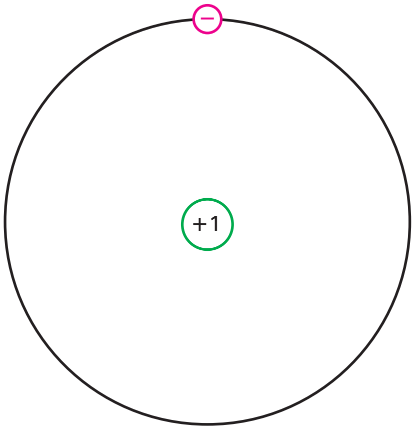


Figure 2-2 Core diagram of copper atom.



Free Electron

Since the attraction between the core and the valence electron is weak, an outside force can easily dislodge this electron from the copper atom. This is why we often call the valence electron a **free electron.** This is also why copper is a good conductor. The slightest voltage causes the free electrons to flow from one atom to the next. The best conductors are silver, copper, and gold. All have a core diagram like Fig. 2-2.

Example 2-1

Suppose an outside force removes the valence electron of Fig. 2-2 from a copper atom. What is the net charge of the copper atom? What is the net charge if an outside electron moves into the valence orbit of Fig. 2-2?

SOLUTION When the valence electron leaves, the net charge of the atom becomes +1. Whenever an atom loses one of its electrons, it becomes positively charged. We call a positively charged atom a *positive ion.*

When an outside electron moves into the valence orbit of Fig. 2-2, the net charge of the atom becomes −1. Whenever an atom has an extra electron in its valence orbit, we call the negatively charged atom a *negative ion.*

2-2 Semiconductors

The best conductors (silver, copper, and gold) have one valence electron, whereas the best insulators have eight valence electrons. A **semiconductor** is an element with electrical properties between those of a conductor and those of an insulator. As you might expect, the best semiconductors have four valence electrons.

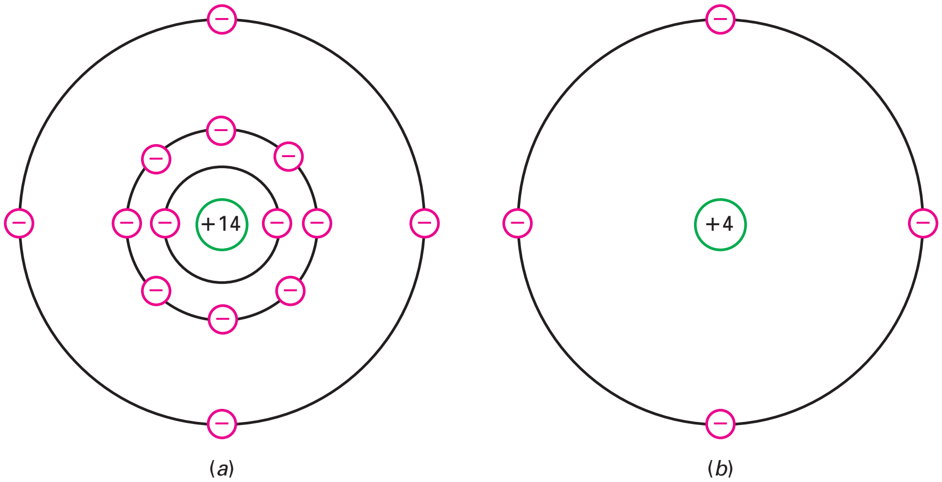
Germanium

Germanium is an example of a semiconductor. It has four electrons in the valence orbit. Many years ago, germanium was the only material suitable for making semiconductor devices. But these germanium devices had a fatal flaw (their excessive reverse current, discussed in a later section) that engineers could not overcome. Eventually, another semiconductor named **silicon** became practical and made germanium obsolete in most electronic applications.

Silicon

Next to oxygen, silicon is the most abundant element on the earth. But there were certain refining problems that prevented the use of silicon in the early days of semiconductors. Once these problems were solved, the advantages of silicon (discussed later) immediately made it the semiconductor of choice. Without it, modern electronics, communications, and computers would be impossible.

Figure 2-3 (*a*) Silicon atom; (*b*) core diagram.



GOOD TO KNOW

Another common semiconductor element is carbon (C), which is used mainly in the production of resistors.

An isolated silicon atom has 14 protons and 14 electrons. As shown in Fig. 2-3*a*, the first orbit contains two electrons and the second orbit contains eight electrons. The four remaining electrons are in the valence orbit. In Fig. 2-3*a*, the core has a net charge of +4 because it contains 14 protons in the nucleus and 10 electrons in the first two orbits.

Figure 2-3*b* shows the core diagram of a silicon atom. The four valence electrons tell us that silicon is a semiconductor.

Example 2-2

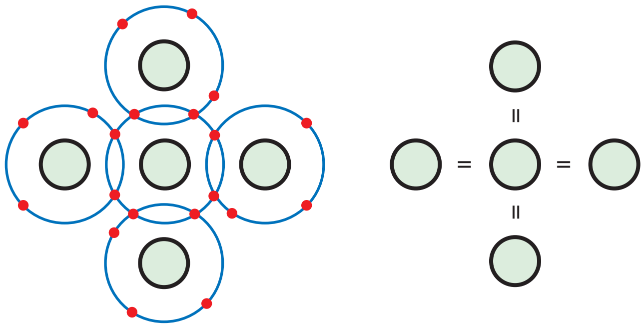
What is the net charge of the silicon atom in Fig. 2-3*b* if it loses one of its valence electrons? If it gains an extra electron in the valence orbit?

SOLUTION If it loses an electron, it becomes a positive ion with a charge of +1. If it gains an extra electron, it becomes a negative ion with a charge of −1.

2-3 Silicon Crystals

When silicon atoms combine to form a solid, they arrange themselves into an orderly pattern called a *crystal.* Each silicon atom shares its electrons with four neighboring atoms in such a way as to have eight electrons in its valence orbit. For instance, Fig. 2-4*a* shows a central atom with four neighbors. The shaded circles represent the silicon cores. Although the central atom originally had four electrons in its valence orbit, it now has eight.

Figure 2-4 (*a*) Atom in crystal has four neighbors; (*b*) covalent bonds.



Covalent Bonds

Each neighboring atom shares an electron with the central atom. In this way, the central atom has four additional electrons, giving it a total of eight electrons in the valence orbit. The electrons no longer belong to any single atom. Each central atom and its neighbors share the electrons. The same idea is true for all the other silicon atoms. In other words, every atom inside a silicon crystal has four neighbors.

In Fig. 2-4*a*, each core has a charge of +4. Look at the central core and the one to its right. These two cores attract the pair of electrons between them with equal and opposite force. This pulling in opposite directions is what holds the silicon atoms together. The idea is similar to tug-of-war teams pulling on a rope. As long as both teams pull with equal and opposite force, they remain bonded together.

