INTRODUCTION TO ELECTRONICS

All matter is composed of atoms
all atoms consist of electrons, protons, and neutrons

except normal hydrogen, which does not have a neutron. Each element in the periodic table has a unique atomic structure, and all atoms within a given element have the same number of protons.

At first, the atom was thought to be a tiny indivisible sphere.
Later it was shown that the atom was not a single particle but was made up of a small dense nucleus around which electrons orbit at great distances from the nucleus, similar to the way planets orbit the sun. Niels Bohr proposed that the electrons in an atom circle the
nucleus in different obits, similar to the way planets orbit the sun in our solar system. The Bohr model is often referred to as the planetary model. Another view of the atom called
the *quantum model* is considered a more accurate representation, but it is difficult to visualize. For most practical purposes in electronics, the Bohr model suffices and is commonly used because it is easy to visualize.
After completing this section, you should be able to

- **Describe the structure of an atom**
    - Discuss the Bohr model of an atom
    - Define *electron, proton, neutron,* and *nucleus*
- Define *atomic number*
- Discuss electron shells and orbits
    - Explain energy levels
- Define *valence electron*
- Discuss ionization
    - Define *free electron* and *ion*
- Discuss the basic concept of the quantum model of the atom

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,
covalent bond: Bond which created by the interaction of the valence electrons of the atoms.

Silicon is a crystalline material.

Insulators

An insulator is a material that does not conduct electrical current under normal conditions.

- Most good insulators are compounds rather than single-element materials
- and have very high resistivities.
- there are very few free electrons in an insulator.
- Examples of insulators are rubber, plastics, glass, mica, and quartz.

Conductors

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),
- characterized by atoms with only **one** valence electron very loosely bound to the atom.
- These loosely bound valence electrons become free electrons. Therefore, in a conductive material the free electrons are valence electrons.

Semiconductors

A semiconductor is a material that is between conductors and insulators in its ability to conduct electrical current.

- A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator.
- Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge).
- Compound semiconductors such as gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium are also commonly used.
- The single-element semiconductors are characterized by atoms with four valence electrons.
- Silicon is the most commonly used semiconductor.

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.*
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.

It is a region in insulators and semiconductors where no electron states exist. Although an electron may not exist in this region, it can "jump" across it under certain conditions. For insulators, the gap can be crossed only when breakdown conditions occur—as when a very high voltage is applied across the material. The band gap is illustrated in Figure 1–7(a) for insulators. In semiconductors the band gap is smaller, allowing an electron in the valence band to jump into the conduction band if it absorbs a photon. The band gap depends on the semiconductor material. This is illustrated in Figure 1–7(b). In conductors, the conduction band and valence band overlap, so there is no gap, as shown in Figure 1–7(c). This means that electrons in the valence band move freely into the conduction band, so there are always electrons available as free electrons.

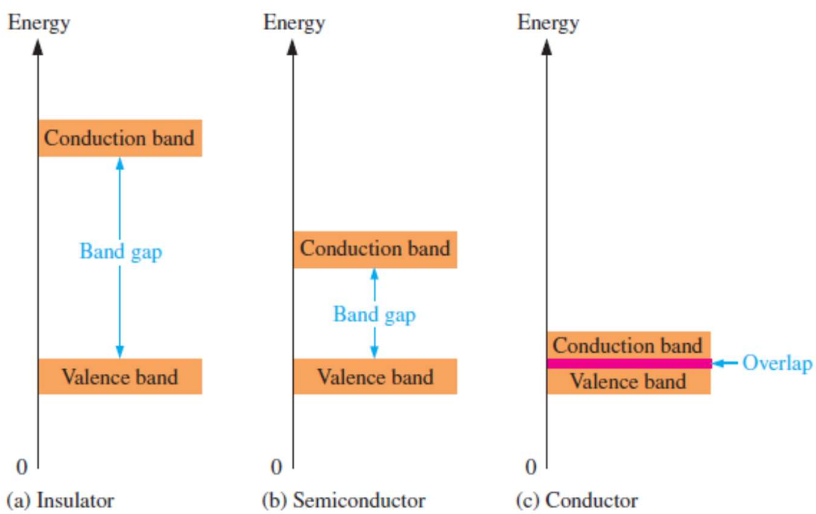


FIGURE 1–7
Energy diagrams for the three types of materials.

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 in Figure 1–8. Notice that the core of the

silicon atom has a net charge of _4 (14 protons _ 10 electrons) and the core of the copper atom has a net charge of _1 (29 protons _ 28 electrons).

