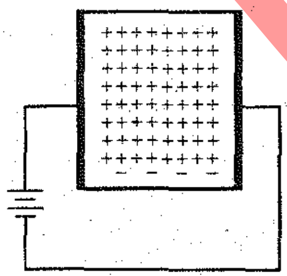
Figure 2-10 *p*-type semiconductor has many holes.



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.

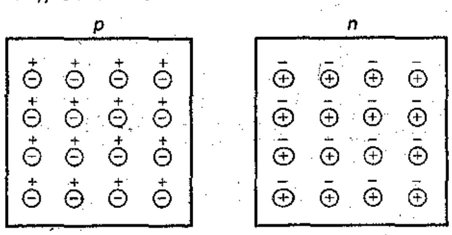
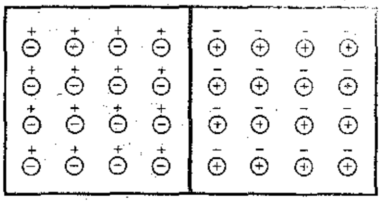


Figure 2-12 The *pn* junction.



The Depletion Layer

Because of their repulsion for each other, the free electrons on the *n* side of Fig. 2-12 tend to diffuse (spread) in all directions. Some of the free electrons diffuse across the junction. When a free electron enters the *p* region, it becomes a minority carrier. With so many holes around it, this minority carrier has a short lifetime. Soon after entering the *p* region, the free electron recombines with a hole. When this happens, the *hole disappears* and the *free electron becomes a valence electron.*

Each time an electron diffuses across a junction, it creates a pair of ions. When an electron leaves the *n* side, it leaves behind a pentavalent atom that is short one negative charge; this pentavalent atom becomes a positive ion. After the migrating electron falls into a hole on the *p* side, it makes a negative ion out of the trivalent atom that captures it.

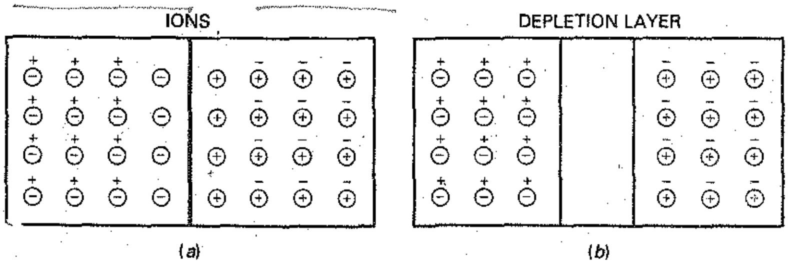
Figure 2-13*a* shows these ions on each side of the junction. The circled plus signs are the positive ions, and the circled minus signs are the negative ions. The ions are fixed in the crystal structure because of covalent bonding, and they cannot move around like free electrons and holes.

Each pair of positive and negative ions at the junction is called a *dipole*. The creation of a dipole means that one free electron and one hole have been taken out of circulation. As the number of dipoles builds up, the region near the junction is emptied of carriers. We call this charge-empty region the **depletion layer** (see Fig. 2-13*b*).

Barrier Potential

Each dipole has an electric field between the positive and negative ions. Therefore, if additional free electrons enter the depletion layer, the electric field tries to push these electrons back into the *n* region. The strength of the electric field increases with each crossing electron until equilibrium is reached. To a first approximation, this means that the electric field eventually stops the diffusion of electrons across the junction.

Figure 2-13 (*a*) Creation of ions at junction; (*b*) depletion layer.



In Fig. 2-13*a*, the electric field between the ions is equivalent to a difference of potential called the **barrier potential.** At 25°C, the barrier potential equals approximately 0.3 V for germanium diodes and 0.7 V for silicon diodes.

2-9 Forward Bias

Figure 2-14 shows a dc source across a diode. The negative source terminal is connected to the *n*-type material, and the positive terminal is connected to the *p*-type material. This connection produces what is called **forward bias.**

Flow of Free Electrons

In Fig. 2-14, the battery pushes holes and free electrons toward the junction. If the battery voltage is less than the barrier potential, the free electrons do not have enough energy to get through the depletion layer. When they enter the depletion layer, the ions will push them back into the *n* region. Because of this, there is no current through the diode.

When the dc voltage source is greater than the barrier potential, the battery again pushes holes and free electrons toward the junction. This time, the free electrons have enough energy to pass through the depletion layer and recombine with the holes. If you visualize all the holes in the *p* region moving to the right and all the free electrons moving to the left, you will have the basic idea. Somewhere in the vicinity of the junction, these opposite charges recombine. Since free electrons continuously enter the right end of the diode and holes are being continuously created at the left end, there is a continuous current through the diode.

The Flow of One Electron

Let us follow a single electron through the entire circuit. After the free electron leaves the negative terminal of the battery, it enters the right end of the diode. It travels through the *n* region until it reaches the junction. When the battery voltage is greater than 0.7 V, the free electron has enough energy to get across the depletion layer. Soon after the free electron has entered the *p* region, it recombines with a hole.

In other words, the free electron becomes a valence electron. As a valence electron, it continues to travel to the left, passing from one hole to the next until it reaches the left end of the diode. When it leaves the left end of the diode, a new hole appears and the process begins again. Since there are billions of electrons taking the same journey, we get a continuous current through the diode. A series resistor is used to limit the amount of forward current.

MultiSim **Figure 2-14** Forward bias.