Since each shared electron in Fig. 2-4*a* is being pulled in opposite directions, the electron becomes a bond between the opposite cores. We call this type of chemical bond a **covalent bond.** Figure 2-4*b* is a simpler way to show the concept of the covalent bonds. In a silicon crystal, there are billions of silicon atoms, each with eight valence electrons. These valence electrons are the covalent bonds that hold the crystal together—that give it solidity.

Valence Saturation

Each atom in a silicon crystal has eight electrons in its valence orbit. These eight electrons produce a chemical stability that results in a solid piece of silicon material. No one is quite sure why the outer orbit of all elements has a predisposition toward having eight electrons. When eight electrons do not exist naturally in an element, there seems to be a tendency for the element to combine and share electrons with other atoms so as to have eight electrons in the outer orbit.

There are advanced equations in physics that partially explain why eight electrons produce chemical stability in different materials, but no one knows the reason why the number eight is so special. It is one of those laws like the law of gravity, Coulomb's law, and other laws that we observe but cannot fully explain.

When the valence orbit has eight electrons, it is *saturated* because no more electrons can fit into this orbit. Stated as a law:

$$\textbf{Valence saturation: } n = 8 \qquad \textbf{(2-1)}$$

In words, *the valence orbit can hold no more than eight electrons.* Furthermore, the eight valence electrons are called *bound electrons* because they are tightly held by the atoms. Because of these bound electrons, a silicon crystal is almost a perfect insulator at room temperature, approximately 25°C.

The Hole

The **ambient temperature** is the temperature of the surrounding air. When the ambient temperature is above absolute zero (−273°C), the heat energy in this air causes the atoms in a silicon crystal to vibrate. The higher the ambient temperature, the stronger the mechanical vibrations become. When you pick up a warm object, the warmth you feel is the effect of the vibrating atoms.

In a silicon crystal, the vibrations of the atoms can occasionally dislodge an electron from the valence orbit. When this happens, the released electron gains enough energy to go into a larger orbit, as shown in Fig. 2-5*a*. In this larger orbit, the electron is a free electron.

But that's not all. The departure of the electron creates a vacancy in the valence orbit called a **hole** (see Fig. 2-5*a*). This hole behaves like a positive charge because the loss of the electron produces a positive ion. The hole will attract and capture any electron in the immediate vicinity. The existence of holes is the critical difference between conductors and semiconductors. Holes enable semiconductors to do all kinds of things that are impossible with conductors.

At room temperature, thermal energy produces only a few holes and free electrons. To increase the number of holes and free electrons, it is necessary to *dope* the crystal. More is said about this in a later section.

GOOD TO KNOW

A hole and an electron each possess a charge of 0.16×10^{-18} C, but of opposite polarity.

Recombination and Lifetime

In a pure silicon crystal, **thermal** (heat) **energy** creates an equal number of free electrons and holes. The free electrons move randomly throughout the crystal. Occasionally, a free electron will approach a hole, feel its attraction, and fall into it. **Recombination** is the merging of a free electron and a hole (see Fig. 2-5*b*).

The amount of time between the creation and disappearance of a free electron is called the *lifetime*. It varies from a few nanoseconds to several microseconds, depending on how perfect the crystal is and other factors.

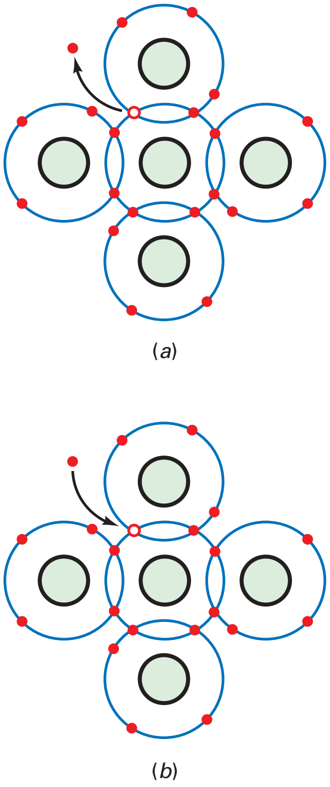


Figure 2-5 (*a*) Thermal energy produces electron and hole; (*b*) recombination of free electron and hole.

Main Ideas

At any instant, the following is taking place inside a silicon crystal:

1. Some free electrons and holes are being created by thermal energy.
2. Other free electrons and holes are recombining.
3. Some free electrons and holes exist temporarily, awaiting recombination.

Example 2-3

If a pure silicon crystal has 1 million free electrons inside it, how many holes does it have? What happens to the number of free electrons and holes if the ambient temperature increases?

SOLUTION Look at Fig. 2-5*a*. When heat energy creates a free electron, it automatically creates a hole at the same time. Therefore, a pure silicon crystal always has the same number of holes and free electrons. If there are 1 million free electrons, there are 1 million holes.

A higher temperature increases the vibrations at the atomic level, which means that more free electrons and holes are created. But no matter what the temperature is, a pure silicon crystal has the same number of free electrons and holes.

2-4 Intrinsic Semiconductors

An **intrinsic semiconductor** is a pure semiconductor. A silicon crystal is an intrinsic semiconductor if every atom in the crystal is a silicon atom. At room temperature, a silicon crystal acts like an insulator because it has only a few free electrons and holes produced by thermal energy.

Flow of Free Electrons

Figure 2-6 shows part of a silicon crystal between charged metallic plates. Assume that thermal energy has produced a free electron and a hole. The free electron is in a large orbit at the right end of the crystal. Because of the negatively charged plate, the free electron is repelled to the left. This free electron can move from one large orbit to the next until it reaches the positive plate.

Flow of Holes

Notice the hole at the left of Fig. 2-6. This hole attracts the valence electron at point *A*. This causes the valence electron to move into the hole.

When the valence electron at point *A* moves to the left, it creates a new hole at point *A*. The effect is the same as moving the original hole to the right. The new hole at point *A* can then attract and capture another valence electron. In this way, valence electrons can travel along the path shown by the arrows. This means the hole can move the opposite way, along path *A*-*B*-*C*-*D*-*E*-*F*, acting the same as a positive charge.

Figure 2-6 Hole flow through a semiconductor.

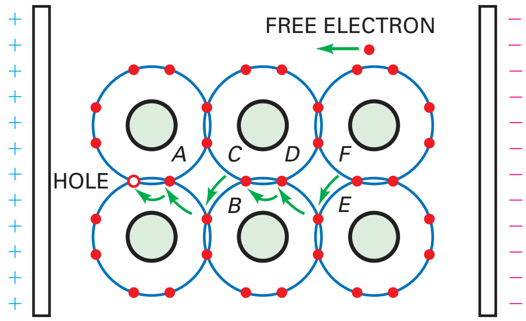
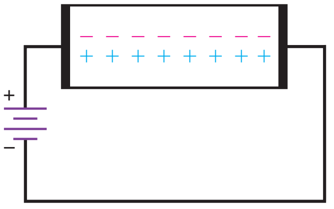


Figure 2-7 Intrinsic semiconductor has equal number of free electrons and holes.



