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.

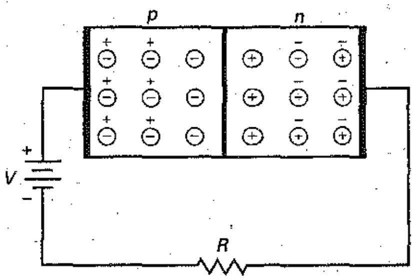
When the dc voltage source is greater than the barrier potential, the battery again pushes holes and free electrons toward the junction. This time, the free electrons have enough energy to pass through the depletion layer and recombine with the holes. If you visualize all the holes in the *p* region 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.

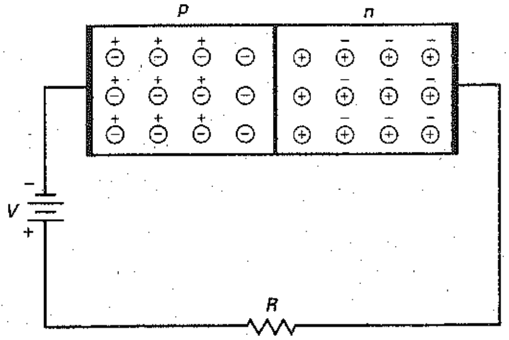
The Flow of One Electron

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.





MultiSim **Figure 2-15** Reverse bias.

What to Remember

Current flows easily in a forward-biased diode. As long as the applied voltage is greater than the barrier potential, there will be a large continuous current in the circuit. In other words, if the source voltage is greater than 0.7 V, a silicon diode allows a continuous current in the forward direction.

2-10 Reverse Bias

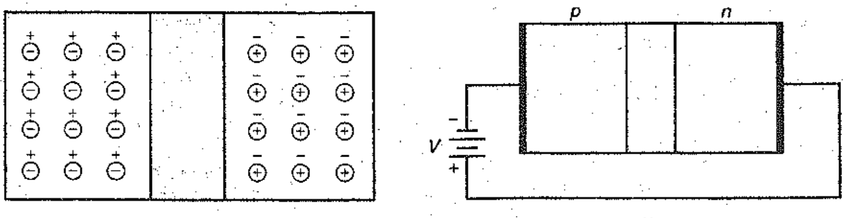
Turn the dc source around and you get Fig. 2-15. This time, the negative battery terminal is connected to the *p* side, and the positive battery terminal to the *n* side. This connection produces what is called **reverse bias.**

Depletion Layer Widens

The negative battery terminal attracts the holes, and the positive battery terminal attracts the free electrons. Because of this, holes and free electrons flow away from the junction. Therefore, the depletion layer gets wider.

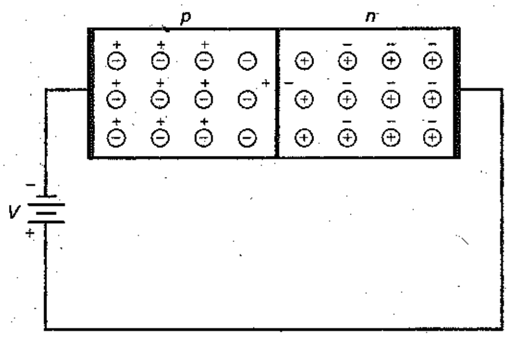
How wide does the depletion layer get in Fig. 2-16*a*? When the holes and electrons move away from the junction, the newly created ions increase the difference of potential across the depletion layer. The wider the depletion layer, the greater the difference of potential. The depletion layer stops growing when its difference of potential equals the applied reverse voltage. When this happens, electrons and holes stop moving away from the junction.

Figure 2-16 (*a*) Depletion layer; (*b*) increasing reverse bias widens depletion layer.



(*a*) (*b*)

Figure 2-17 Thermal production of free electron and hole in depletion layer produces reverse minority saturation current.



Sometimes the depletion layer is shown as a shaded region like that of Fig. 2-16*b*. The width of this shaded region is proportional to the reverse voltage. *As the reverse voltage increases, the depletion layer gets wider.*

Minority-Carrier Current

Is there any current after the depletion layer stabilizes? Yes. A small current exists with reverse bias. Recall that thermal energy continuously creates pairs of free electrons and holes. This means that a few minority carriers exist on both sides of the junction. Most of these recombine with the majority carriers. But those inside the depletion layer may exist long enough to get across the junction. When this happens, a small current flows in the external circuit.

Figure 2-17 illustrates the idea. Assume that thermal energy has created a free electron and hole near the junction. The depletion layer pushes the free electron to the right, forcing one electron to leave the right end of the crystal. The hole in the depletion layer is pushed to the left. This extra hole on the *p* side lets one electron enter the left end of the crystal and fall into a hole. Since thermal energy is continuously producing electron-hole pairs inside the depletion layer, a small continuous current flows in the external circuit.

