Applied Physics

(PHC-103)

Lecture 03 & 04

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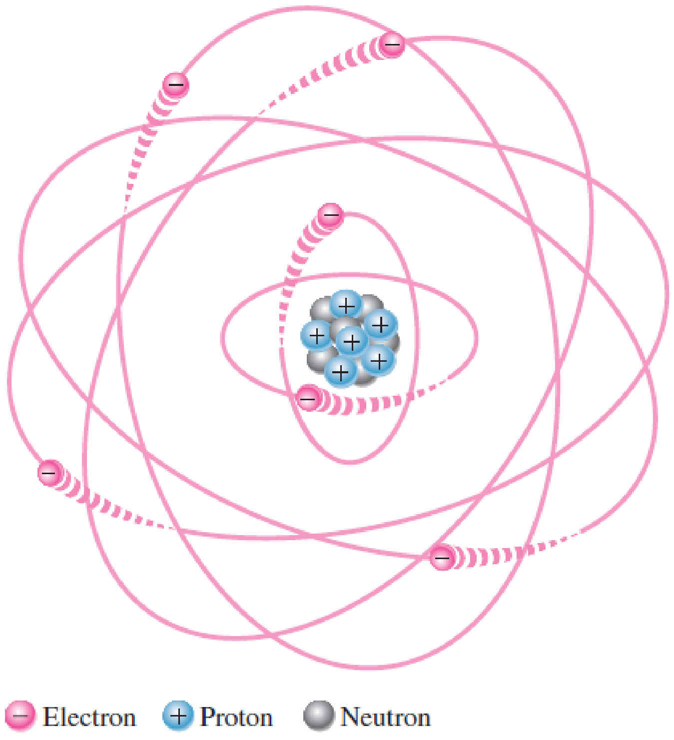
The Bohr Model

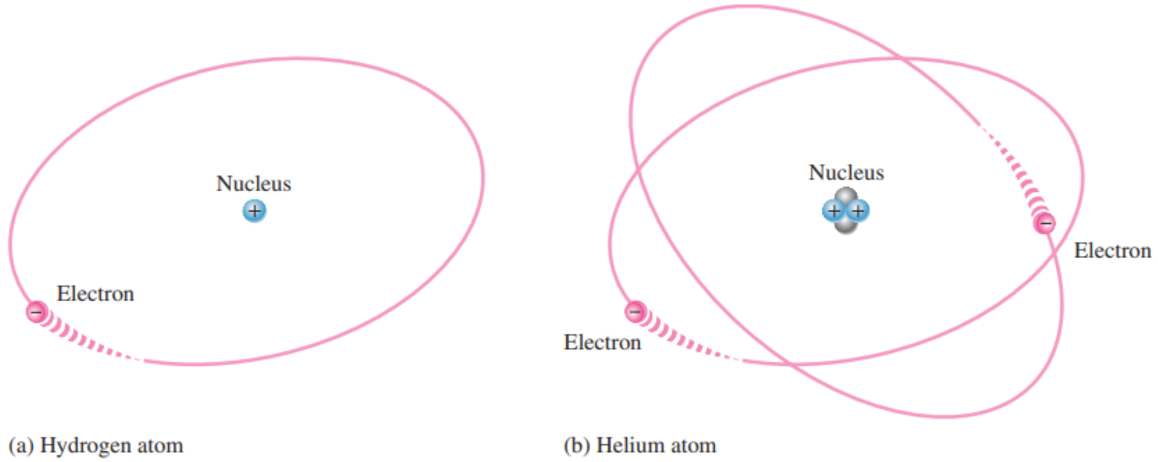
An **atom*** is the smallest particle of an element that retains the characteristics of that element. Each of the known 118 elements has atoms that are different from the atoms of all other elements. This gives each element a unique atomic structure. According to the classical Bohr model, atoms have a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons, as illustrated in Figure 1–1. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons.** The basic particles of negative charge are called **electrons**.

Each type of atom has a certain number of electrons and protons that distinguishes it from the atoms of all other elements. For example, the simplest atom is that of hydrogen, which has one proton and one electron, as shown in Figure 1–2(a). As another example, the helium atom, shown in Figure 1–2(b), has two protons and two neutrons in the nucleus and two electrons orbiting the nucleus.



▲ FIGURE 1–1

The Bohr model of an atom showing electrons in orbits around the nucleus, which consists of protons and neutrons. The "tails" on the electrons indicate motion.



▲ FIGURE 1–2

Two simple atoms, hydrogen and helium.

The Atom

- **Theory:** An atom is the fundamental unit of matter, consisting of a nucleus (center) made up of protons and neutrons. Protons are positively charged, neutrons have no charge, and electrons tiny, negatively charged particles orbit around the nucleus. Atoms are unique to each element, meaning the atomic structure of hydrogen differs from oxygen.

- **Example:** Compare an atom to a solar system where the nucleus is like the sun, and electrons orbit around it like planets.

- **Key Idea:** The structure of atoms forms the basis for understanding electricity, as the behavior of electrons determines how materials will conduct electrical current.

Atomic Number

- **Theory:** The atomic number represents the number of protons in an atom's nucleus and defines the type of element.

- **Example:** For example, hydrogen has one proton, so its atomic number is 1, while oxygen has eight protons, giving it an atomic number of 8.

- **Importance:** The atomic number is crucial for identifying elements and understanding their properties, as it affects the number of electrons and the atom's behavior in chemical reactions.

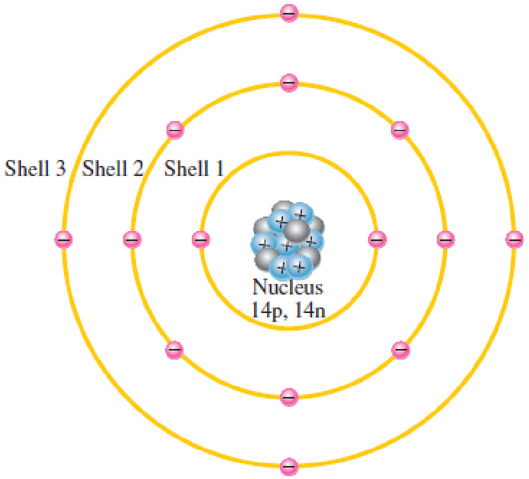
Electrons and Shells

Energy Levels Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits. Only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Each discrete distance (**orbit**) from the nucleus corresponds to a certain energy level. In an atom, the orbits are grouped into energy levels known as **shells**. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons. The shells (energy levels) are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. The Bohr model of the silicon atom is shown in Figure 1–4. Notice that there are 14 electrons and 14 each of protons and neutrons in the nucleus.

▶ FIGURE 1–4

Illustration of the Bohr model of the silicon atom.



The Maximum Number of Electrons in Each Shell The maximum number of electrons (N_e) that can exist in each shell of an atom is a fact of nature and can be calculated by the formula,

Equation 1–1

$$N_e = 2n^2$$

where n is the number of the shell. The maximum number of electrons that can exist in the innermost shell (shell 1) is

$$N_e = 2n^2 = 2(1)^2 = 2$$

The maximum number of electrons that can exist in shell 2 is

$$N_e = 2n^2 = 2(2)^2 = 2(4) = 8$$

The maximum number of electrons that can exist in shell 3 is

$$N_e = 2n^2 = 2(3)^2 = 2(9) = 18$$

The maximum number of electrons that can exist in shell 4 is

$$N_e = 2n^2 = 2(4)^2 = 2(16) = 32$$

Valence Electrons

- **Valence electrons** are the electrons in the outermost shell, known as the **valence shell**. They are significant because they are involved in bonding and reactions between atoms.
- When a valence electron gains sufficient energy from an external source, it can break free from its atom. This is the basis for conduction in materials.

Ionization

- When an atom absorbs energy, the energies of the electrons are raised. If a valence electron acquires a sufficient amount of energy, called **ionization energy**, it can actually escape from the atom's influence.
- The process of losing a valence electron is known as **ionization**, and the resulting positively charged atom is called a **positive ion**.
- The escaped valence electron is called a **free electron**. The reverse can occur when a free electron collides with an atom and is captured, releasing energy. The atom that acquired the extra electron is called a **negative ion**.

The Quantum Model

Although the Bohr model of an atom is widely used because of its simplicity and ease of visualization, it is not a complete model. The quantum model, a more recent model, is considered to be more accurate. The quantum model is a statistical model and very difficult to understand or visualize. Like the Bohr model, the quantum model has a nucleus of protons and neutrons surrounded by electrons. Unlike the Bohr model, the electrons in the quantum model do not exist in precise circular orbits as particles. Two important theories underlie the quantum model: the wave-particle duality and the uncertainty principle.

- *Wave-particle duality.* Just as light can be both a wave and a particle (**photon**), electrons are thought to exhibit a dual characteristic. The velocity of an orbiting electron is considered to be its wavelength, which interferes with neighboring electron waves by amplifying or canceling each other.
- *Uncertainly principle.* As you know, a wave is characterized by peaks and valleys; therefore, electrons acting as waves cannot be precisely identified in terms of their position. According to Heisenberg, it is impossible to determine simultaneously both the position and velocity of an electron with any degree of accuracy or certainty. The result of this principle produces a concept of the atom with *probability clouds,* which are mathematical descriptions of where electrons in an atom are most likely to be located.

In the quantum model, each shell or energy level consists of up to four subshells called **orbitals**, which are designated *s*, *p*, *d*, and *f*. Orbital *s* can hold a maximum of two electrons, orbital *p* can hold six electrons, orbital *d* can hold ten electrons, and orbital *f* can hold fourteen electrons. Each atom can be described by an electron configuration table that shows the shells or energy levels, the orbitals, and the number of electrons in each orbital. For example, the electron configuration table for the nitrogen atom is given in Table 1–1. The first full-size number is the shell or energy level, the letter is the orbital, and the exponent is the number of electrons in the orbital.

▶ TABLE 1–1

Electron configuration table for nitrogen.