2-5 Two Types of Flow

Figure 2-7 shows an intrinsic semiconductor. It has the same number of free electrons and holes. This is because *thermal energy produces free electrons and holes in pairs.* The applied voltage will force the free electrons to flow left and the holes to flow right. When the free electrons arrive at the left end of the crystal, they enter the external wire and flow to the positive battery terminal.

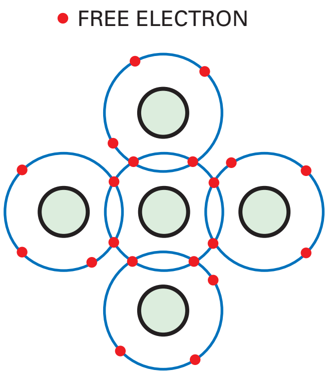
On the other hand, the free electrons at the negative battery terminal will flow to the right end of the crystal. At this point, they enter the crystal and recombine with holes that arrive at the right end of the crystal. In this way, a steady flow of free electrons and holes occurs inside the semiconductor. Note that there is no hole flow outside the semiconductor.

In Fig. 2-7, *the free electrons and holes move in opposite directions.* From now on, we will visualize the current in a semiconductor as the combined effect of the two types of flow: the flow of free electrons in one direction and the flow of holes in the other direction. Free electrons and holes are often called *carriers* because they carry a charge from one place to another.

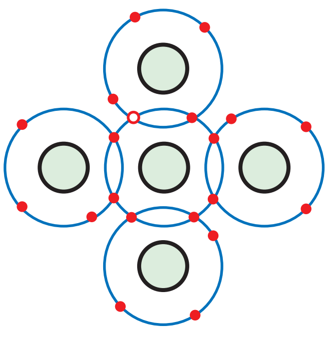
2-6 Doping a Semiconductor

One way to increase conductivity of a semiconductor is by **doping.** This means adding impurity atoms to an intrinsic crystal to alter its electrical conductivity. A doped semiconductor is called an **extrinsic semiconductor.**

Figure 2-8 (*a*) Doping to get more free electrons; (*b*) doping to get more holes.



(*a*)



(*b*)

Increasing the Free Electrons

How does a manufacturer dope a silicon crystal? The first step is to melt a pure silicon crystal. This breaks the covalent bonds and changes the silicon from a solid to a liquid. To increase the number of free electrons, *pentavalent atoms* are added to the molten silicon. Pentavalent atoms have five electrons in the valence orbit. Examples of pentavalent atoms include arsenic, antimony, and phosphorus. Because these materials *will donate an extra electron* to the silicon crystal, they are often referred to as *donor impurities.*

Figure 2-8*a* shows how the doped silicon crystal appears after it cools down and re-forms its solid crystal structure. A pentavalent atom is in the center, surrounded by four silicon atoms. As before, the neighboring atoms share an electron with the central atom. But this time, there is an extra electron left over. Remember that each pentavalent atom has five valence electrons. Since only eight electrons can fit into the valence orbit, the extra electron remains in a larger orbit. In other words, it is a free electron.

Each pentavalent or donor atom in a silicon crystal produces one free electron. This is how a manufacturer controls the conductivity of a doped semiconductor. The more impurity that is added, the greater the conductivity. In this way, a semiconductor may be lightly or heavily doped. A lightly doped semiconductor has a high resistance, whereas a heavily doped semiconductor has a low resistance.

Increasing the Number of Holes

How can we dope a pure silicon crystal to get an excess of holes? By using a *trivalent impurity,* one whose atoms have only three valence electrons. Examples include aluminum, boron, and gallium.

Figure 2-8*b* shows a trivalent atom in the center. It is surrounded by four silicon atoms, each sharing one of its valence electrons. Since the trivalent atom originally had only three valence electrons and each neighbor shares one electron, only seven electrons are in the valence orbit. This means that a hole exists in the valence orbit of each trivalent atom. A trivalent atom is also called an *acceptor atom* because each hole it contributes can accept a free electron during recombination.

Points to Remember

Before manufacturers can dope a semiconductor, they must produce it as a pure crystal. Then, by controlling the amount of impurity, they can precisely control the properties of the semiconductor. Historically, pure germanium crystals were easier to produce than pure silicon crystals. This is why the earliest semiconductor devices were made of germanium. Eventually, manufacturing techniques improved and pure silicon crystals became available. Because of its advantages, silicon has become the most popular and useful semiconductor material.

Example 2-4

A doped semiconductor has 10 billion silicon atoms and 15 million pentavalent atoms. If the ambient temperature is 25°C, how many free electrons and holes are there inside the semiconductor?

SOLUTION Each pentavalent atom contributes one free electron. Therefore, the semiconductor has 15 million free electrons produced by doping. There will be almost no holes by comparison because the only holes in the semiconductor are those produced by heat energy.

PRACTICE PROBLEM 2-4 As in Example 2-4, if 5 million trivalent atoms are added instead of pentavalent atoms, how many holes are there inside the semiconductor?

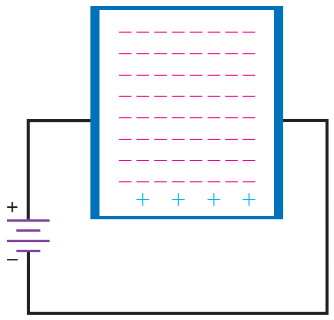
2-7 Two Types of Extrinsic Semiconductors

A semiconductor can be doped to have an excess of free electrons or an excess of holes. Because of this, there are two types of doped semiconductors.

n-Type Semiconductor

Silicon that has been doped with a pentavalent impurity is called an ***n*-type semiconductor,** where the *n* stands for negative. Figure 2-9 shows an *n*-type semiconductor. Since the free electrons outnumber the holes in an *n*-type semiconductor, the free electrons are called the **majority carriers** and the holes are called the **minority carriers.**

Figure 2-9 *n*-type semiconductor has many free electrons.



Because of the applied voltage, the *free electrons move to the left* and the *holes move to the right*. When a hole arrives at the right end of the crystal, one of the free electrons from the external circuit enters the semiconductor and recombines with the hole.

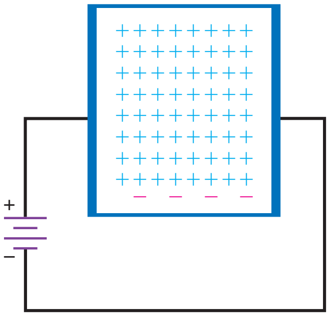


Figure 2-10 *p*-type semiconductor has many holes.

The free electrons shown in Fig. 2-9 flow to the left end of the crystal, where they enter the wire and flow on to the positive terminal of the battery.

p-Type Semiconductor

Silicon that has been doped with a trivalent impurity is called a ***p*-type semiconductor,** where the *p* stands for positive. Figure 2-10 shows a *p*-type semiconductor. Since holes outnumber free electrons, the holes are referred to as the majority carriers and the free electrons are known as the minority carriers.