The reverse current caused by the thermally produced minority carriers is called the **saturation current.** In equations, the saturation current is symbolized by I_S. The name *saturation* means that we cannot get more minority-carrier current than is produced by the thermal energy. In other words, *increasing the reverse voltage will not increase the number of thermally created minority carriers.*

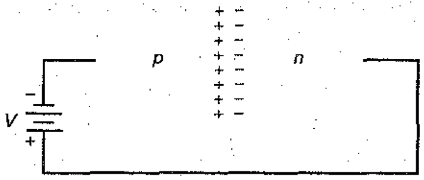
Surface-Leakage Current

Besides the thermally produced minority-carrier current, does any other current exist in a reverse-biased diode? Yes. A small current flows on the surface of the crystal. Known as the **surface-leakage current,** it is caused by surface impurities and imperfections in the crystal structure.

What to Remember

The reverse current in a diode consists of a minority-carrier current and a surface-leakage current. In most applications, the reverse current in a silicon diode is so small that you don't even notice it. The main idea to remember is this: *Current is approximately zero in a reverse-biased silicon diode.*

Figure 2-18 Avalanche produces many free electrons and holes in depletion layer.



2-11 Breakdown

Diodes have maximum voltage ratings. There is a limit to how much reverse voltage a diode can withstand before it is destroyed. If you continue increasing the reverse voltage, you will eventually reach the **breakdown voltage** of the diode. For many diodes, breakdown voltage is at least 50 V. The breakdown voltage is shown on the *data sheet* for the diode. We will discuss data sheets in Chap. 3.

Once the breakdown voltage is reached, a large number of the minority carriers suddenly appears in the depletion layer and the diode conducts heavily.

Where do the carriers come from? They are produced by the **avalanche effect** (see Fig. 2-18), which occurs at higher reverse voltages. Here is what happens. As usual, there is a small reverse minority-carrier current. When the reverse voltage increases, it forces the minority carriers to move more quickly. These minority carriers collide with the atoms of the crystal. When these minority carriers have enough energy, they can knock valence electrons loose, producing free electrons. These new minority carriers then join the existing minority carriers to collide with other atoms. The process is geometric, because one free electron liberates one valence electron to get two free electrons. These two free electrons then free two more electrons to get four free electrons. The process continues until the reverse current becomes huge.

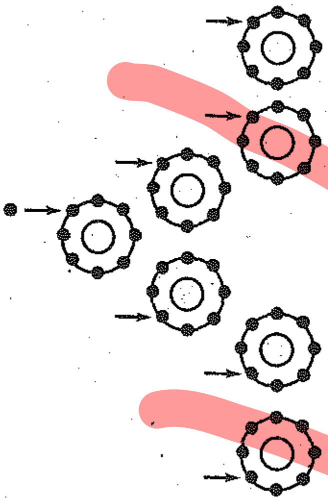
Figure 2-19 shows a magnified view of the depletion layer. The reverse bias forces the free electron to move to the right. As it moves, the electron gains speed. The larger the reverse bias, the faster the electron moves. If the high-speed electron has enough energy, it can bump the valence electron of the first atom into a larger orbit. This results in two free electrons. Both of these then accelerate and go on to dislodge two more electrons. In this way, the number of minority carriers may become quite large and the diode can conduct heavily.

The breakdown voltage of a diode depends on how heavily doped the diode is. With rectifier diodes (the most common type), the breakdown voltage is usually greater than 50 V. Summary Table 2-1 illustrates the difference between a forward- and reverse-biased diode.

GOOD TO KNOW

Exceeding the breakdown voltage of a diode does not necessarily mean that you will destroy the diode. As long as the product of reverse voltage and reverse current does not exceed the diode's power rating, the diode will recover fully.

Figure 2-19 The process of avalanche is a geometric progression: 1, 2, 4, 8, . . .



2-12 Energy Levels

To a good approximation, we can identify the total energy of an electron with the size of its orbit. That is, we can think of each radius of Fig. 2-20*a* as equivalent to an energy level in Fig. 2-20*b*. Electrons in the smallest orbit are on the first energy level; electrons in the second orbit are on the second energy level; and so on.

Higher Energy in Larger Orbit

Since an electron is attracted by the nucleus, extra energy is needed to lift an electron into a larger orbit. When an electron is moved from the first to the second orbit, it gains potential energy with respect to the nucleus. Some of the external forces that can lift an electron to higher energy levels are heat, light, and voltage.