NOTATION	EXPLANATION
$1s^2$	2 electrons in shell 1, orbital *s*
$2s^2$ $2p^3$	5 electrons in shell 2: 2 in orbital *s*, 3 in orbital *p*

Atomic orbitals do not resemble a discrete circular path for the electron as depicted in Bohr's planetary model. In the quantum picture, each shell in the Bohr model is a three-dimensional space surrounding the atom that represents the mean (average) energy of the electron cloud. The term **electron cloud** (probability cloud) is used to describe the area around an atom's nucleus where an electron will probably be found.

In a three-dimensional representation of the quantum model of an atom, the *s*-orbitals are shaped like spheres with the nucleus in the center. For energy level 1, the sphere is "solid" but for energy levels 2 or more, each single *s*-orbital is composed of spherical surfaces that are nested shells. A *p*-orbital for shell 2 has the form of two ellipsoidal lobes with a point of tangency at the nucleus (sometimes referred to as a dumbbell shape.) The three *p*-orbitals in each energy level are oriented at right angles to each other. One is oriented on the *x*-axis, one on the *y*-axis, and one on the *z*-axis. For example, a view of the quantum model of a sodium atom (Na) that has 11 electrons is shown in Figure 1–5. The three axes are shown to give you a 3-D perspective.

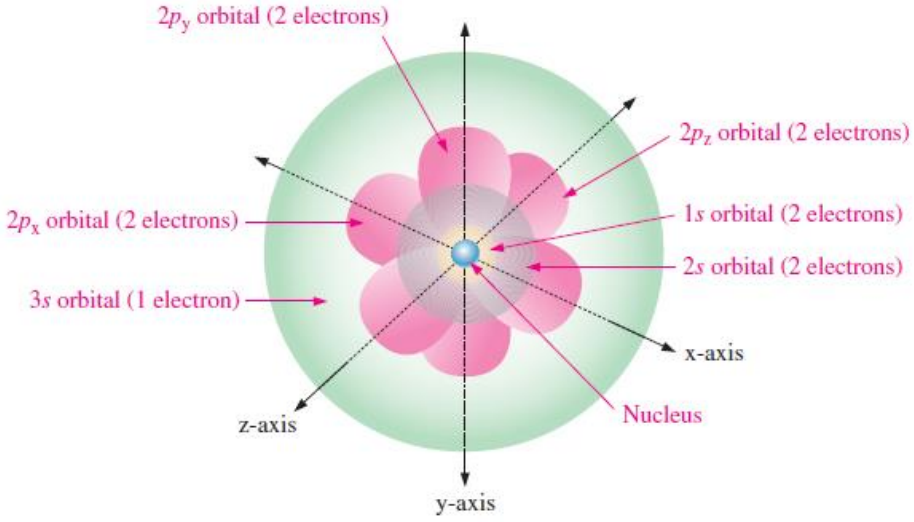


FIGURE 1–5

Three-dimensional quantum model of the sodium atom, showing the orbitals and number of electrons in each orbital.

MATERIALS USED IN ELECTRONICS

In terms of their electrical properties, materials can be classified into three groups: conductors, semiconductors, and insulators. When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within the crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms. Silicon is a crystalline material.

Insulators, Conductors, and Semiconductors

- An **insulator** is a material that does not conduct electrical current under normal conditions. Valence electrons are tightly bound to the atoms; therefore, there are very few free electrons in an insulator. **Examples** of insulators are rubber, plastics, glass, mica, and quartz.
- A **conductor** is a material that easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminum (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom. These loosely bound valence electrons become free electrons.
- A **semiconductor** is a material that is between conductors and insulators in its ability to conduct electrical current.

Band Gap

- When an electron acquires enough additional energy, it can leave the valence shell, become a free electron, and exist in what is known as the **conduction band**. or A higher energy band where electrons are free to move, allowing conduction of electricity.
- The difference in energy between the valence band and the conduction band is called an **energy gap or band gap**.
- This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move throughout the material and is not tied to any given atom.

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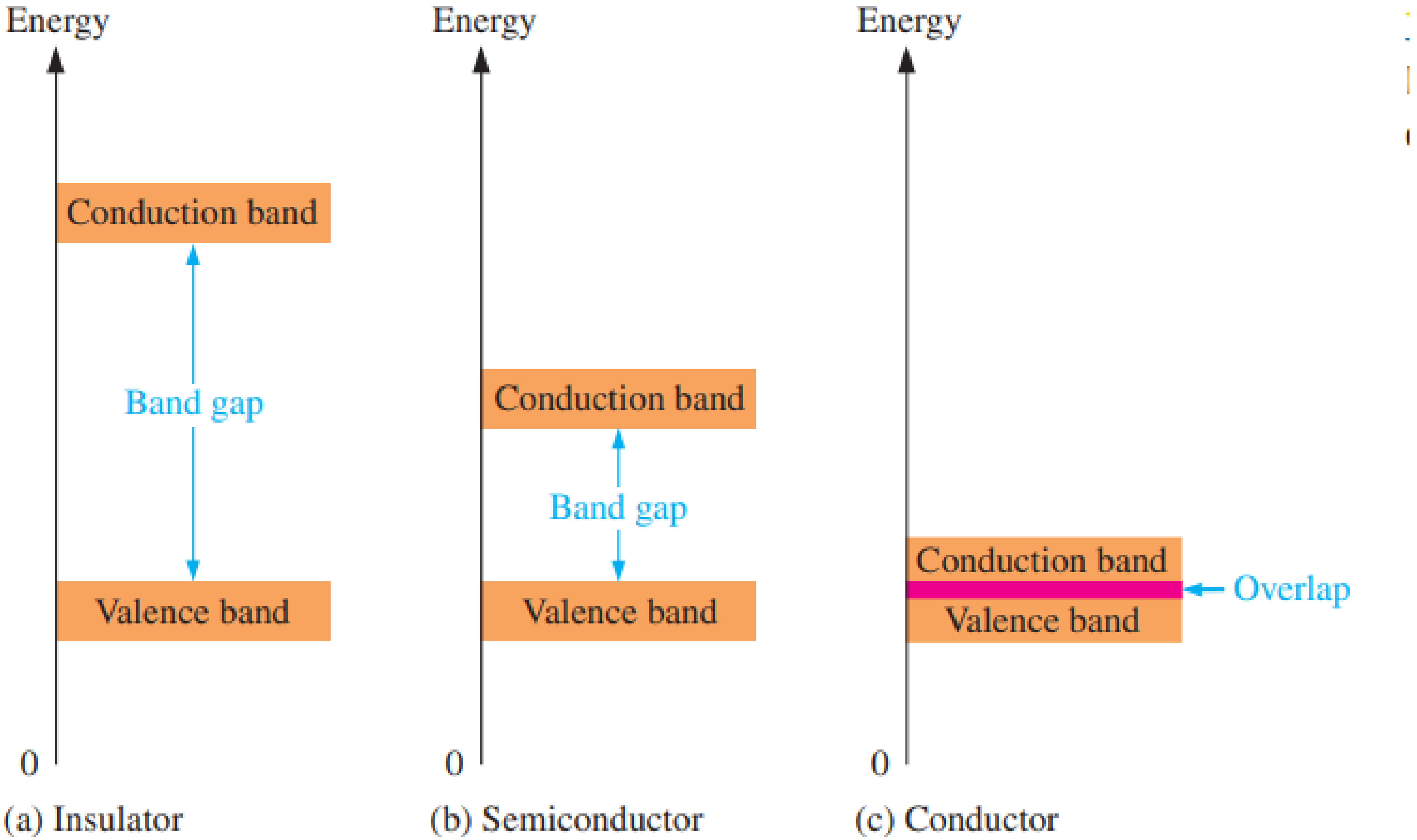
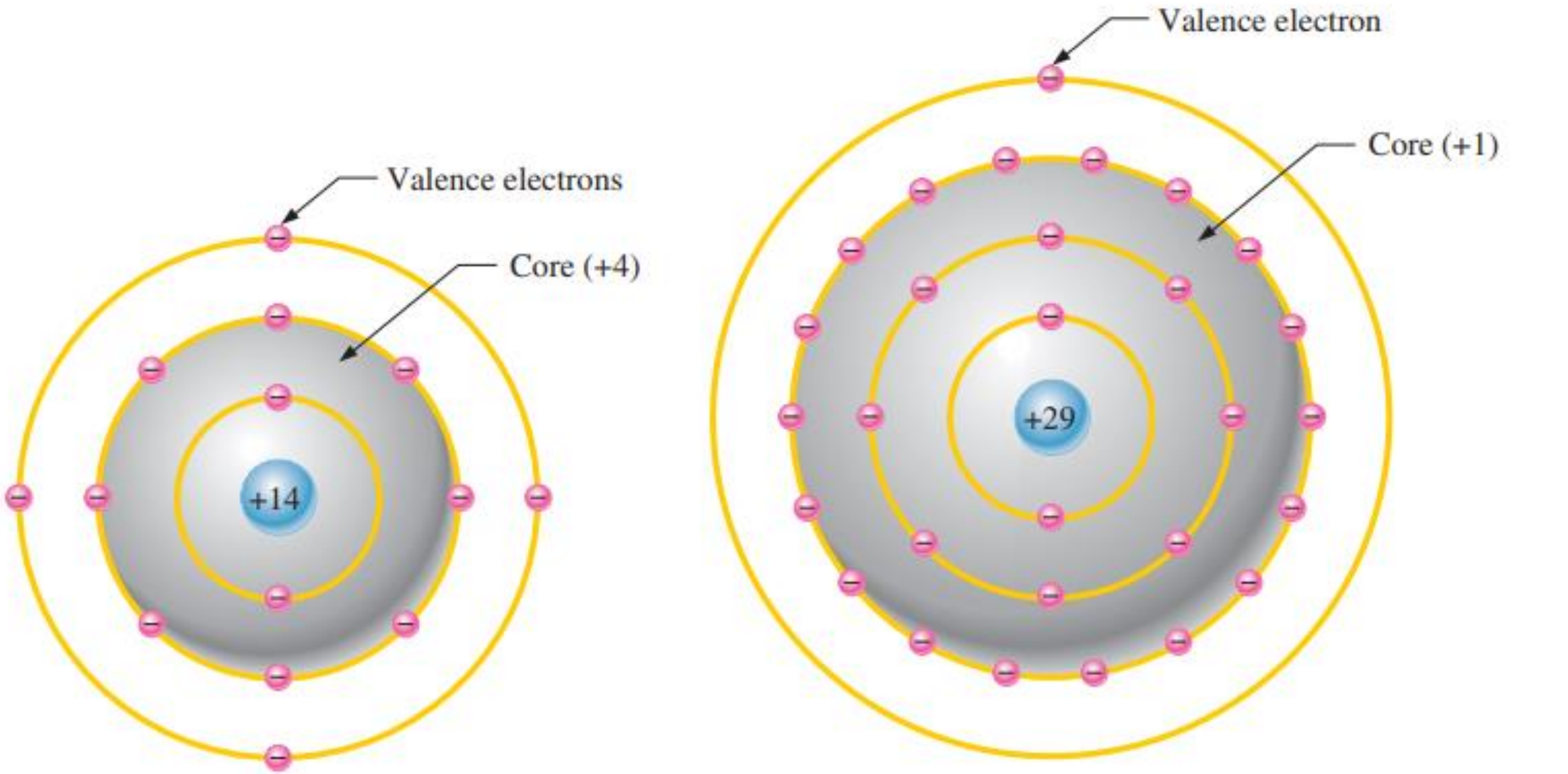