Because of the applied voltage, the *free electrons move to the left* and the *holes move to the right.* In Fig. 2-10, the holes arriving at the right end of the crystal will recombine with free electrons from the external circuit.

There is also a flow of minority carriers in Fig. 2-10. The free electrons inside the semiconductor flow from right to left. Because there are so few minority carriers, they have almost no effect in this circuit.

2-8 The Unbiased Diode

By itself, a piece of *n*-type semiconductor is about as useful as a carbon resistor; the same can be said for a *p*-type semiconductor. But when a manufacturer dopes a crystal so that one-half of it is *p*-type and the other half is *n*-type, something new comes into existence.

The border between *p*-type and *n*-type is called the ***pn* junction.** The *pn* junction has led to all kinds of inventions, including diodes, transistors, and integrated circuits. Understanding the *pn* junction enables you to understand all kinds of semiconductor devices.

The Unbiased Diode

As discussed in the preceding section, each trivalent atom in a doped silicon crystal produces one hole. For this reason, we can visualize a piece of *p*-type semiconductor as shown on the left side of Fig. 2-11. Each circled minus sign is the trivalent atom, and each plus sign is the hole in its valence orbit.

Similarly, we can visualize the pentavalent atoms and free electrons of an *n*-type semiconductor as shown on the right side of Fig. 2-11. Each circled plus sign represents a pentavalent atom, and each minus sign is the free electron it contributes to the semiconductor. Notice that each piece of semiconductor material is *electrically neutral because the number of pluses and minuses is equal.*

A manufacturer can produce a single crystal with *p*-type material on one side and *n*-type on the other side, as shown in Fig. 2-12. The junction is the border where the *p*-type and the *n*-type regions meet, and **junction diode** is another name for a *pn* crystal. The word **diode** is a contraction of two electrodes, where *di* stands for "two."

Figure 2-11 Two types of semiconductor.

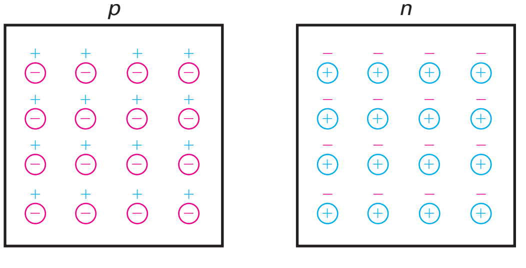
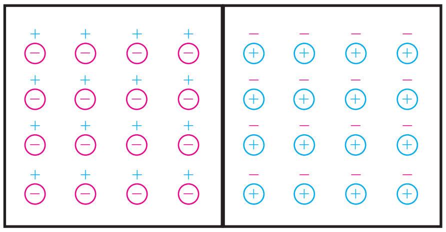


Figure 2-12 The *pn* junction.



The Depletion Layer

Because of their repulsion for each other, the free electrons on the *n* side of Fig. 2-12 tend to diffuse (spread) in all directions. Some of the free electrons diffuse across the junction. When a free electron enters the *p* region, it becomes a minority carrier. With so many holes around it, this minority carrier has a short lifetime. Soon after entering the *p* region, the free electron recombines with a hole. When this happens, the *hole disappears* and the *free electron becomes a valence electron.*

Each time an electron diffuses across a junction, it creates a pair of ions. When an electron leaves the *n* side, it leaves behind a pentavalent atom that is short one negative charge; this pentavalent atom becomes a positive ion. After the migrating electron falls into a hole on the *p* side, it makes a negative ion out of the trivalent atom that captures it.

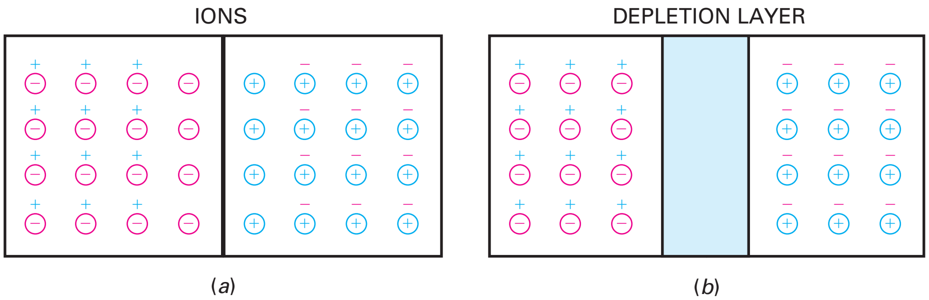
Figure 2-13*a* shows these ions on each side of the junction. The circled plus signs are the positive ions, and the circled minus signs are the negative ions. The ions are fixed in the crystal structure because of covalent bonding, and they cannot move around like free electrons and holes.

Each pair of positive and negative ions at the junction is called a *dipole.* The creation of a dipole means that one free electron and one hole have been taken out of circulation. As the number of dipoles builds up, the region near the junction is emptied of carriers. We call this charge-empty region the **depletion layer** (see Fig. 2-13*b*).

Barrier Potential

Each dipole has an electric field between the positive and negative ions. Therefore, if additional free electrons enter the depletion layer, the electric field tries to push these electrons back into the *n* region. The strength of the electric field increases with each crossing electron until equilibrium is reached. To a first approximation, this means that the electric field eventually stops the diffusion of electrons across the junction.

Figure 2-13 (*a*) Creation of ions at junction; (*b*) depletion layer.



In Fig. 2-13*a*, the electric field between the ions is equivalent to a difference of potential called the **barrier potential.** At 25°C, the barrier potential equals approximately 0.3 V for germanium diodes and 0.7 V for silicon diodes.

2-9 Forward Bias

Figure 2-14 shows a dc source across a diode. The negative source terminal is connected to the *n*-type material, and the positive terminal is connected to the *p*-type material. This connection produces what is called **forward bias.**

Flow of Free Electrons

In Fig. 2-14, the battery pushes holes and free electrons toward the junction. If the battery voltage is less than the barrier potential, the free electrons do not have enough energy to get through the depletion layer. When they enter the depletion layer, the ions will push them back into the *n* region. Because of this, there is no current through the diode.

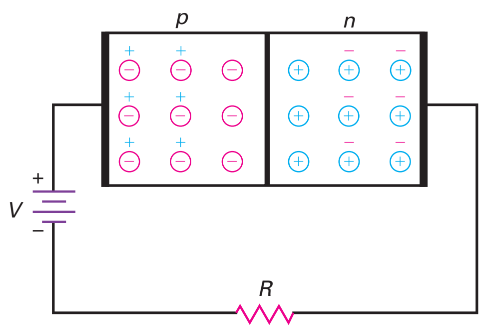
When the dc voltage source is greater than the barrier potential, the battery again pushes holes and free electrons toward the junction. This time, the free electrons have enough energy to pass through the depletion layer and recombine with the holes. If you visualize all the holes in the *p* region moving to the right and all the free electrons moving to the left, you will have the basic idea. Somewhere in the vicinity of the junction, these opposite charges recombine. Since free electrons continuously enter the right end of the diode and holes are being continuously created at the left end, there is a continuous current through the diode.