The core includes everything except the valence electrons.

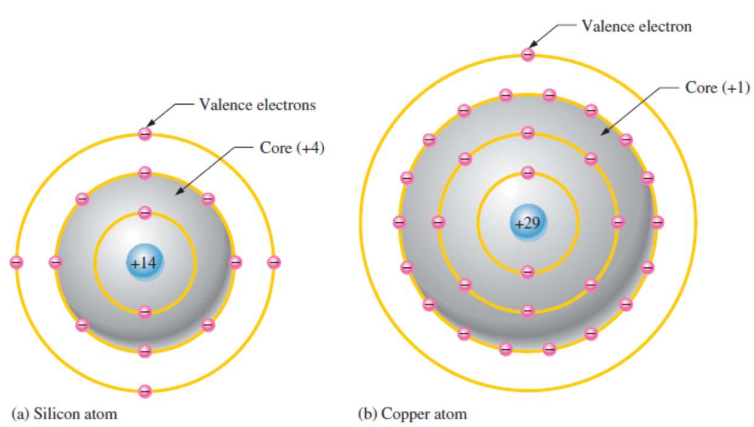


FIGURE 1–8
Bohr diagrams of the silicon and copper atoms.

The valence electron in the copper atom "feels" an attractive force of _1 compared to a valence electron in the silicon atom which "feels" an attractive force of _4.

Therefore, there is more force trying to hold a valence electron to the atom in silicon than in copper.

▶ FIGURE 1–9

Diagrams of the silicon and germanium atoms.

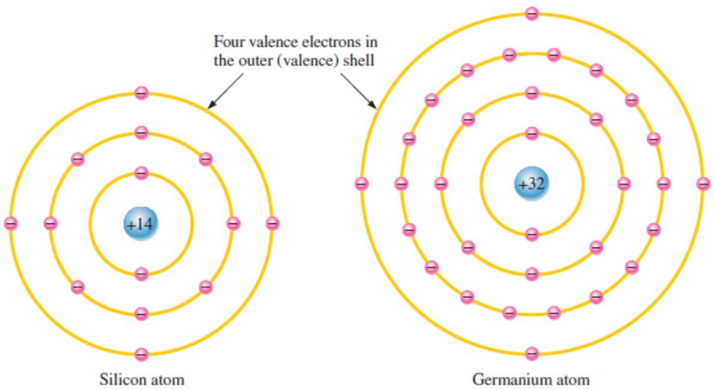
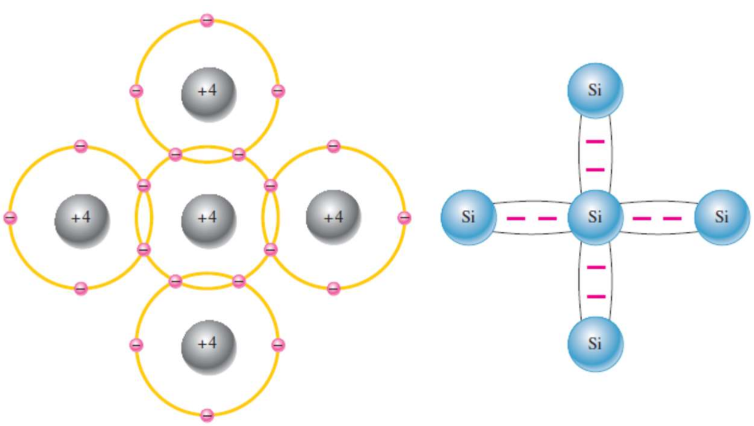


Figure 1–10 shows how each silicon atom positions itself with four adjacent silicon atoms to form a silicon **crystal**.

A silicon (Si) atom with its four valence electrons shares an electron with each of its four neighbors.

▶ 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.