Energy
Conduction band
Band gap
Valence band
0
(a) Insulator
Energy
Conduction band
Band gap
Valence band
0
(b) Semiconductor
Energy
Conduction band
Overlap
Valence band
0
(c) Conductor

Comparison of a Semiconductor Atom to a Conductor Atom

- Silicon is a semiconductor and copper is a conductor. Bohr diagrams of the silicon atom and the copper atom are shown .



(a) Silicon atom (b) Copper atom

- The core of the silicon atom has a net charge of +4 (14 p+, 10 e-) and the core of the copper atom has a net charge of +1 (29 p+, 28 e-). The core includes everything except the valence electrons.

- There is more force trying to hold a valence electron to the atom in silicon than in copper.

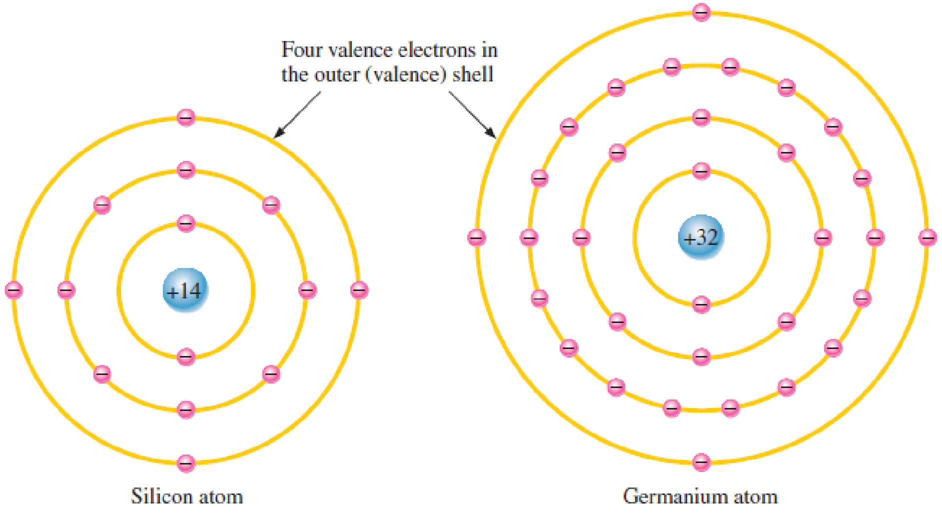
- The copper's valence electron is in the 4th shell, while silicon's valence electrons are in the 3rd shell. Thus, the valence electron in copper has more energy than the valence electrons in silicon.

- It is easier for valence electrons in copper to acquire enough additional energy to escape from their atoms and become free electrons.

Silicon and Germanium

The atomic structures of silicon and germanium are compared in Figure 1–9. **Silicon** is used in diodes, transistors, integrated circuits, and other semiconductor devices. Notice that both silicon and **germanium** have the characteristic four valence electrons.

The valence electrons in germanium are in the fourth shell while those in silicon are in the third shell, closer to the nucleus. This means that the germanium valence electrons are at higher energy levels than those in silicon and, therefore, require a smaller amount of additional energy to escape from the atom. This property makes germanium more unstable at high temperatures and results in excessive reverse current. This is why silicon is a more widely used semiconductive material.



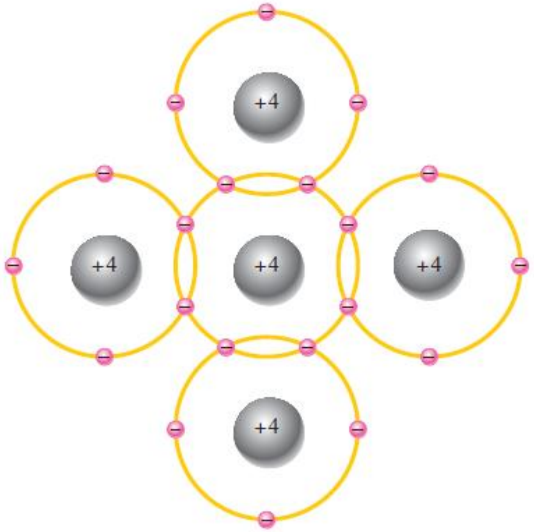
▶ FIGURE 1–9

Diagrams of the silicon and germanium atoms.

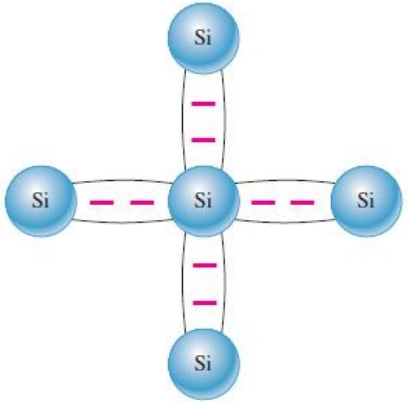
Covalent Bonds Figure 1–10 shows how each silicon atom positions itself with four adjacent silicon atoms to form a silicon **crystal**. A silicon (Si) atom with its four valence electrons shares an electron with each of its four neighbors. This effectively creates eight shared valence electrons for each atom and produces a state of chemical stability. Also, this sharing of valence electrons produces the **covalent** bonds that hold the atoms together; each valence electron is attracted equally by the two adjacent atoms which share it. Covalent bonding in an intrinsic silicon crystal is shown in Figure 1–11. An **intrinsic** crystal is one that has no impurities. Covalent bonding for germanium is similar because it also has four valence electrons.

FIGURE 1–10

Illustration of covalent bonds in silicon.



(a) The center silicon atom shares an electron with each of the four surrounding silicon atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.



(b) Bonding diagram. The red negative signs represent the shared valence electrons.

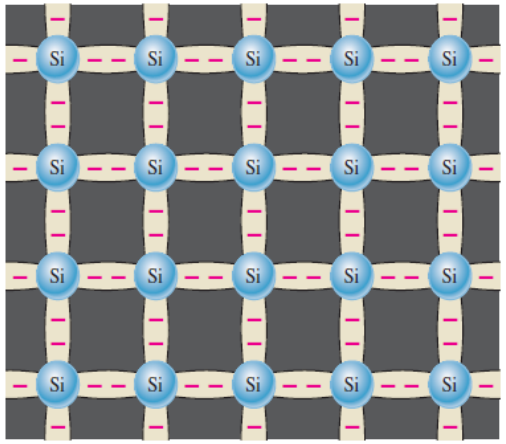


FIGURE 1–11

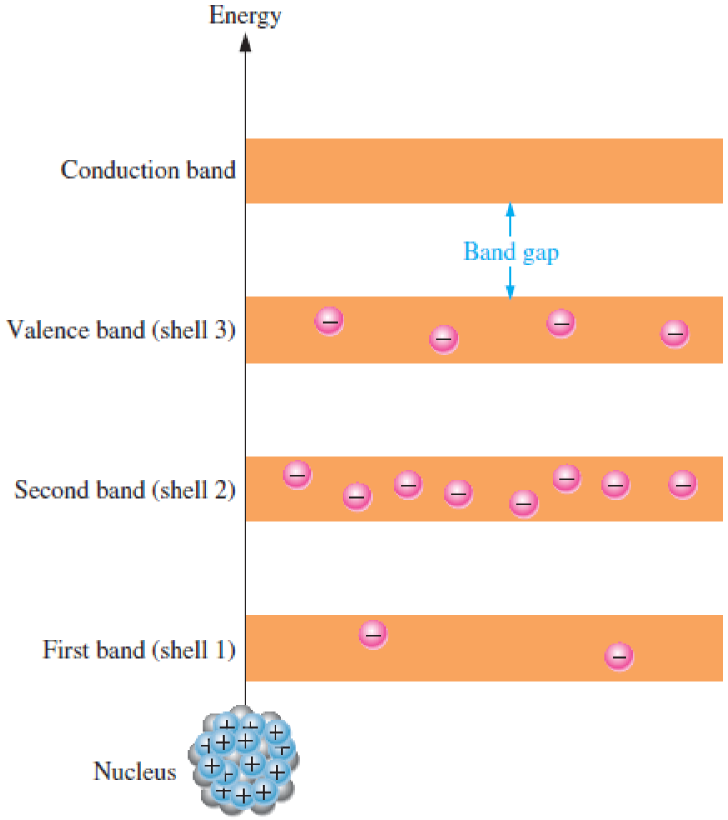
Covalent bonds in a silicon crystal.

CURRENT IN SEMICONDUCTORS

As you have learned, the electrons of an atom can exist only within prescribed energy bands. Each shell around the nucleus corresponds to a certain energy band and is separated from adjacent shells by band gaps, in which no electrons can exist. Figure 1–12 shows the energy band diagram for an unexcited (no external energy such as heat) atom in a pure silicon crystal. This condition occurs *only* at a temperature of absolute 0 Kelvin.