The Flow of One Electron

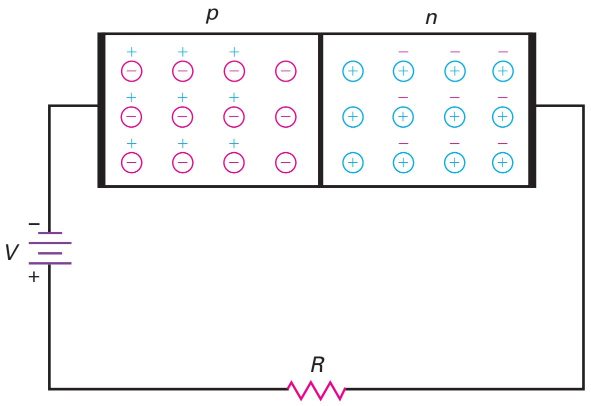
Let us follow a single electron through the entire circuit. After the free electron leaves the negative terminal of the battery, it enters the right end of the diode. It travels through the *n* region until it reaches the junction. When the battery voltage is greater than 0.7 V, the free electron has enough energy to get across the depletion layer. Soon after the free electron has entered the *p* region, it recombines with a hole.

In other words, the free electron becomes a valence electron. As a valence electron, it continues to travel to the left, passing from one hole to the next until it reaches the left end of the diode. When it leaves the left end of the diode, a new hole appears and the process begins again. Since there are billions of electrons taking the same journey, we get a continuous current through the diode. A series resistor is used to limit the amount of forward current.

Multisim **Figure 214** Forward bias.



Multisim **Figure 2-15** Reverse bias.



What to Remember

Current flows easily in a forward-biased diode. As long as the applied voltage is greater than the barrier potential, there will be a large continuous current in the circuit. In other words, if the source voltage is greater than 0.7 V, a silicon diode allows a continuous current in the forward direction.

2-10 Reverse Bias

Turn the dc source around and you get Fig. 2-15. This time, the negative battery terminal is connected to the *p* side and the positive battery terminal to the *n* side. This connection produces what is called **reverse bias.**

Depletion Layer Widens

The negative battery terminal attracts the holes, and the positive battery terminal attracts the free electrons. Because of this, holes and free electrons flow away from the junction. Therefore, the depletion layer gets wider.

How wide does the depletion layer get in Fig. 2-16*a*? When the holes and electrons move away from the junction, the newly created ions increase the difference of potential across the depletion layer. The wider the depletion layer, the greater the difference of potential. The depletion layer stops growing when its difference of potential equals the applied reverse voltage. When this happens, electrons and holes stop moving away from the junction.

Figure 2-16 (*a*) Depletion layer; (*b*) increasing reverse bias widens depletion layer.

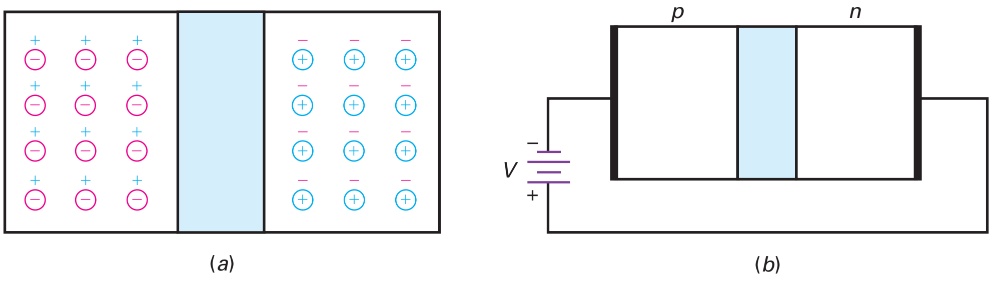
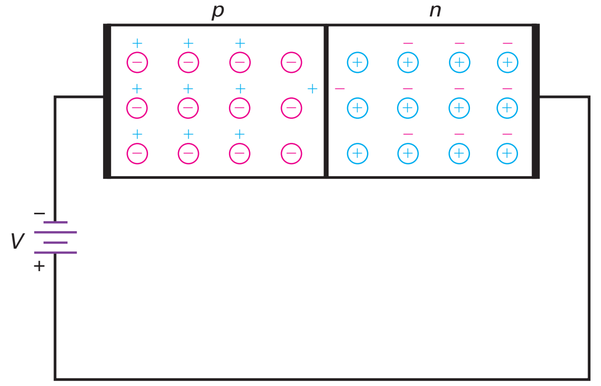


Figure 2-17 Thermal production of free electron and hole in depletion layer produces reverse minority-saturation current.



Sometimes the depletion layer is shown as a shaded region like that of Fig. 2-16*b*. The width of this shaded region is proportional to the reverse voltage. *As the reverse voltage increases, the depletion layer gets wider.*

Minority-Carrier Current

Is there any current after the depletion layer stabilizes? Yes. A small current exists with reverse bias. Recall that thermal energy continuously creates pairs of free electrons and holes. This means that a few minority carriers exist on both sides of the junction. Most of these recombine with the majority carriers. But those inside the depletion layer may exist long enough to get across the junction. When this happens, a small current flows in the external circuit.

Figure 2-17 illustrates the idea. Assume that thermal energy has created a free electron and hole near the junction. The depletion layer pushes the free electron to the right, forcing one electron to leave the right end of the crystal. The hole in the depletion layer is pushed to the left. This extra hole on the *p* side lets one electron enter the left end of the crystal and fall into a hole. Since thermal energy is continuously producing electron-hole pairs inside the depletion layer, a small continuous current flows in the external circuit.

The reverse current caused by the thermally produced minority carriers is called the **saturation current.** In equations, the saturation current is symbolized by I_S. The name *saturation* means that we cannot get more minority-carrier current than is produced by the thermal energy. In other words, *increasing the reverse voltage will not increase the number of thermally created minority carriers.*

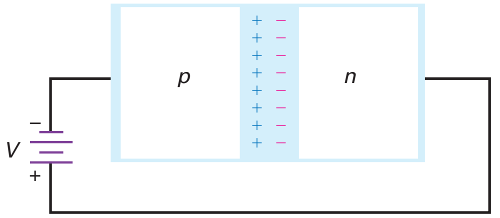
Surface-Leakage Current

Besides the thermally produced minority-carrier current, does any other current exist in a reverse-biased diode? Yes. A small current flows on the surface of the crystal. Known as the **surface-leakage current,** it is caused by surface impurities and imperfections in the crystal structure.

What to Remember

The reverse current in a diode consists of a minority-carrier current and a surface-leakage current. In most applications, the reverse current in a silicon diode is so small that you don't even notice it. The main idea to remember is this: *Current is approximately zero in a reverse-biased silicon diode.*

Figure 2-18 Avalanche produces many free electrons and holes in depletion layer.