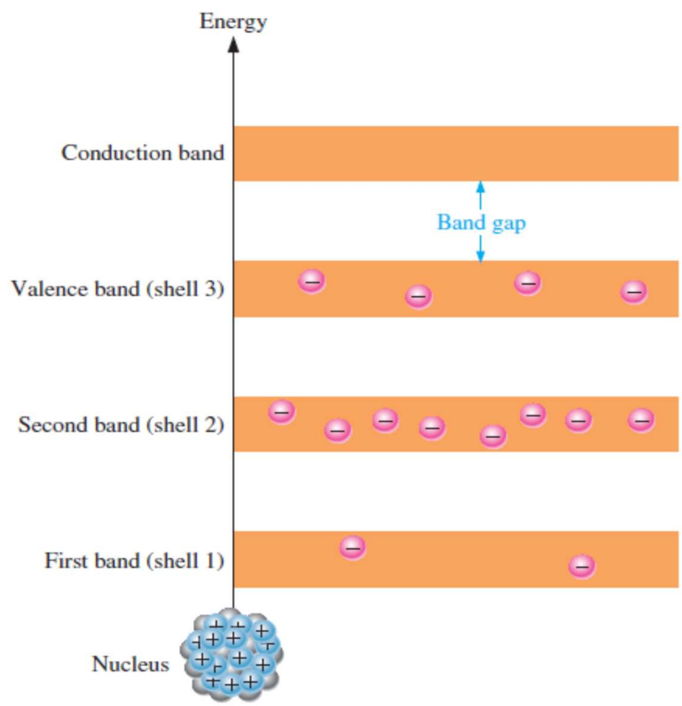
(b) Bonding diagram. The red negative signs represent the shared valence electrons.

1–3 **CURRENT IN SEMICONDUCTORS**

- 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.



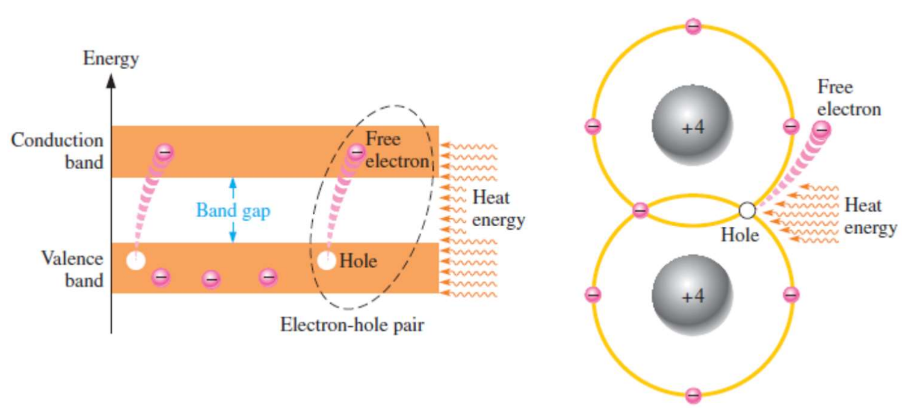
Conduction Electrons and Holes

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.**

▶ 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.

To summarize, a piece of intrinsic silicon at room temperature has, at any instant, a number of conduction-band (free) electrons that are unattached to any atom and are essentially drifting randomly throughout the material.
There is also an equal number of holes in the valence band created when these electrons jump into the conduction band. This is illustrated in Figure 1–14.

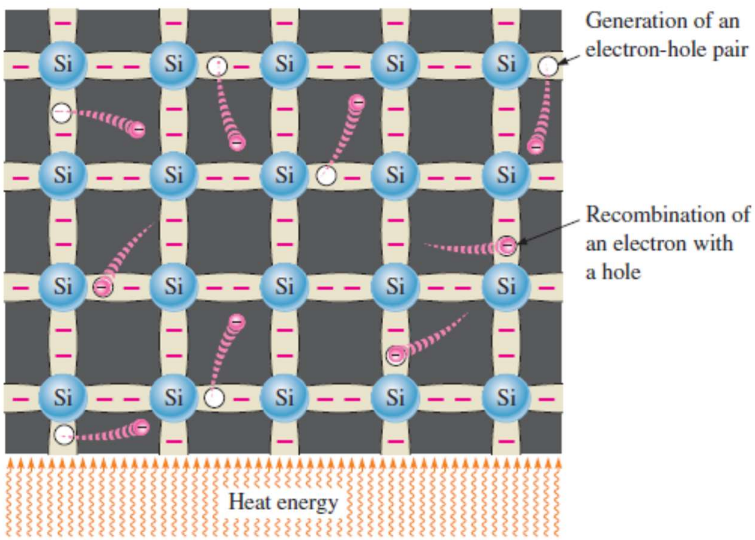


FIGURE 1–14

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 the thermally generated free electrons in the conduction band are now easily attracted toward the positive end.