▶ FIGURE 1–12

Energy band diagram for an unexcited atom in a pure (intrinsic) silicon crystal. There are no electrons in the conduction band.

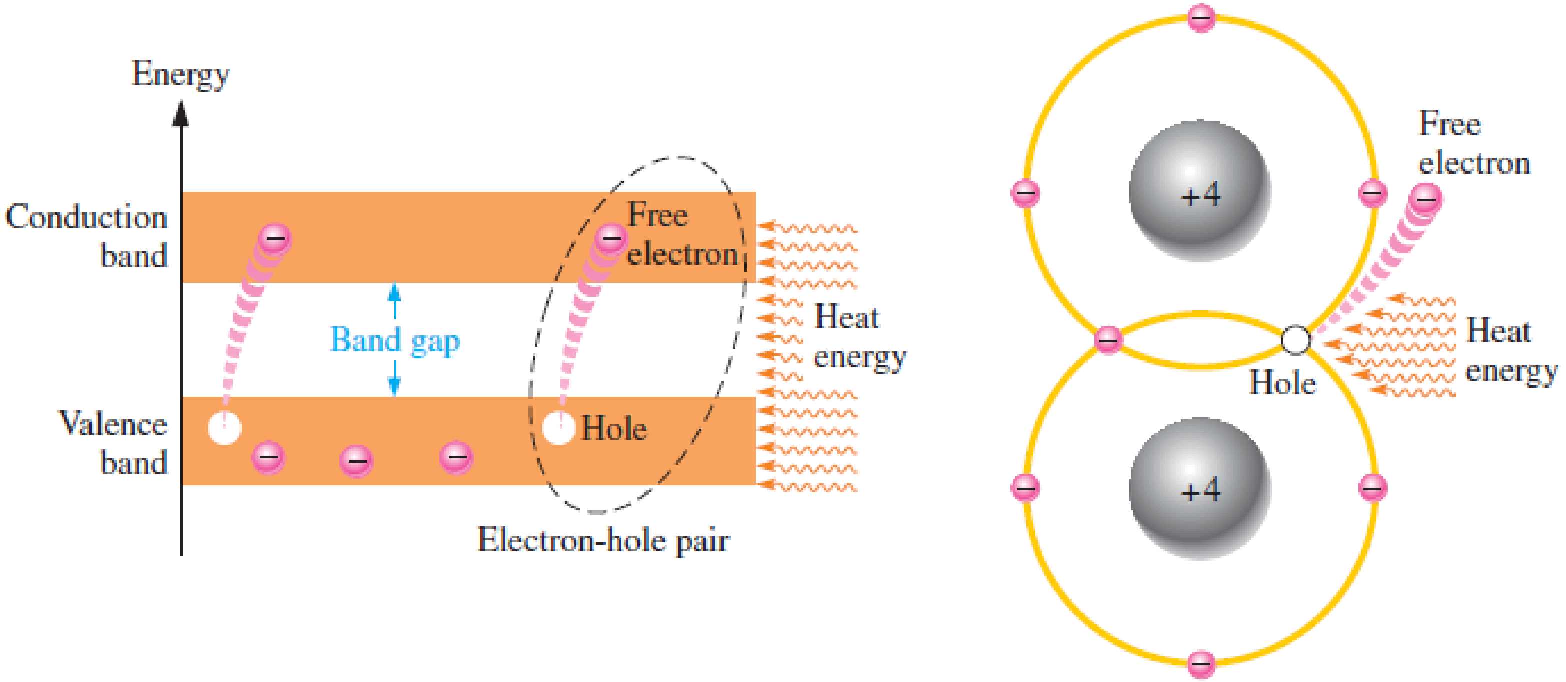


Conduction Electrons and Holes

An intrinsic (pure) silicon crystal at room temperature has sufficient heat (thermal) energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electrons. Free electrons are also called **conduction electrons.** This is illustrated in the energy diagram of Figure 1–13(a) and in the bonding diagram of Figure 1–13(b).

▶ FIGURE 1–13

Creation of electron-hole pairs in a silicon crystal. Electrons in the conduction band are free electrons.



(a) Energy diagram (b) Bonding diagram

When an electron jumps to the conduction band, a vacancy is left in the valence band within the crystal. This vacancy is called a **hole**. For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an **electron-hole pair. Recombination** occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

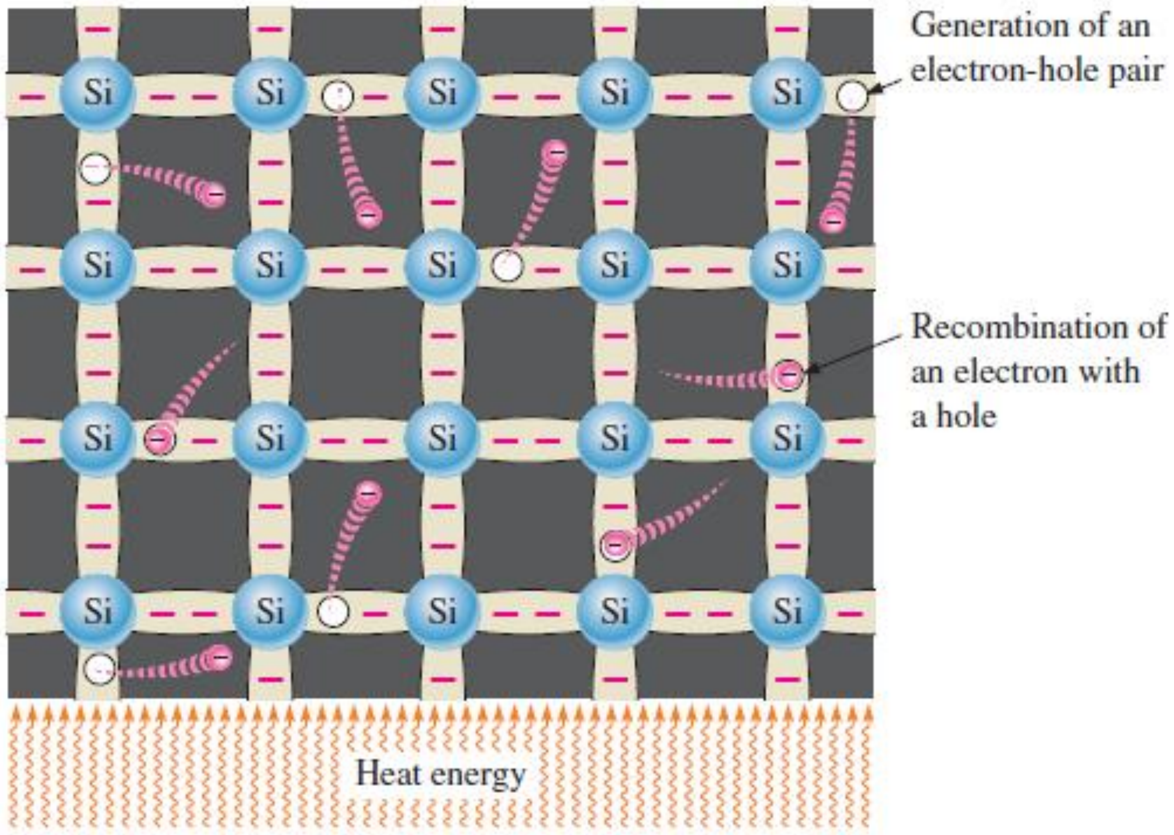


FIGURE 1–14

Electron-hole pairs in a silicon crystal. Free electrons are being generated continuously while some recombine with holes.

Electron and Hole Current

When a voltage is applied across a piece of intrinsic silicon, as shown in Figure 1-15, the thermally generated free electrons in the conduction band, which are free to move randomly in the crystal structure, are now easily attracted toward the positive end. This movement of free electrons is one type of **current** in a semiconductive material and is called *electron current*.