2-11 Breakdown

Diodes have maximum voltage ratings. There is a limit to how much reverse voltage a diode can withstand before it is destroyed. If you continue increasing the reverse voltage, you will eventually reach the **breakdown voltage** of the diode. For many diodes, breakdown voltage is at least 50 V. The breakdown voltage is shown on the *data sheet* for the diode. A data sheet, produced by the manufacturer of the diode, lists important information and typical applications for the device.

Once the breakdown voltage is reached, a large number of the minority carriers suddenly appears in the depletion layer and the diode conducts heavily.

Where do the carriers come from? They are produced by the **avalanche effect** (see Fig. 2-18), which occurs at higher reverse voltages. Here is what happens. As usual, there is a small reverse minority-carrier current. When the reverse voltage increases, it forces the minority carriers to move more quickly. These minority carriers collide with the atoms of the crystal. When these minority carriers have enough energy, they can knock valence electrons loose, producing free electrons. These new minority carriers then join the existing minority carriers to collide with other atoms. The process is geometric because one free electron liberates one valence electron to get two free electrons. These two free electrons then free two more electrons to get four free electrons. The process continues until the reverse current becomes huge.

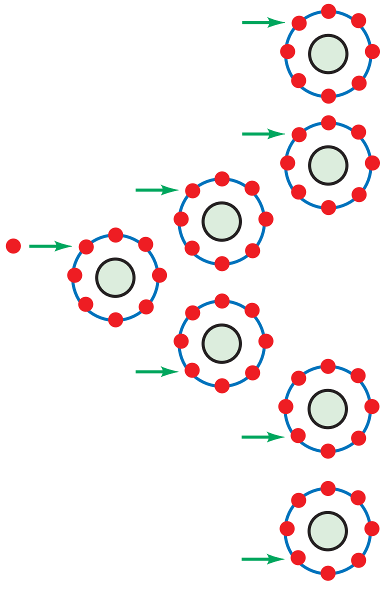
Figure 2-19 shows a magnified view of the depletion layer. The reverse bias forces the free electron to move to the right. As it moves, the electron gains speed. The larger the reverse bias, the faster the electron moves. If the high-speed electron has enough energy, it can bump the valence electron of the first atom into a larger orbit. This results in two free electrons. Both of these then accelerate and go on to dislodge two more electrons. In this way, the number of minority carriers may become quite large and the diode can conduct heavily.

The breakdown voltage of a diode depends on how heavily doped the diode is. With rectifier diodes (the most common type), the breakdown voltage is usually greater than 50 V. Summary Table 2-1 illustrates the difference between a forward- and reverse-biased diode.

GOOD TO KNOW

Exceeding the breakdown voltage of a diode does not necessarily mean that you will destroy the diode. As long as the product of reverse voltage and reverse current does not exceed the diode's power rating, the diode will recover fully.

Figure 2-19 The process of avalanche is a geometric progression: 1, 2, 4, 8, . . .



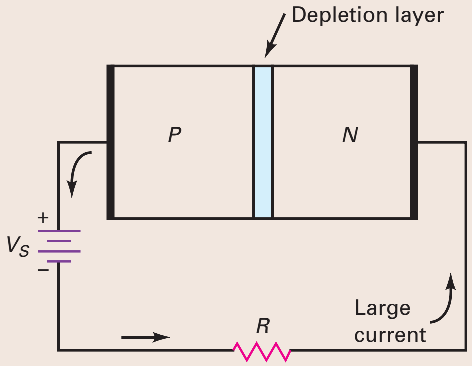
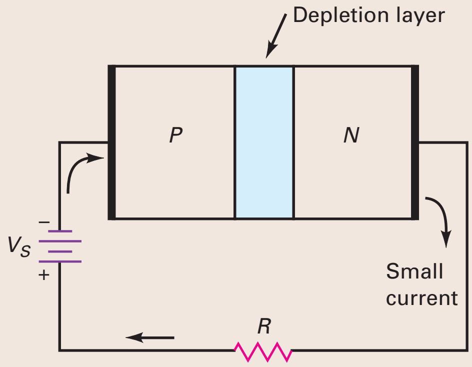
2-12 Energy Levels

We can identify the total energy of an electron with the size of its orbit to a good approximation. That is, we can think of each radius of Fig. 2-20*a* as equivalent to an energy level in Fig. 2-20*b*. Electrons in the smallest orbit are on the first energy level; electrons in the second orbit are on the second energy level; and so on.

Higher Energy in Larger Orbit

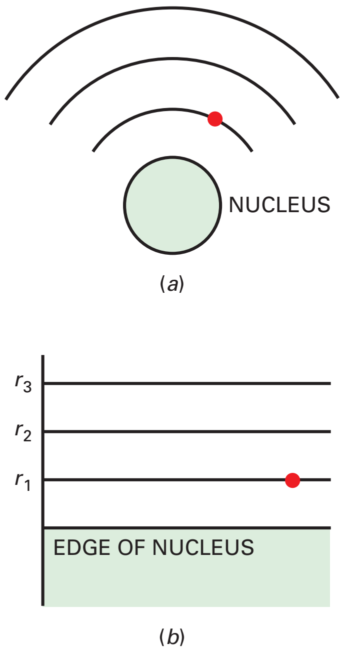
Since an electron is attracted by the nucleus, extra energy is needed to lift an electron into a larger orbit. When an electron is moved from the first to the second orbit, it gains potential energy with respect to the nucleus. Some of the external forces that can lift an electron to higher energy levels are heat, light, and voltage.

Summary Table 2-1 Diode Bias

	Forward bias	Reverse bias
		
V_s polarity	(+) to *P* material (−) to *N* material	(−) to *P* materials (+) to *N* material
Current flow	Large forward current if $V_s > 0.7$ V	Small reverse current (saturation current and surface leakage current) if $V_s <$ breakdown voltage
Depletion layer	Narrow	Wide

For instance, assume that an outside force lifts the electron from the first orbit to the second in Fig. 2-20*a*. This electron has more potential energy because it is farther from the nucleus (Fig. 2-20*b*). It is like an object above the earth: The higher the object, the greater its potential energy with respect to the earth. If released, the object falls farther and does more work when it hits the earth.

Figure 2-20 Energy level is proportional to orbit size. (*a*) Orbits; (*b*) energy levels.



Falling Electrons Radiate Light

After an electron has moved into a larger orbit, it may fall back to a lower energy level. If it does, it will give up its extra energy in the form of heat, light, and other radiation.

