1–2 Materials used in Electronic devices

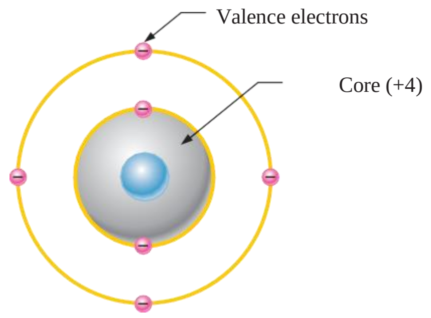
In terms of their electrical properties, materials can be classified into three groups:

A) Conductors, B) Semiconductors, and C) Insulators.

When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within a semiconductor 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.

After completing this section, one should be able to

- **discuss conductors, insulators, and semiconductors and how they differ.**
  - Define the *core* of an atom ◆ Describe the carbon atom
  - Name two examples of each of semiconductors, conductors, and insulators
- Explain the band gap
  - Define *valence band* and *conduction band*
  - Compare a semiconductor atom to a conductor atom
- Discuss silicon and germanium atoms
- Explain covalent bonds



▲ **FIGURE 1–6**

Diagram of a carbon atom.

All materials are made up of atoms. These atoms contribute to the electrical properties of a material, including its ability to conduct electricity. For the purpose of discussing electrical properties, an atom can be represented by the **valence shell** and a **core** that consists of all the inner shells and the nucleus. This concept is illustrated in Figure 1–6 for a carbon atom.

Carbon is used in some types of electrical resistors. Notice that the carbon atom has four electrons in the valence shell and two electrons in the inner shell. The nucleus consists of six protons and six neutrons, so the + 6 indicates the positive charge of the six protons. The core has a net charge of +4 (+6 for the nucleus and -2 for the two inner-shell electrons).

Energy band Theory of solid and Band Gap

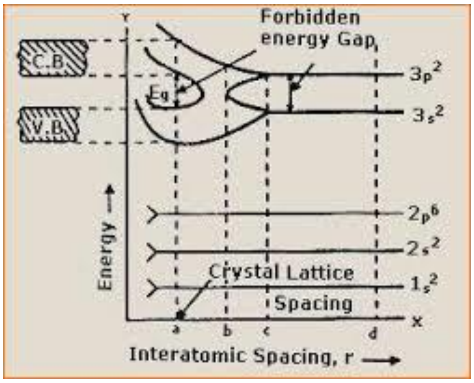


Figure 1–7

In an isolated atom the electrons have certain definite discrete energy levels as 1s, 2s, 3s, 3p, etc. But when atoms come very close to each other to form a solid, the outermost orbits come very close or may even overlap. Then the discrete energy levels of the electrons of the outermost orbit of the atom may increase or decrease due to their interaction with the electrons of the neighboring atoms or with ion cores which result a spreading of energy level. For inner energy levels, this spreading is less due to weak interaction. As a result, each of the sharply defined energy levels (1s, 2s, 2p, 3s, 3p etc) of the isolated atom becomes a combination of a number of very closely spaced energy levels or a band in a solid or a group of closely spaced atoms in crystal) that is called **Energy band** as shown in Figure1-7.

In an atom, electrons start filling up the inner energy bands correspond to the lowest energy levels of the atom according to the Pauli Exclusion Principle. Therefore, the inner energy levels of the atom are completely filled up with electrons. The highest energy band partially or completely filled with electrons outside the core is called ***valence band***. Valence electrons confined to that band. This depends upon the nature of the atom and the kind of bonding in the solid.