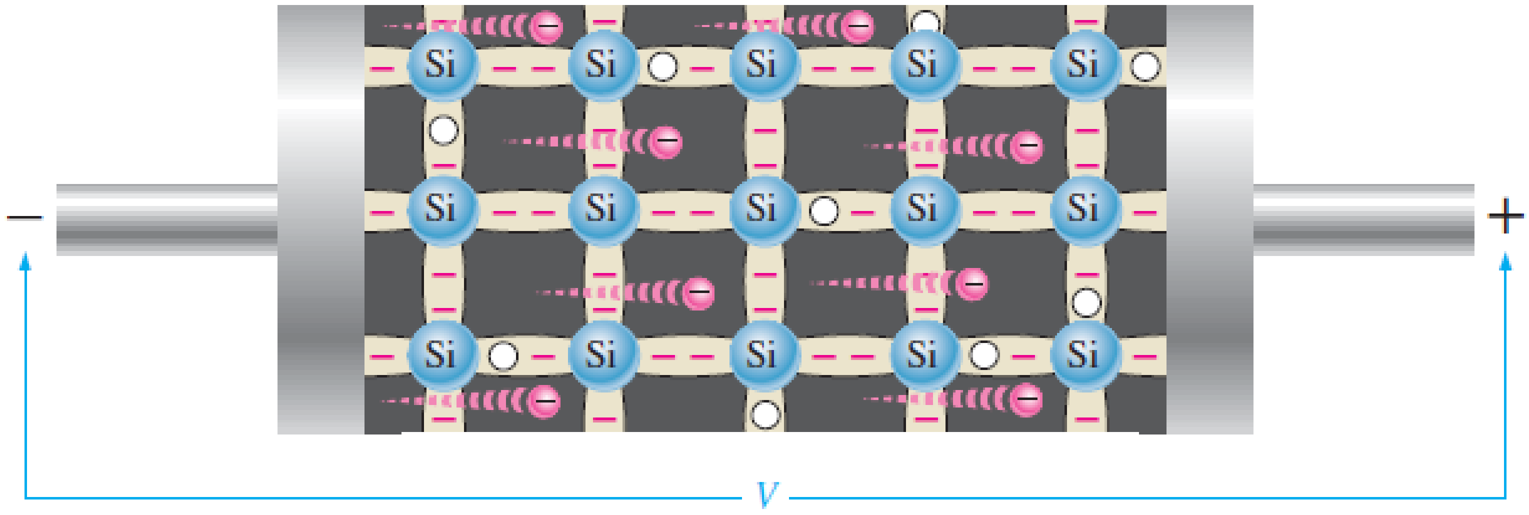


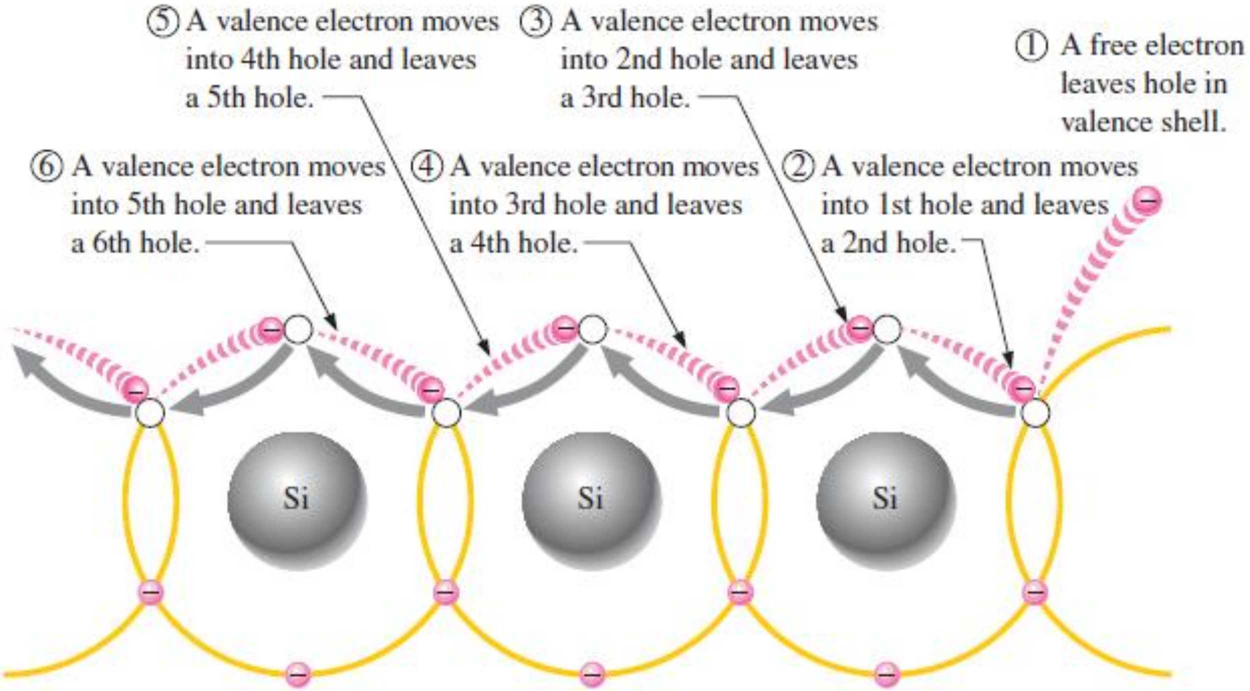
FIGURE 1–15

Electron current in intrinsic silicon is produced by the movement of thermally generated free electrons.

Another type of current occurs in the valence band, where the holes created by the free electrons exist. Electrons remaining in the valence band are still attached to their atoms and are not free to move randomly in the crystal structure as are the free electrons. However, a valence electron can move into a nearby hole with little change in its energy level, thus leaving another hole where it came from. Effectively the hole has moved from one place to another in the crystal structure, as illustrated in Figure 1–16. Although current in the valence band is produced by valence electrons, it is called *hole current* to distinguish it from electron current in the conduction band.

▶ FIGURE 1–16

Hole current in intrinsic silicon.



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

N-Type and *P*-Type Semiconductors

Semiconductive materials do not conduct current well and are of limited value in their intrinsic state. This is because of the limited number of free electrons in the conduction band and holes in the valence band. Intrinsic silicon (or germanium) must be modified by increasing the number of free electrons or holes to increase its conductivity and make it useful in electronic devices. This is done by adding impurities to the intrinsic material. Two types of extrinsic (impure) semiconductive materials, *n*-type and *p*-type, are the key building blocks for most types of electronic devices.

Since semiconductors are generally poor conductors, their conductivity can be drastically increased by the controlled addition of impurities to the intrinsic (pure) semiconductive material. This process, called **doping**, increases the number of current carriers (electrons or holes).

The two categories of impurities are

- n-type and
- p-type

N-Type Semiconductor

To increase the number of conduction-band electrons in intrinsic silicon, pentavalent impurity atoms are added. These are atoms with five valence electrons such as arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb).

As illustrated in below figure, each pentavalent atom (antimony, in this case) forms covalent bonds with four adjacent silicon atoms. Four of the antimony atom’s valence electrons are used to form the covalent bonds with silicon atoms, leaving one extra electron.

This extra electron becomes a conduction electron because it is not involved in bonding. Because the pentavalent atom gives up an electron, it is often called a **donor atom**. The number of conduction electrons can be carefully controlled by the number of impurity atoms added to the silicon. A conduction electron created by this doping process does not leave a hole in the valence band because it is in excess of the number required to fill the valence band.

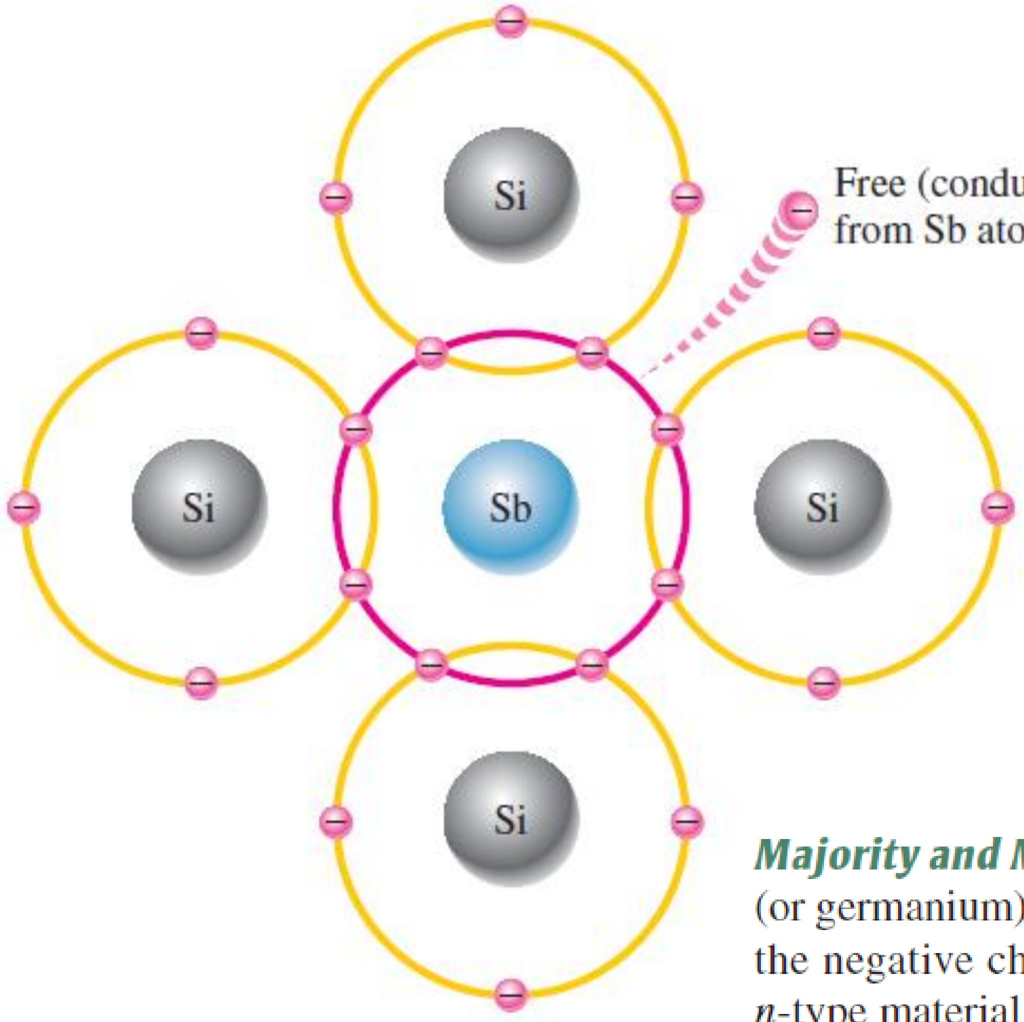


FIGURE 1–17

Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

Majority and Minority Carriers Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron). The electrons are called the **majority carriers** in *n*-type material. Although the majority of current carriers in *n*-type material are electrons, there are also a few holes that are created when electron-hole pairs are thermally generated. These holes are *not* produced by the addition of the pentavalent impurity atoms. Holes in an *n*-type material are called **minority carriers.**

P-Type Semiconductor

To increase the number of holes in intrinsic silicon, **trivalent** impurity atoms are added. These are atoms with three valence electrons such as boron (B), indium (In), and gallium (Ga). As illustrated in Figure 1–18, each trivalent atom (boron, in this case) forms covalent bonds with four adjacent silicon atoms. All three of the boron atom's valence electrons are used in the covalent bonds; and, since four electrons are required, a hole results when each trivalent atom is added. Because the trivalent atom can take an electron, it is often referred to as an *acceptor atom*. The number of holes can be carefully controlled by the number of trivalent impurity atoms added to the silicon. A hole created by this doping process is *not* accompanied by a conduction (free) electron.