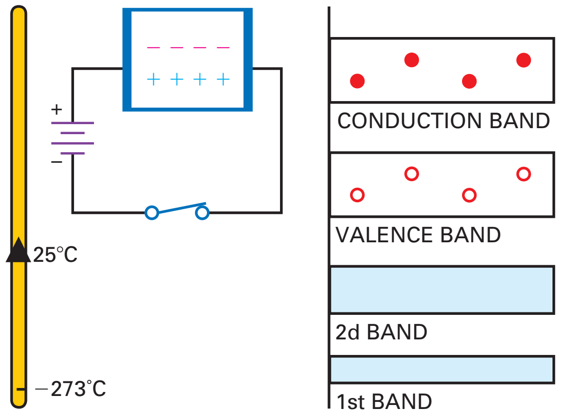
In a *light-emitting diode (LED),* the applied voltage lifts the electrons to higher energy levels. When these electrons fall back to lower energy levels, they give off light. Depending on the material used, the radiated light can be a variety of colors, including red, green, orange, or blue. Some LEDs produce infrared radiation (invisible), which is useful in burglar alarm systems.

Energy Bands

When a silicon atom is isolated, the orbit of an electron is influenced only by the charges of the isolated atom. This results in energy levels like the lines of Fig. 2-20*b*. But when silicon atoms are in a crystal, the orbit of each electron is also influenced by the charges of many other silicon atoms. Since each electron has a unique position inside the crystal, no two electrons see exactly the same pattern of surrounding charges. Because of this, the orbit of each electron is different; or, to put it another way, the energy level of each electron is different.

Figure 2-21 shows what happens to the energy levels. All electrons in the first orbit have slightly different energy levels because no two electrons see exactly the same charge environment. Since there are billions of first-orbit electrons, the slightly different energy levels form a cluster, or *band*, of energy. Similarly, the billions of second-orbit electrons, all with slightly different energy levels, form the second energy band—and so on for remaining bands.

Figure 2-21 Intrinsic semiconductor and its energy bands.



Another point: As you know, thermal energy produces a few free electrons and holes. The holes remain in the valence band, but the free electrons go to the next-higher energy band, which is called the **conduction band.** This is why Fig. 2-21 shows a conduction band with some free electrons and a valence band with some holes. When the switch is closed, a small current exists in the pure semiconductor. The free electrons move through the conduction band, and holes move through the valence band.

n-Type Energy Bands

Figure 2-22 shows the energy bands for an *n*-type semiconductor. As you would expect, the majority carriers are the free electrons in the conduction band, and the minority carriers are the holes in the valence band. Since the switch is closed in Fig. 2-22, the majority carriers flow to the left, and the minority carriers flow to the right.

p-Type Energy Bands

Figure 2-23 shows the energy bands for a *p*-type semiconductor. Here you see a reversal of the carrier roles. Now, the majority carriers are the holes in the valence band, and the minority carriers are the free electrons in the conduction band. Since the switch is closed in Fig. 2-23, the majority carriers flow to the right, and the minority carriers flow to the left.

GOOD TO KNOW

For both *n*- and *p*-type semiconductors, an increase in temperature produces an identical increase in the number of minority and majority current carriers.

Figure 2-22 *n*-type semiconductor and its energy bands.

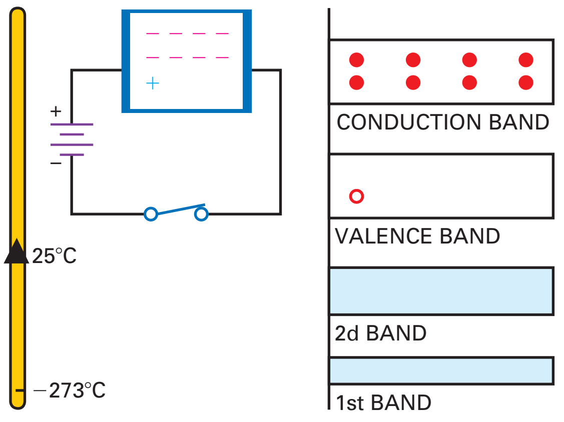
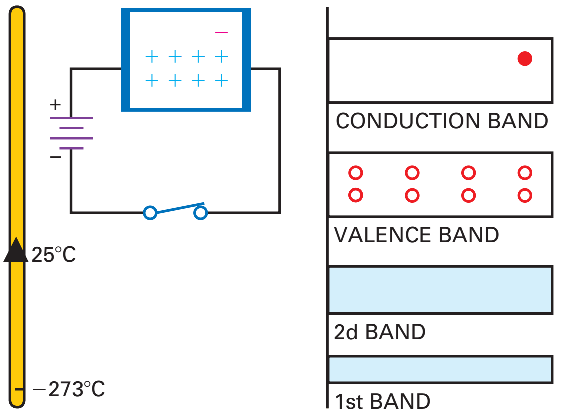


Figure 2-23 *p*-type semiconductor and its energy bands.



2-13 Barrier Potential and Temperature

The **junction temperature** is the temperature inside a diode, right at the *pn* junction. The *ambient temperature* is different. It is the temperature of the air outside the diode, the air that surrounds the diode. When the diode is conducting, the junction temperature is higher than the ambient temperature because of the heat created by recombination.

The barrier potential depends on the junction temperature. An increase in junction temperature creates more free electrons and holes in the doped regions. As these charges diffuse into the depletion layer, it becomes narrower. This means that there is *less barrier potential at higher junction temperatures.*

Before continuing, we need to define a symbol:

$$\boldsymbol{\Delta = \textbf{the change in}} \tag{2-2}$$

The Greek letter Δ (delta) stands for "the change in." For instance, ΔV means the change in voltage, and ΔT means the change in temperature. The ratio $\Delta V/\Delta T$ stands for the change in voltage divided by the change in temperature.

Now we can state a rule for estimating the change in barrier potential: *The barrier potential of a silicon diode decreases by 2 mV for each degree Celsius rise.*

As a derivation:

$$\frac{\Delta V}{\Delta T} = -2 \text{ mV}/^\circ\text{C} \tag{2-3}$$

By rearranging:

$$\Delta V = (-2 \text{ mV}/^\circ\text{C})\ \Delta T \tag{2-4}$$

With this, we can calculate the barrier potential at any junction temperature.

Example 2-5

Assuming a barrier potential of 0.7 V at an ambient temperature of 25°C, what is the barrier potential of a silicon diode when the junction temperature is 100°C? At 0°C?

SOLUTION When the junction temperature is 100°C, the change in barrier potentiali s:

$$\Delta V = (-2 \text{ mV}/^\circ\text{C})\ \Delta T = (-2 \text{ mV}/^\circ\text{C})(100^\circ\text{C} - 25^\circ\text{C}) = -150 \text{ mV}$$

This tells us that the barrier potential decreases 150 mV from its room temperature value, so it equals:

$$V_B = 0.7 \text{ V} - 0.15 \text{ V} = 0.55 \text{ V}$$

When the junction temperature is 0°C, the change in barrier potential is:

$$\Delta V = (-2 \text{ mV}/^\circ\text{C})\ \Delta T = (-2 \text{ mV}/^\circ\text{C})(0^\circ\text{C} - 25^\circ\text{C}) = 50 \text{ mV}$$

This tells us that the barrier potential increases 50 mV from its room temperature value, so it equals:

$$V_B = 0.7 \text{ V} + 0.05 \text{ V} = 0.75 \text{ V}$$

PRACTICE PROBLEM 2-5 What would be the barrier potential in Example 2-5 when the junction temperature is 50°C?