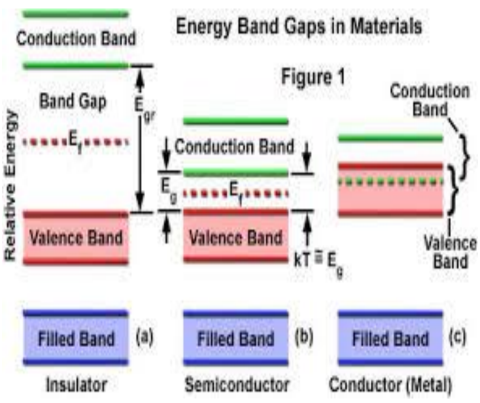


Figure 1–8

When an electron acquires enough additional energy, it can leave the valence shell and becomes *free* to move. If the valence band is partially filled with electrons, the energy band consisting free movable electrons, just above the valence band is 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.

Figure 1–8 shows energy diagrams for conductors, insulators, and semiconductors. The energy gap or band gap is the difference between two energy levels and electrons are "not allowed" in this energy gap based on quantum theory. Although an electron may not exist in this region, it can "jump" across it under certain conditions absorbing large energy from external sources. For insulators, the gap can be crossed only when breakdown conditions occur—as when a very high voltage is applied across the material.

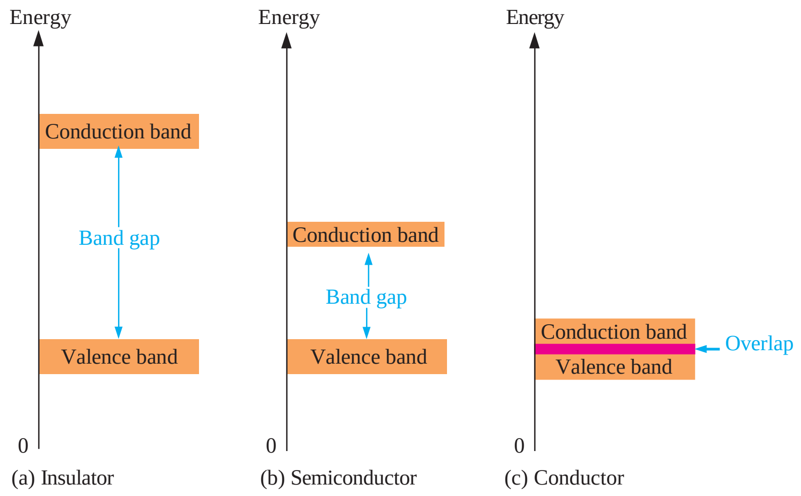
Conductors, Insulators, and Semiconductors

Conductors

A **conductor** is a material that easily conducts electric 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 or two or three valence electron, very loosely bound to the atom. These loosely bound valence electrons can become free from the atom after absorbing a small amount of energy. Therefore, these free electrons in a conductive material are available to carry current.

Insulators

An **insulator** is a material that does not conduct electrical current under normal conditions. Most good insulators are compounds rather than single-element material and have very high resistivity. 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.



◄ **FIGURE 1–9**

Energy diagrams for the three types sof materials.

Semiconductors

A **semiconductor** is a material that has the intermediate property between conductors and insulators in respect of conduction of electricity. 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 of 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. At absolute zero the valence band is completely filled whereas, the next higher conduction band is completely empty therefore, it behaves as an insulator.

The band gap (~6 ev) is illustrated in above Figure 1–9(a) for insulators. In semiconductors the band gap is smaller (Si~1.12ev, Ge~0.75ev), 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 1–9(b). In conductors, the conduction band and valence band overlap, so there is no gap, as shown in Figure 1–9(c). This means that electrons in the valence band move freely into the conduction band, so a large no of free electrons available in valence band of these materials.

FYI

Next to silicon, the second most common semiconductive material is gallium arsenide, GaAs. This is a crystalline compound, not an element. Its properties can be controlled by varying the relative amount of Gallium and Arsenic.

GaAs has the advantage of making semiconductor devices that respond very quickly to electrical signals. It is widely used in high-frequency applications and in light-emitting diodes and solar cells.

Comparison of a Semiconductor Atom to a Conductor Atom

Bohr diagrams of the silicon atom (semiconductor) and the copper atom (conductor) are shown in Figure 1–10. 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). Recall that the core includes everything except the valence electrons.