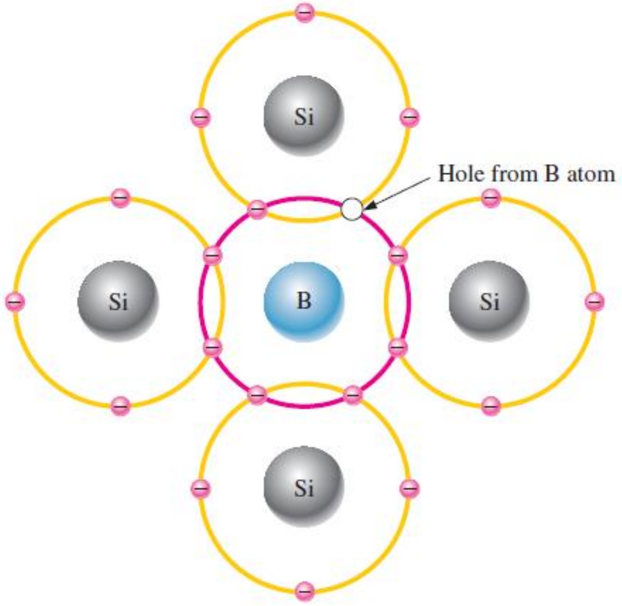


FIGURE 1–18

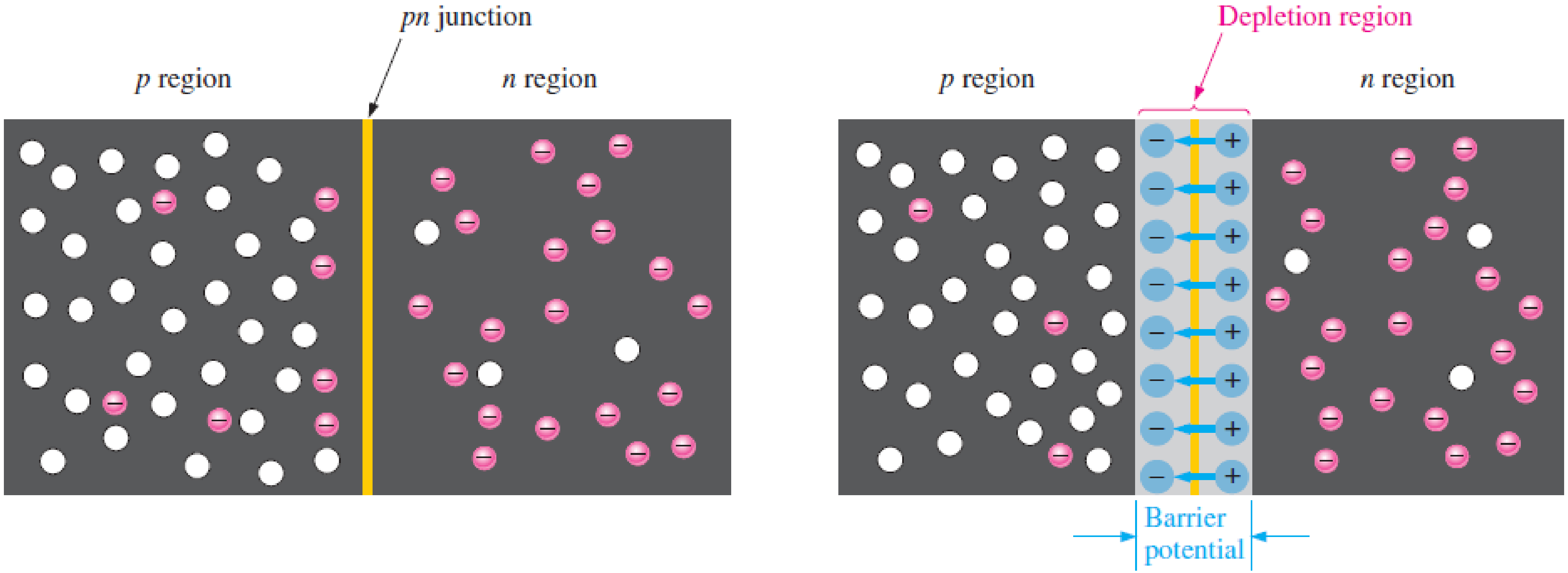
Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

Majority and Minority Carriers Since most of the current carriers are holes, silicon (or germanium) doped with trivalent atoms is called a *p*-type semiconductor. The holes are the majority carriers in *p*-type material. Although the majority of current carriers in *p*-type material are holes, there are also a few conduction-band electrons that are created when electron-hole pairs are thermally generated. These conduction-band electrons are *not* produced by the addition of the trivalent impurity atoms. Conduction-band electrons in *p*-type material are the minority carriers.

THE PN JUNCTION

When you take a block of silicon and **dope** part of it with a **trivalent impurity** and the other part with a **pentavalent impurity**, a boundary called the **pn junction** is formed between the resulting **p-type and n-type portions**. The pn junction is the basis for diodes, certain transistors, solar cells, and other devices.

If a piece of intrinsic silicon is doped so that part is *n*-type and the other part is *p*-type, a ***pn* junction** forms at the boundary between the two regions and a diode is created, as indicated in Figure 1–19(a). The *p* region has many holes (majority carriers) from the impurity atoms and only a few thermally generated free electrons (minority carriers). The *n* region has many free electrons (majority carriers) from the impurity atoms and only a few thermally generated holes (minority carriers).



(a) The basic silicon structure at the instant of junction formation showing only the majority and minority carriers. Free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion. The blue arrows between the positive and negative charges in the depletion region represent the electric field.

▲ FIGURE 1–19

Formation of the depletion region. The width of the depletion region is exaggerated for illustration purposes.

Formation of the Depletion Region

The free electrons in the n region are randomly drifting in all directions. At the instant of the **pn junction** formation, the free electrons near the junction in the **n region** begin to diffuse across the junction into the **p region** where they combine with holes near the junction, as shown in Figure 1–19(b).

Before the **pn junction is formed**, recall that there are as many electrons as protons in the n-type material, making the material neutral in terms of net charge. The same is true for the p-type material.

When the **pn junction** is formed, the **n region loses free electrons** as they diffuse across the junction. This creates a **layer of positive charges (pentavalent ions) near the junction**. As the electrons move across the junction, **the p region loses holes as the electrons** and holes combine. This creates a **layer of negative charges (trivalent ions) near the junction.**

- These two layers of positive and negative charges form the depletion region, as shown in Figure 1–19(b). The term **depletion** refers to the fact that **the region near the pn junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction.**
- After the initial surge of free electrons across the pn junction, the depletion region has expanded to a point where equilibrium is established and there is no further diffusion of electrons across the junction. This occurs as follows.
- As electrons continue to diffuse across the junction, more and more positive and negative charges are created near the junction as the depletion region is formed. A point is reached where the total negative charge in the depletion region repels any further diffusion of electrons (negatively charged particles) into the p region (like charges repel) and the diffusion stops.
- In other words, the depletion region acts as a barrier to the further movement of electrons across the junction.

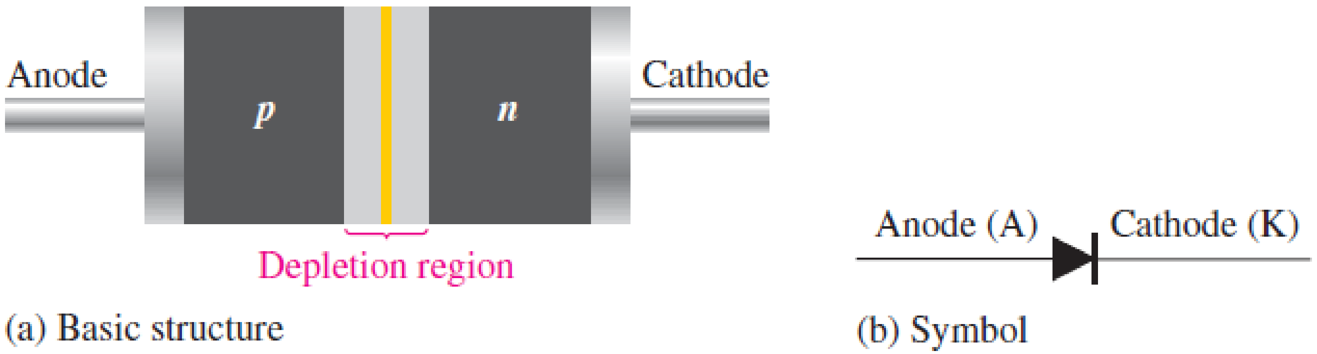
Barrier Potential Any time there is a positive charge and a negative charge near each other, there is a force acting on the charges as described by Coulomb's law. In the depletion region there are many positive charges and many negative charges on opposite sides of the *pn* junction. The forces between the opposite charges form an *electric field,* as illustrated in Figure 1–19(b) by the blue arrows between the positive charges and the negative charges. This electric field is a barrier to the free electrons in the *n* region, and energy must be expended to move an electron through the electric field. That is, external energy must be applied to get the electrons to move across the barrier of the electric field in the depletion region.

The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field. This potential difference is called the **barrier potential** and is expressed in volts.

The barrier potential of a *pn* junction depends on several factors, including the type of semiconductive material, the amount of doping, and the temperature. The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at 25°C. Because germanium devices are not widely used, silicon will be used throughout the rest of the book.

The Diode

As mentioned, a **diode** is made from a small piece of semiconductor material, usually silicon, in which half is doped as a *p* region and half is doped as an *n* region with a *pn* junction and depletion region in between. The *p* region is called the **anode** and is connected to a conductive terminal. The *n* region is called the **cathode** and is connected to a second conductive terminal. The basic diode structure and schematic symbol are shown in Figure 2–1.