Electron current

The movement of free electrons in a semiconductive material

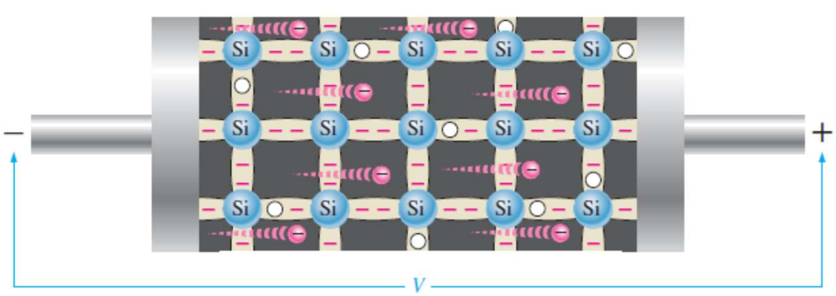


FIGURE 1–15

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

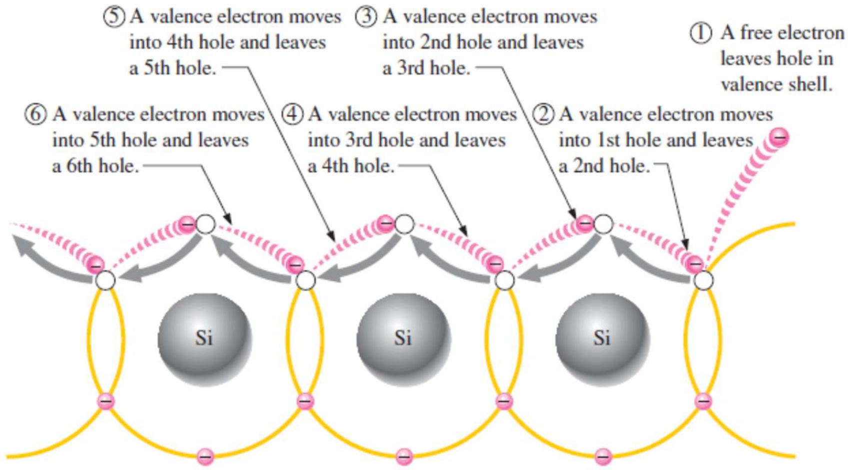
Another type of current occurs in the valence band, where the holes created by the free electrons exist. Electrons remaining in the valence band are still attached to their atoms and are not free to move randomly in the crystal structure as are the free electrons.
➔ **a valence electron can move into 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,

hole current

The current in the valence band is produced by valence electrons move into a nearby holes.

▶ 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.

conduction in semiconductors is considered to be either the **movement of free electrons in the conduction band or the movement of holes in the valence band**, which is actually the movement of valence electrons to nearby atoms, creating hole current in the opposite direction.

It is interesting to contrast the two types of charge movement in a semiconductor with the charge movement in a metallic conductor, such as copper. Copper atoms form a different type of crystal in which the atoms are not covalently bonded to each other but consist of a "sea" of positive ion cores, which are atoms stripped of their valence electrons.

The valence electrons are attracted to the positive ions, keeping the positive ions together and forming the metallic bond.

The valence electrons do not belong to a given atom, but to the crystal as a whole. **Since the valence electrons in copper are free to move, the application of a voltage results in current**.

There is only one type of current—the movement of free electrons—because there are no "holes" in the metallic crystal structure.

1–4 *N*-TYPE AND *P*-TYPE SEMICONDUCTORS

- Semiconductive materials do not conduct current well because of the limited number of free electrons in the conduction band and holes in the valence band.

Intrinsic Semiconductor:
An almost pure semiconductor.

- 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

- This process, called **doping**, increases the number of current carriers (electrons or holes). The two categories of impurities are *n*-type and *p*-type.

Extrinsic semiconductor:
Material that have been doped.

N-Type Semiconductor

To increase the number of conduction-band electrons in intrinsic silicon, **pentavalent** impurity atoms are added.

Pentavalent atoms have **five** valence electrons such as arsenic (As), **phosphorus (P)**, bismuth (Bi), and antimony (Sb).

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.

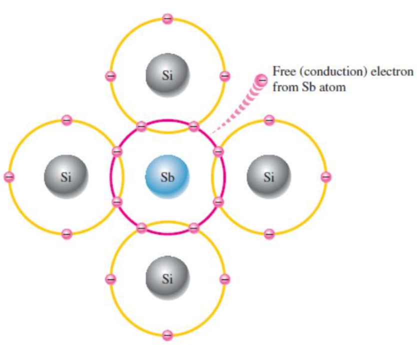


FIGURE 1–17
Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

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).

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.