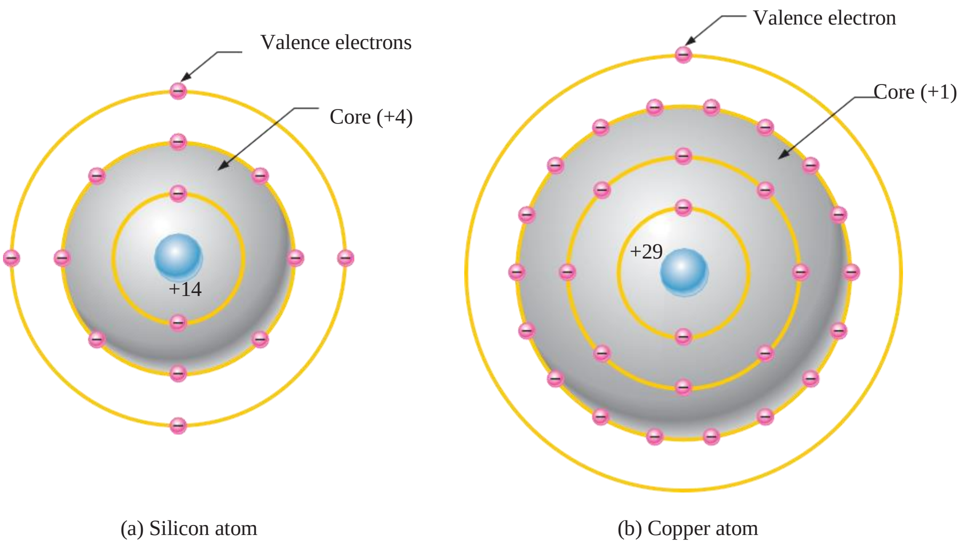


FIGURE 1–10

Bohr diagrams of silicon and copper atom

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. The copper's valence electron is in the fourth shell, which is a greater distance from its nucleus than the silicon's valence electron in the third shell. Recall that, electrons farthest from the nucleus have the most energy.

The valence electron in copper has more energy than the valence electron in silicon. This means that it is easier for valence electrons in copper to acquire enough additional energy to escape from their atoms and become free electrons than it is in silicon. In fact, large numbers of valence electrons in copper, already, have sufficient energy to be free at normal room temperature.

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 semi-conductive material.

Silicon and Germanium

The atomic structures of silicon and germanium are compared in Figure 1–11. **Silicon** is used in diodes, transistors, integrated circuits, and other semiconductor devices. Notice that both silicon and **Germanium** have the characteristic four valence electrons.

