always has the same number of holes and free electrons. If there are 1 million free electrons, there are 1 million holes.

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

2-4 Intrinsic Semiconductors

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

Flow of Free Electrons

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

Flow of Holes

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

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

Figure 2-6 Hole flow through a semiconductor.

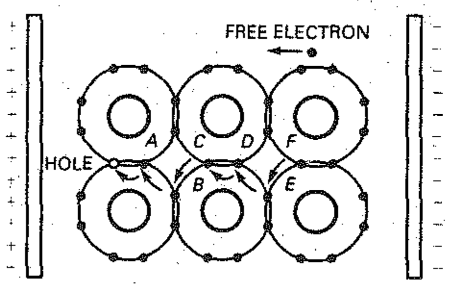
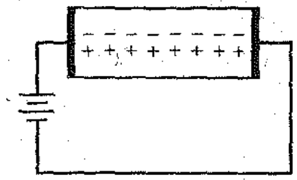


Figure 2-7 Intrinsic semiconductor has equal number of free electrons and holes.



2-5 Two Types of Flow

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

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

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

2-6 Doping a Semiconductor

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

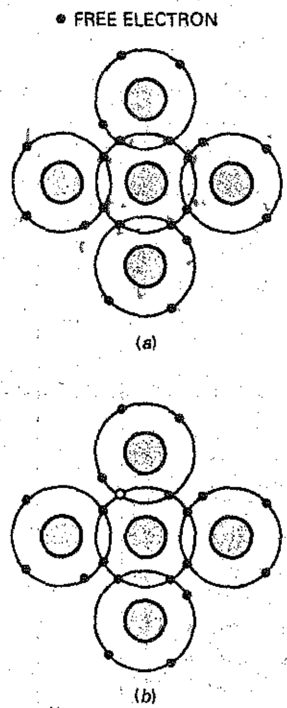
Increasing the Free Electrons

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

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

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

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



Increasing the Number of Holes

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

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

Points to Remember

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

Example 2-4

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

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

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

2-7 Two Types of Extrinsic Semiconductors

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

n-Type Semiconductor

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

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

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

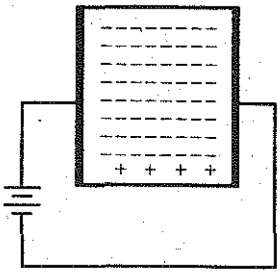
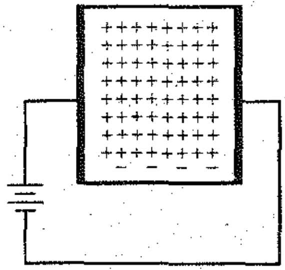


Figure 2-10 *p*-type semiconductor has many holes.



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

p-Type Semiconductor

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

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

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

2-8 The Unbiased Diode

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

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

The Unbiased Diode

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

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

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

Figure 2-11 Two types of semiconductor.