Majority and Minority Carriers

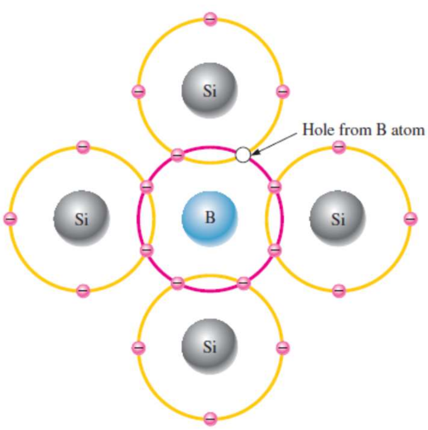
Since most of the current carriers are holes, silicon (or germanium) doped with trivalent atoms is called a *p*-type semiconductor.

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.**

► FIGURE 1–18

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



SECTION 1–4 CHECKUP

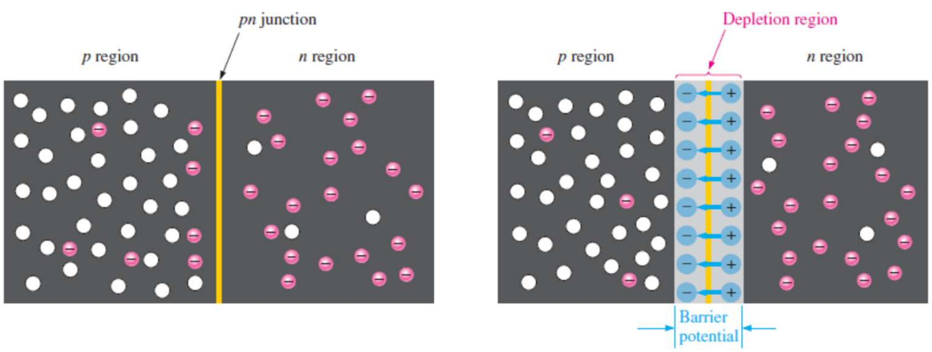
1. Define *doping.*
2. What is the difference between a pentavalent atom and a trivalent atom?
3. What are other names for the pentavalent and trivalent atoms?
4. How is an *n*-type semiconductor formed?
5. How is a *p*-type semiconductor formed?
6. What is the majority carrier in an *n*-type semiconductor?
7. What is the majority carrier in a *p*-type semiconductor?
8. By what process are the majority carriers produced?
9. By what process are the minority carriers produced?
10. What is the difference between intrinsic and extrinsic semiconductors?

1–5 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, as you will learn later.

A *p*-type material consists of silicon atoms and trivalent impurity atoms such as boron. The boron atom adds a hole when it bonds with the silicon atoms. However, since the number of protons and the number of electrons are equal throughout the material, there is no net charge in the material and so it is neutral.

An *n*-type silicon material consists of silicon atoms and pentavalent impurity atoms such as antimony. As you have seen, an impurity atom releases an electron when it bonds with four silicon atoms. Since there is still an equal number of protons and electrons (including the free electrons) throughout the material, there is no net charge in the material and so it is neutral. 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

1–5 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.

A ***p*-type** material consists of silicon atoms and trivalent impurity atoms such as boron.

The boron atom adds a hole when it bonds with the silicon atoms. However, since the number of protons and the number of electrons are equal throughout the material, there is no net charge in the **material and so it is neutral.**

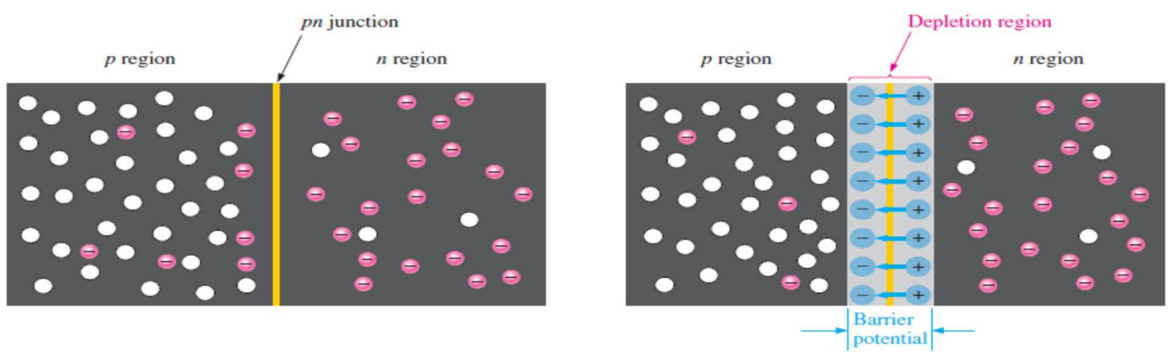
An ***n*-type** silicon material consists of silicon atoms and pentavalent impurity atoms such as antimony. As you have seen, an impurity atom releases an electron when it bonds with four silicon atoms.