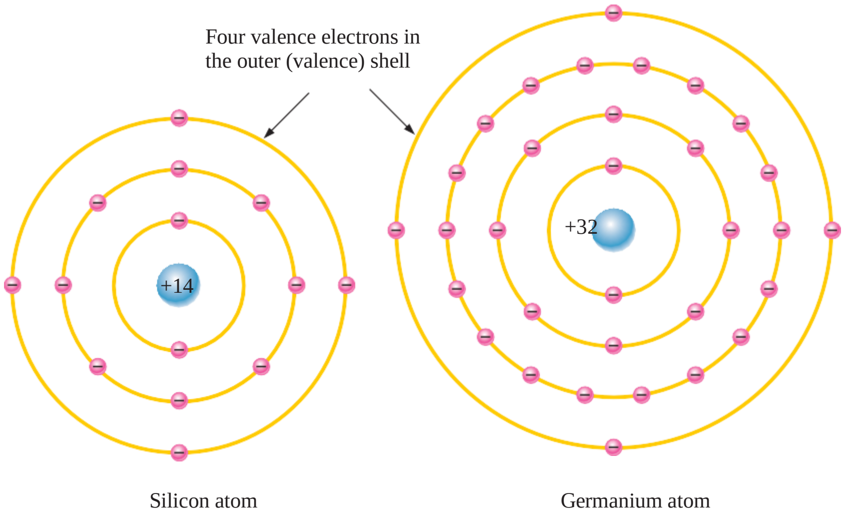


FIGURE 1–11

Diagram of the Silicon and Germanium

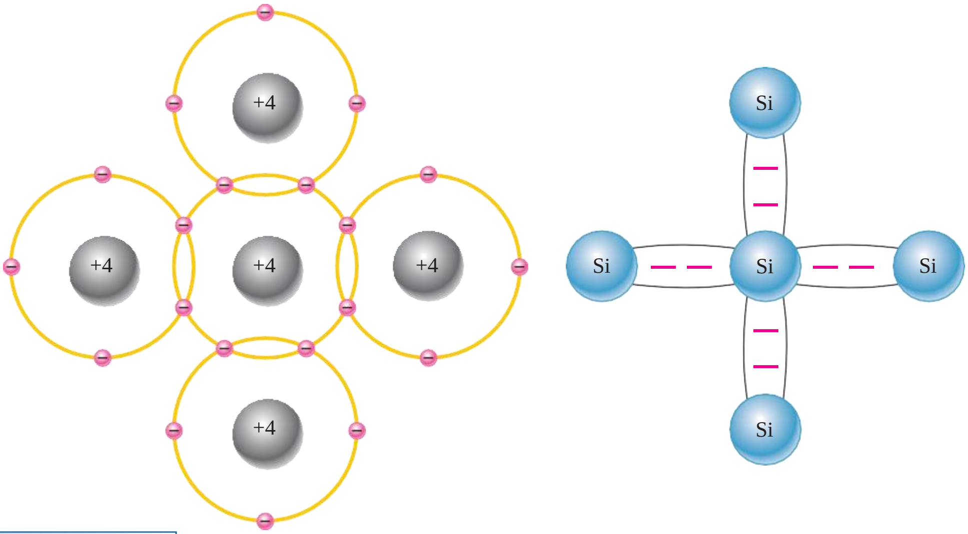
Covalent Bonds

In an atom with 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 strong **covalent bond** that holds the atoms together; each valence electron is attracted equally by the two adjacent atoms which share it equally. Covalent bonding in an intrinsic semiconductor like silicon crystal is shown in Figure 1–12. How each silicon atom positions itself with four adjacent silicon atoms is shown in Figure 1-12 in a three-dimensional symmetrical arrangement of atoms to form a silicon **crystal**.

An **intrinsic** crystal is one that has no impurities. Covalent bonding for Germanium is similar because it also has four valence electrons. Electric conductivity of the intrinsic semiconductor is very low but can be increased and controlled artificially.

▸ **FIGURE 1–12**
Illustration of covalent bonds in silicon.

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.



SECTION 1-2 CHECK UP

1. Difference between conductor and insulators?
2. How many valence electrons does a conductor such as copper and semiconductor have?
3. What is the most widely used semi conductive material?
4. How are covalent bonds formed?
5. What are meant by *intrinsic extrinsic semiconductor*?
6. What is a crystal?

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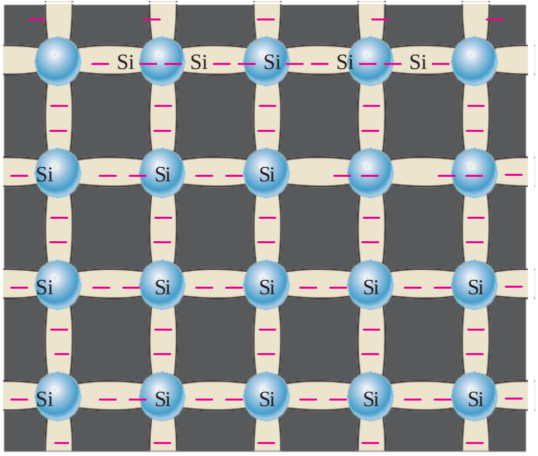

◂ **FIGURE 1–11**

Covalent bonds in a silicon crystal