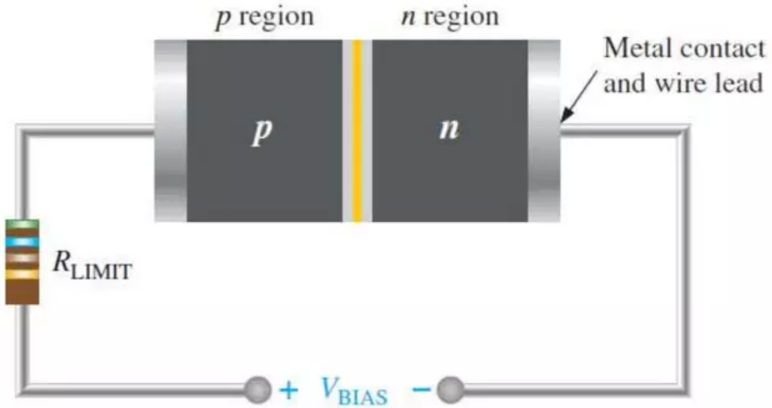


◄ FIGURE 2–1

The diode.

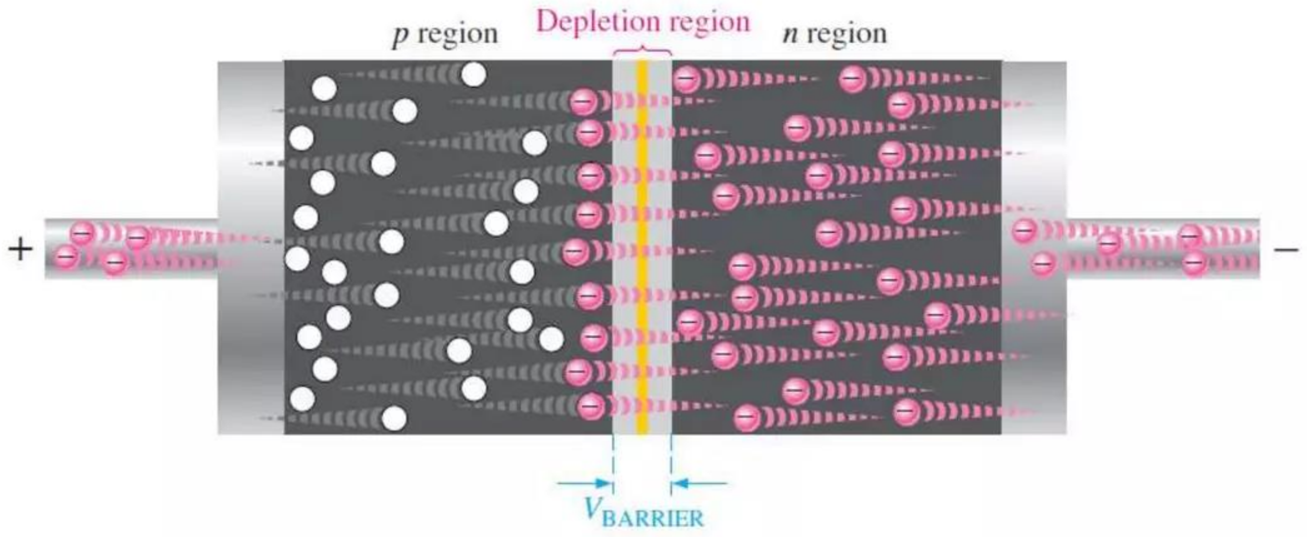
Forward Bias

- Forward bias is the condition that allows current through the PN junction.
- Figure shows a dc voltage source connected by conductive material (contacts and wire) across a diode in the direction to produce forward bias.
- This external bias voltage is designated as VBIAS.
- The resistor limits the forward current to a value that will not damage the diode.
- The **negative side of VBIAS** is connected to the **n region** of the diode and the **positive side** is connected to the **p region.**
- This is one requirement for forward bias.
- A second requirement is that the bias voltage, VBIAS, must be greater than the barrier potential.



Forward Bias

- Because like charges repel, the negative side of the bias-voltage source “pushes” the free electrons, which are the majority carriers in the n region, toward the PN junction.
- This flow of free electrons is called electron current. The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the n region as shown.
- The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the p region.
- Once in the p region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.



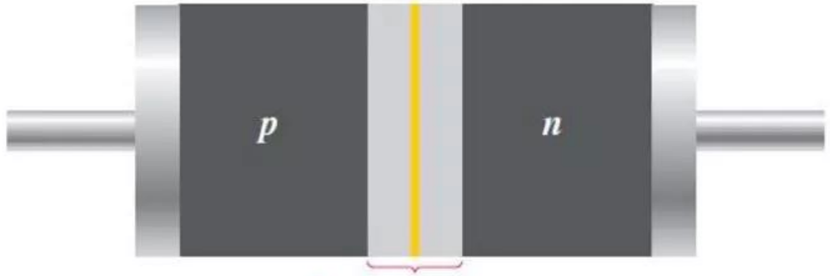
- Since unlike charges attract, the positive side of the bias-voltage source attracts the valence electrons toward the left end of the p region. The holes in the p region provide the medium or “pathway” for these valence electrons to move through the p region.

- The valence electrons move from one hole to the next toward the left. The holes, which are the majority carriers in the p region, effectively (not actually) move to the right toward the junction, as in Figure.

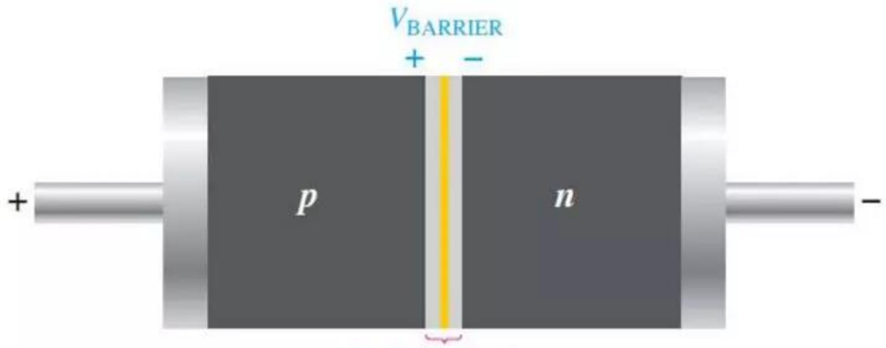
- This effective flow of holes is the hole current. The hole current as being created by the flow of valence electrons through the p region, with the holes providing the only means for these electrons to flow.

- As the electrons flow out of the p region through the external connection (conductor) and to the positive side of the bias-voltage source, they leave holes behind in the p region; at the same time, these electrons become conduction electrons in the metal conductor.

- There is a continuous availability of holes effectively moving toward the pn junction to combine with the continuous stream of electrons as they come across the junction into the p region.



(a) At equilibrium (no bias)

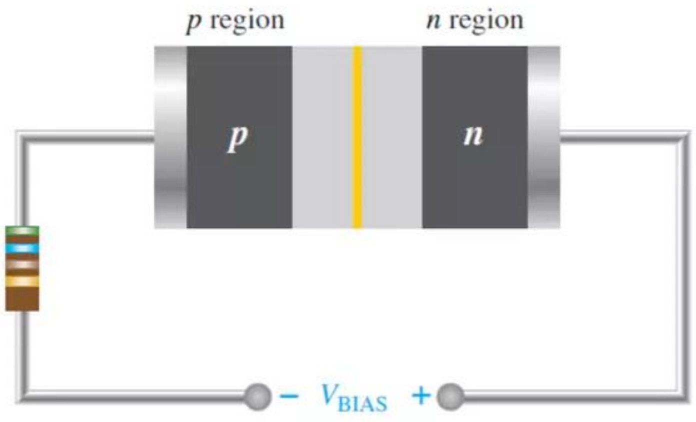


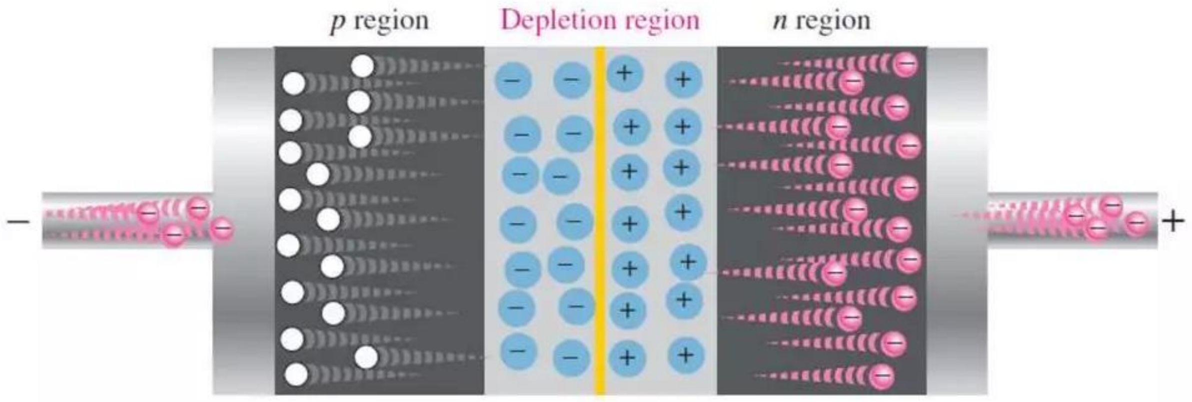
(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

- The electric field between the positive and negative ions in the depletion region on either side of the junction creates an “energy hill” that prevents free electrons from diffusing across the junction at equilibrium. This is known as the barrier potential.
- When forward bias is applied, the free electrons are provided with enough energy from the bias-voltage source to overcome the barrier potential and effectively “climb the energy hill” and cross the depletion region.
- The energy that the electrons require in order to pass through the depletion region is equal to the barrier potential.
- In other words, the electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region. This energy loss results in a voltage drop across the pn junction equal to the barrier potential (0.7 V) .
- An additional small voltage drop occurs across the p and n regions due to the internal resistance of the material. For doped semiconductive material, this resistance, called the dynamic resistance, is very small and can usually be neglected.

Reverse Bias

- Reverse bias is the condition that essentially prevents current through the diode.
- Figure shows a dc voltage source connected across a diode in the direction to produce reverse bias.
- This external bias voltage is designated as VBIAS just as it was for forward bias.
- The positive side of VBIAS is connected to the n region of the diode and the negative side is connected to the p region.
- Also note that the depletion region is shown much wider than in forward bias or equilibrium.



