
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 that 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 very 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 and 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.

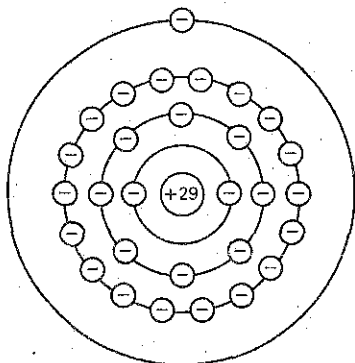
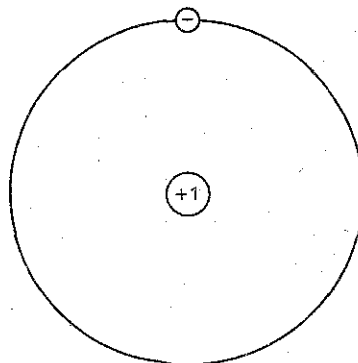


Figure 2-2 Core diagram of copper atom.



Free Electron

Since the attraction between the core and the valence electron is very 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.

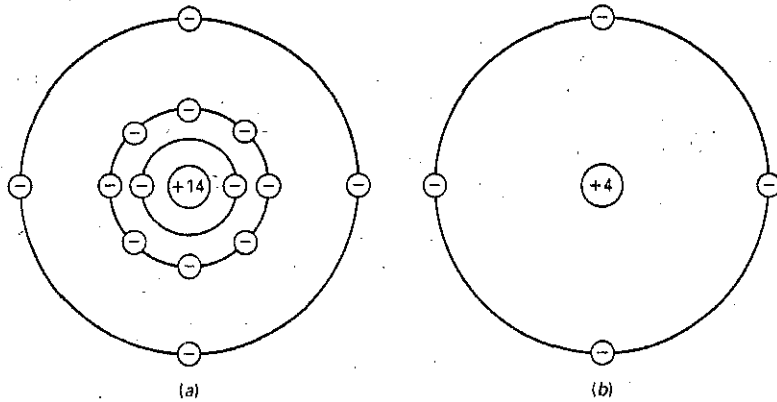
Germanium

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. 2-3a, the first orbit contains 2 electrons and the second orbit contains 8 electrons. The 4 remaining electrons are in the valence orbit. In Fig. 2-3a, 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 2-3b shows the core diagram of a silicon atom. The 4 valence electrons tell us that silicon is a semiconductor.

Example 2-2

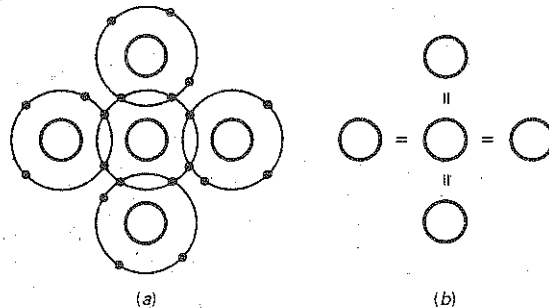
What is the net charge of the silicon atom in Fig. 2-3b if it loses one of its valence electrons? If it gains an extra electron in the valence orbit?

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. 2-4a 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. 2-4a, 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. 2-4a 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 2-4b 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:

$$\text{Valence saturation: } n = 8 \quad (2-1)$$

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. 2-5a. 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. 2-5a). 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.

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. 2-5b).

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.

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

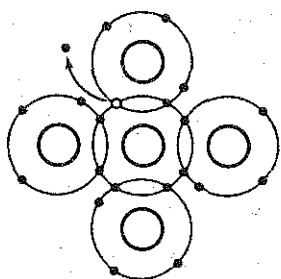
If a pure silicon crystal has 1 million free electrons inside it, how many holes does it have? What happens to the number of free electrons and holes if the ambient temperature increases?

SOLUTION Look at Fig. 2-5a. When heat energy creates a free electron, it automatically creates a hole at the same time. Therefore, a pure silicon crystal

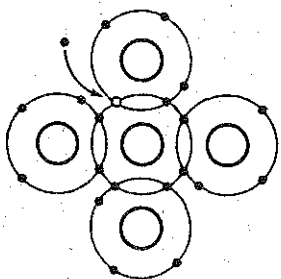
GOOD TO KNOW

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

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



(a)



(b)

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.