Since there is still an equal number of protons and electrons (including the free electrons) throughout the material, there is **no net charge in the material and so it is neutral.**

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.

Keep in mind that the depletion region is formed very quickly and is very thin compared to the *n* region and *p* region.

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. Stated another way, a certain amount of voltage equal to the barrier potential and with the proper polarity must be applied across a *pn* junction before electrons will begin to flow across the junction.

You will learn more about this when we discuss *biasing* in Chapter 2.

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 Because germanium devices are not widely used, silicon will be used throughout the rest of the book.

Energy Diagrams of the *PN* Junction and Depletion Region

The valence and conduction bands in an *n*-type material are at slightly lower energy levels than the valence and conduction bands in a *p*-type material.

Recall that *p*-type material has trivalent impurities and *n*-type material has pentavalent impurities. The trivalent impurities **exert lower forces on the outer-shell** electrons **than the pentavalent impurities**.

The lower forces in *p*-type materials mean that the electron orbits are slightly larger and hence have greater energy than the electron orbits in the *n*-type materials.

An energy diagram for a *pn* junction at the instant of formation is shown in Figure 1–20(a). As you can see, the valence and conduction bands in the *n* region are at lower energy levels than those in the *p* region, but there is a significant amount of overlapping.

The free electrons in the *n* region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the *p*-region conduction band.

After crossing the junction, the electrons quickly lose energy and fall into the holes in the *p*-region valence band as indicated in Figure 1-20(a).

As the diffusion continues, the depletion region begins to form and the energy level of the *n*-region conduction band decreases.

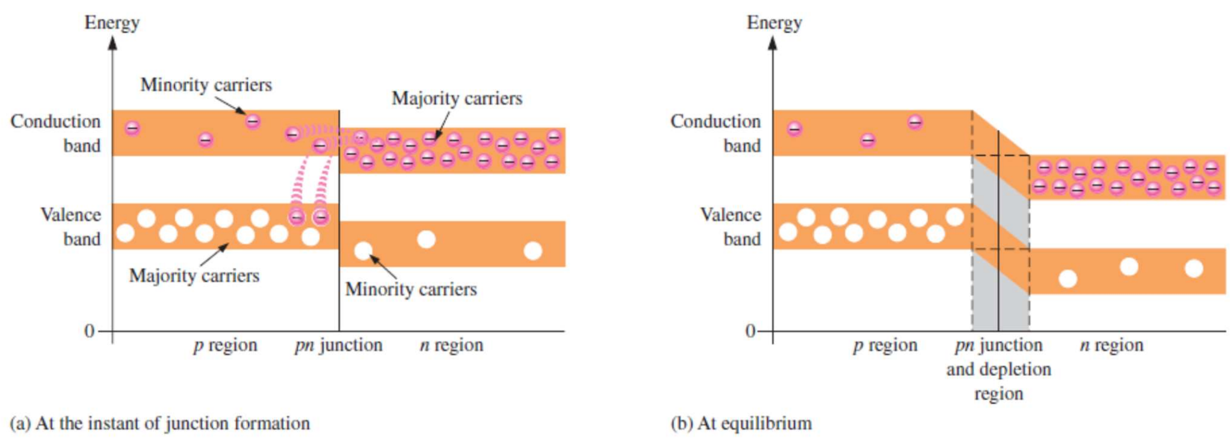
The decrease in the energy level of the conduction band in the *n* region is due to the loss of the higher-energy electrons that have diffused across the junction to the *p* region.

Soon, there are no electrons left in the *n*-region conduction band with enough energy to get across the junction to the *p*-region conduction band, as indicated by the alignment of the top of the *n*-region conduction band and the bottom of the *p*-region conduction band in Figure 1–20(b).

At this point, the junction is at equilibrium; and the depletion region is complete because diffusion has ceased. There is an energy gradiant across the depletion region which acts as an "energy hill" that an *n*-region electron must climb to get to the *p* region.

Notice that as the energy level of the *n*-region conduction band has shifted downward, the energy level of the valence band has also shifted downward.

It still takes the same amount of energy for a valence electron to become a free electron. In other words, the energy gap between the valence band and the conduction band remains the same.



▲ FIGURE 1–20

Energy diagrams illustrating the formation of the *pn* junction and depletion region.