2-14 Reverse-Biased Diode

Let's discuss a few advanced ideas about a reverse-biased diode. To begin with, the depletion layer changes in width when the reverse voltage changes. Let us see what this implies.

Transient Current

When the reverse voltage increases, holes and electrons move away from the junction. As the free electrons and holes move away from the junction, they leave positive and negative ions behind. Therefore, the depletion layer gets wider. The greater the reverse bias, the wider the depletion layer becomes. While the depletion layer is adjusting to its new width, a current flows in the external circuit. This transient current drops to zero after the depletion layer stops growing.

The amount of time the transient current flows depends on the *RC* time constant of the external circuit. It typically happens in a matter of nanoseconds. Because of this, you can ignore the effects of the transient current below approximately 10 MHz.

Reverse Saturation Current

As discussed earlier, forward-biasing a diode decreases the width of the depletion layer and allows free electrons to cross the junction. Reverse bias has the opposite effect: It widens the depletion layer by moving holes and free electrons away from the junction.

Suppose that thermal energy creates a hole and free electron inside the depletion layer of a reverse-biased diode, as shown in Fig. 2-24. The free electron at *A* and the hole at *B* can now contribute to reverse current. Because of the reverse bias, the free electron will move to the right, effectively pushing an electron out of the right end of the diode. Similarly, the hole will move to the left. This extra hole on the *p* side lets an electron enter the left end of the crystal.

Figure 2-24 Thermal energy produces free electron and hole inside depletion layer.

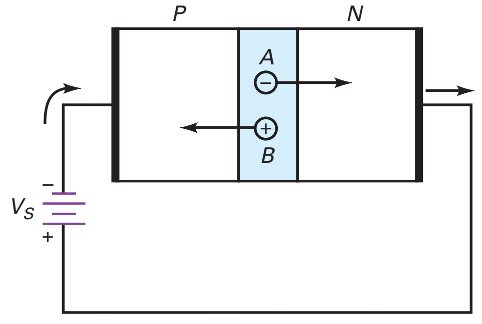
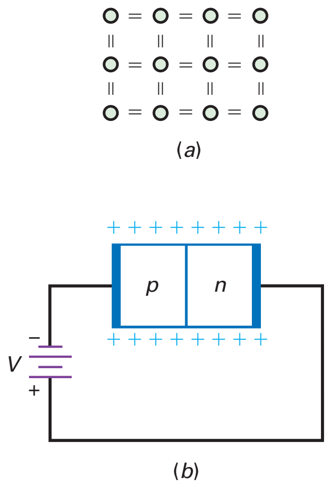


Figure 2-25 (*a*) Atoms on the surface of a crystal have no neighbors; (*b*) surface of crystal has holes.



The higher the junction temperature, the greater the saturation current. A useful approximation to remember is this: I_S doubles for each 10°C rise. As a derivation,

$$\textbf{Percent } \Delta I_S = 100\% \textbf{ for a 10°C increase} \tag{2-5}$$

In words, *the change in saturation current is* 100 *percent for each* 10°*C rise in temperature.* If the changes in temperature are less than 10°C, you can use this equivalent rule:

$$\textbf{Percent } \Delta I_S = 7\% \textbf{ per °C} \tag{2-6}$$

In words, *the change in saturation current is* 7 *percent for each Celsius degree rise*. This 7 percent solution is a close approximation of the 10° rule.

Silicon versus Germanium

In a silicon atom, the distance between the valence band and the conduction band is called the *energy gap.* When thermal energy produces free electrons and holes, it has to give the valence electrons enough energy to jump into the conduction band. The larger the energy gap, the more difficult it is for thermal energy to produce electron-hole pairs. Fortunately, silicon has a large energy gap; this means that thermal energy does not produce many electron-hole pairs at normal temperatures.

In a germanium atom, the valence band is much closer to the conduction band. In other words, germanium has a much smaller energy gap than silicon has. For this reason, thermal energy produces many more electron-hole pairs in germanium devices. This is the fatal flaw mentioned earlier. The excessive reverse current of germanium devices precludes their widespread use in modern computers, consumer electronics, and communications circuits.

Surface-Leakage Current

We discussed surface-leakage current briefly in Sec. 2-10. Recall that it is a reverse current on the surface of the crystal. Here is an explanation of why surface-leakage current exists. Suppose that the atoms at the top and bottom of Fig. 2-25*a* are on the surface of the crystal. Since these atoms have no neighbors, they have only six electrons in the valence orbit, implying two holes in each surface atom. Visualize these holes along the surface of the crystal shown in Fig. 2-25*b*. Then you can see that the skin of a crystal is like a *p*-type semiconductor. Because of this, electrons can enter the left end of the crystal, travel through the surface holes, and leave the right end of the crystal. In this way, we get a small reverse current along the surface.

The surface-leakage current is directly proportional to the reverse voltage. For instance, if you double the reverse voltage, the surface-leakage current I_{SL} doubles. We can define the surface-leakage resistance as follows:

$$R_{SL} = \frac{V_R}{I_{SL}} \tag{2-7}$$

Example 2-6

A silicon diode has a saturation current of 5 nA at 25°C. What is the saturation current at 100°C?

SOLUTION The change in temperature is:

$$\Delta T = 100°\text{C} - 25°\text{C} = 75°\text{C}$$

With Eq. (2-5), there are seven doublings between 25°C and 95°C:

$$I_S = (2^7)(5 \text{ nA}) = 640 \text{ nA}$$

With Eq. (2-6), there are an additional 5° between 95°C and 100°C:

$$I_S = (1.07^5)(640 \text{ nA}) = 898 \text{ nA}$$

PRACTICE PROBLEM 2-6 Using the same diode as in Example 2-6, what would be the saturation current at 80°C?

Example 2-7

If the surface-leakage current is 2 nA for a reverse voltage of 25 V, what is the surface-leakage current for a reverse voltage of 35 V?

SOLUTION There are two ways to solve this problem. First, calculate the surface-leakage resistance:

$$R_{SL} = \frac{25 \text{ V}}{2 \text{ nA}} = 12.5(10^9)\ \Omega$$

Then, calculate the surface-leakage current at 35 V as follows:

$$I_{SL} = \frac{35 \text{ V}}{12.5(10^9)\ \Omega} = 2.8 \text{ nA}$$

Here is a second method. Since surface-leakage current is directly proportional to reverse voltage:

$$I_{SL} = \frac{35 \text{ V}}{25 \text{ V}} 2 \text{ nA} = 2.8 \text{ nA}$$

PRACTICE PROBLEM 2-7 In Example 2-7, what is the surface-leakage current for a reverse voltage of 100 V?