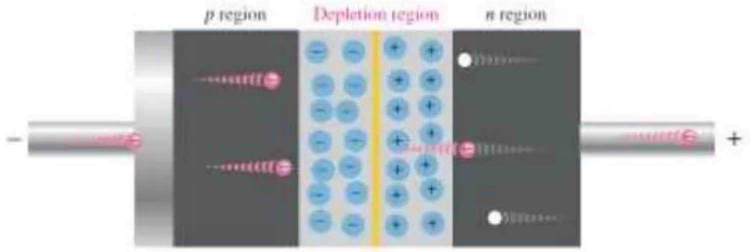


Reverse Bias

- Because unlike charges attract, the positive side of the bias-voltage source “pulls” the free electrons, which are the majority carriers in the n region, away from the pn junction.
- As the electrons flow toward the positive side of the voltage source, additional positive ions are created. This results in a widening of the depletion region and a depletion of majority carriers.
- In the p region, electrons from the negative side of the voltage source enter as valence electrons and move from hole to hole toward the depletion region where they create additional negative ions.
- This results in a widening of the depletion region and a depletion of majority carriers. The flow of valence electrons can be viewed as holes being “pulled” toward the positive side.
- The initial flow of charge carriers is transitional and lasts for only a very short time after the reverse-bias voltage is applied. As the depletion region widens, the availability of majority carriers decreases.
- As more of the n and p regions become depleted of majority carriers, the electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage, VBIAS.
- At this point, the transition current essentially ceases except for a very small reverse current that can usually be neglected.

Reverse Bias

- Reverse Current : The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the n and p regions that are produced by thermally generated electron-hole pairs.
- The small number of free minority electrons in the p region are “pushed” toward the PN junction by the negative bias voltage.



- When these electrons reach the wide depletion region, they “fall down the energy hill” and combine with the minority holes in the n region as valence electrons and flow toward the positive bias voltage, creating a small hole current.
- The conduction band in the p region is at a higher energy level than the conduction band in the n region.
- Therefore, the minority electrons easily pass through the depletion region because they require no additional energy.

Reverse Bias

- Reverse Breakdown : Normally, the reverse current is so small that it can be neglected. However, if the external reverse-bias voltage is increased to a value called the breakdown voltage, the reverse current will drastically increase.

- The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the p region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band.

- The newly created conduction electrons are also high in energy and repeat the process. If one electron knocks only two others out of their valence orbit during its travel through the p region, the numbers quickly multiply.

- As these high-energy electrons go through the depletion region, they have enough energy to go through the n region as conduction electrons, rather than combining with holes.

- The multiplication of conduction electrons just discussed is known as the avalanche effect, and reverse current can increase dramatically if steps are not taken to limit the current.

- When the reverse current is not limited, the resulting heating will permanently damage the diode. Most diodes are not operated in reverse breakdown, but if the current is limited (by adding a series-limiting resistor for example), there is no permanent damage to the diode

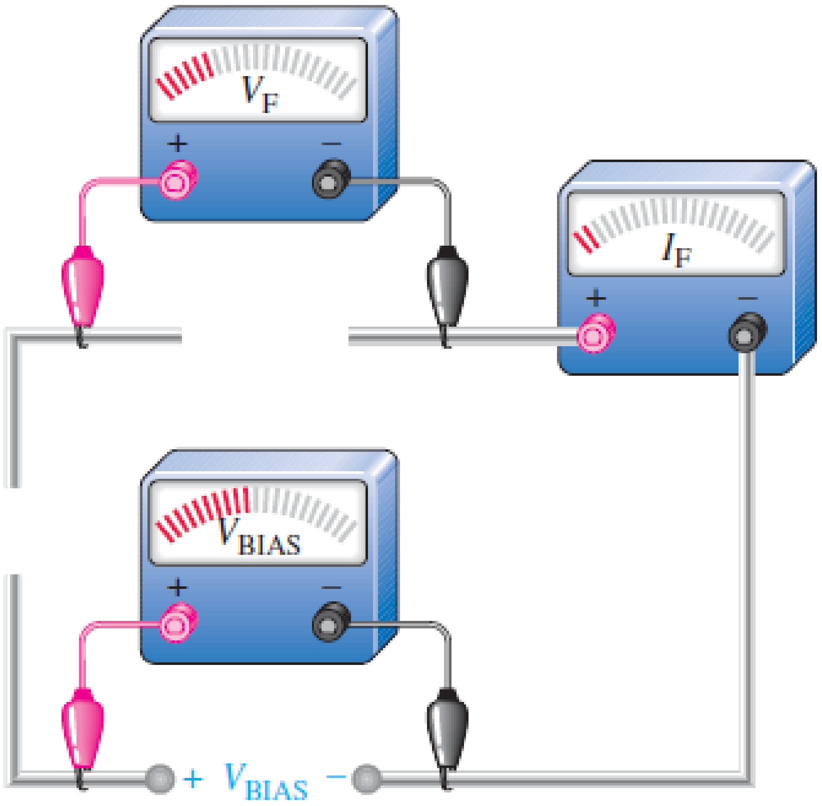
VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE

V-I Characteristic for Forward Bias

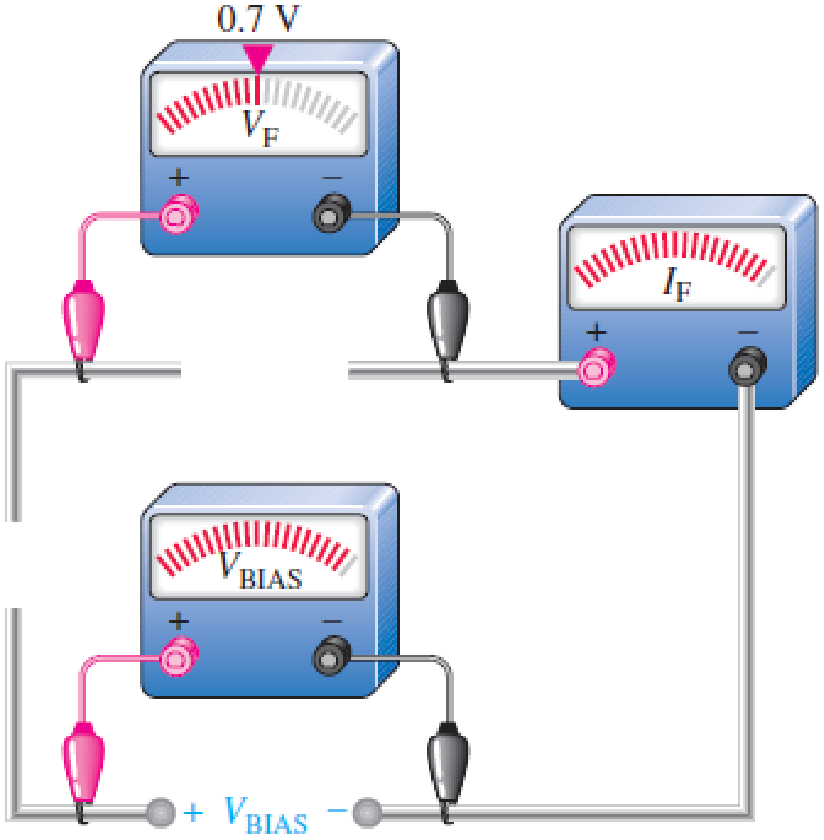
When a forward-bias voltage is applied across a diode, there is current. This current is called the *forward current* and is designated I_F. Figure 2–9 illustrates what happens as the forward-bias voltage is increased positively from 0 V. The resistor is used to limit the forward current to a value that will not overheat the diode and cause damage.

With 0 V across the diode, there is no forward current. As you gradually increase the forward-bias voltage, the forward current *and* the voltage across the diode gradually increase, as shown in Figure 2–9(a). A portion of the forward-bias voltage is dropped across the limiting resistor. When the forward-bias voltage is increased to a value where the voltage across the diode reaches approximately 0.7 V (barrier potential), the forward current begins to increase rapidly, as illustrated in Figure 2–9(b).

As you continue to increase the forward-bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases only gradually above 0.7 V. This small increase in the diode voltage above the barrier potential is due to the voltage drop across the internal dynamic resistance of the semiconductive material.



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

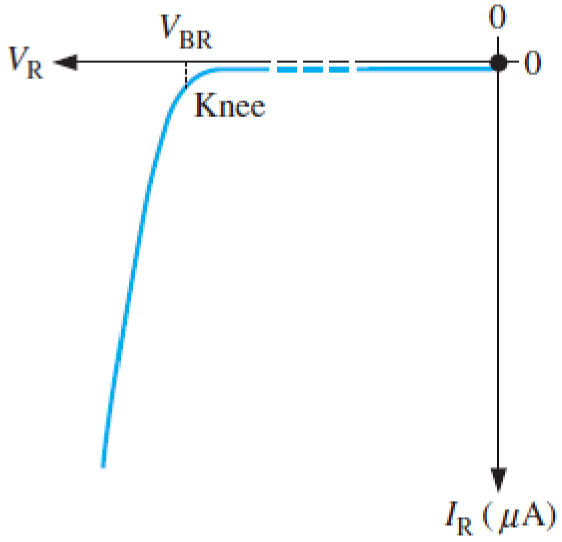


(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

V-I Characteristic for Reverse Bias

When a reverse-bias voltage is applied across a diode, there is only an extremely small reverse current (I_R) through the *pn* junction. With 0 V across the diode, there is no reverse current. As you gradually increase the reverse-bias voltage, there is a very small reverse current and the voltage across the diode increases. When the applied bias voltage is increased to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), the reverse current begins to increase rapidly.

As you continue to increase the bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases very little above V_{BR}. Breakdown, with exceptions, is not a normal mode of operation for most *pn* junction devices.



▲ FIGURE 2–11

V-I characteristic curve for a reverse-biased diode.

The Complete *V-I* Characteristic Curve

Combine the curves for both forward bias and reverse bias, and you have the complete *V-I* characteristic curve for a diode, as shown in Figure 2–12.

▶ FIGURE 2–12

The complete *V-I* characteristic curve for a diode.