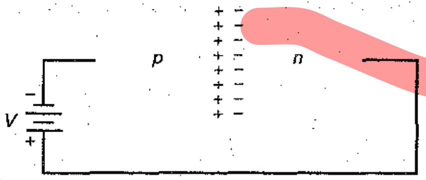
Figure 2-18 Avalanche produces many free electrons and holes in depletion layer.



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.

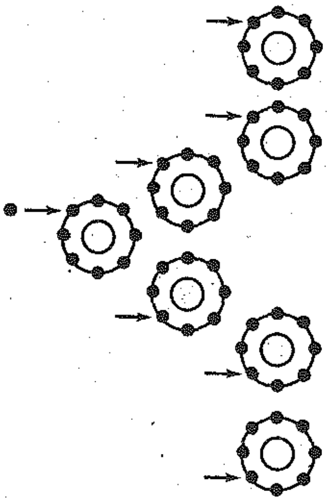
Figure 2-19 shows a magnified view of the depletion layer. The reverse bias forces the free electron to move to the right. As it moves, the electron gains speed. The larger the reverse bias, the faster the electron moves. If the high-speed electron has enough energy, it can bump the valence electron 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, . . .



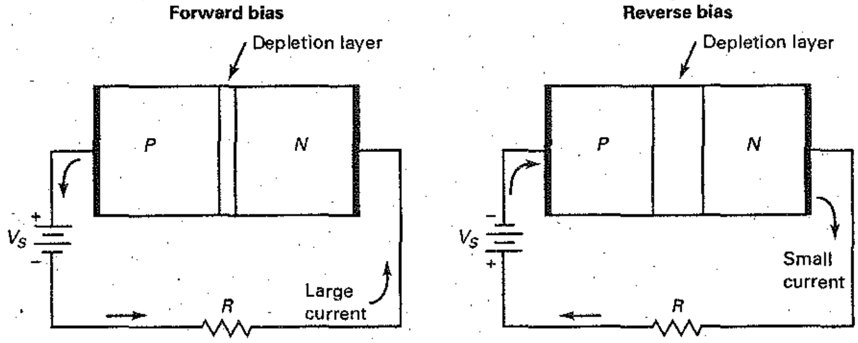
2-12 Energy Levels

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.

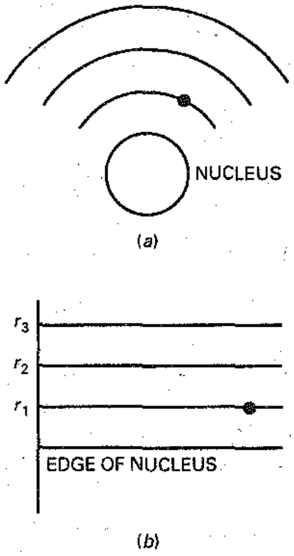
Summary Table 2-1 | Diode Bias



	Forward bias	Reverse bias
V_s polarity	(+) to P material (−) to N material	(−) to P materials (+) to N material
Current flow	Large forward current if $V_s > 0.7$ V	Small reverse current (saturation current and surface leakage current) if $V_s <$ breakdown voltage
Depletion layer	Narrow	Wide

For instance, assume that an outside force lifts the electron from the first to the second orbit in Fig. 2-20*a*. This electron has more potential energy because it is farther from the nucleus (Fig. 2-20*b*). It is like an object above the earth: The higher the object, the greater its potential energy with respect to the earth. If released, the object falls farther and does more work when it hits the earth.

Figure 2-20 Energy level is proportional to orbit size. (*a*) Orbits; (*b*) energy levels.



Falling Electrons Radiate Light

After an electron has moved into a larger orbit, it may fall back to a lower energy level. If it does, it will give up its extra energy in the form of heat, light, and other radiation.

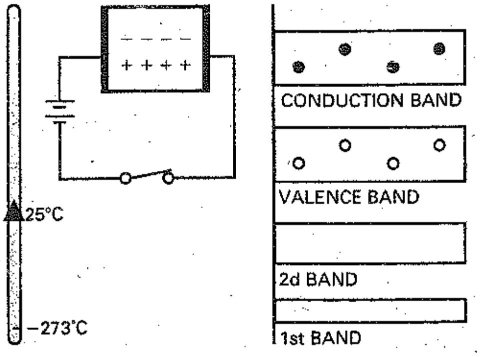
In a *light-emitting diode (LED)*, the applied voltage lifts the electrons to higher energy levels. When these electrons fall back to lower energy levels, they give off light. Depending on the material used, the light is red, green, orange, or blue. Some LEDs produce infrared radiation (invisible), which is useful in burglar alarm systems.

Energy Bands

When a silicon atom is isolated, the orbit of an electron is influenced only by the charges of the isolated atom. This results in energy levels like the lines of Fig. 2-20*b*. But when silicon atoms are in a crystal, the orbit of each electron is also influenced by the charges of many other silicon atoms. Since each electron has a unique position inside the crystal, no two electrons see exactly the same pattern of surrounding charges. Because of this, the orbit of each electron is different; or, to put it another way, the energy level of each electron is different.

Figure 2-21 shows what happens to the energy levels. All electrons in first orbit have slightly different energy levels because no two electrons see

Figure 2-21 Intrinsic semiconductor and its energy bands.



exactly the same charge environment. Since there are billions of first-orbit electrons, the slightly different energy levels form a cluster or *band* of energy. Similarly, the billions of second-orbit electrons, all with slightly different energy levels, form the second energy band—and so on for remaining bands.

Another point. As you know, thermal energy produces a few free electrons and holes. The holes remain in the valence band, but the free electrons go to the next-higher energy band, which is called the **conduction band.** This is why Fig. 2-21 shows a conduction band with some free electrons and a valence band with some holes. When the switch is closed, a small current exists in the pure semiconductor. The free electrons move through the conduction band, and holes move through the valence band.

n-Type Energy Bands

Figure 2-22 shows the energy bands for an *n*-type semiconductor. As you would expect, the majority carriers are the free electrons in the conduction band, and the minority carriers are the holes in the valence band. Since the switch is closed in Fig. 2-22, the majority carriers flow to the left, and the minority carriers flow to the right.

GOOD TO KNOW

For both *n*- and *p*-type semiconductors, an increase in temperature produces an identical increase in the number of minority and majority current carriers.

p-Type Energy Bands

Figure 2-23 shows the energy bands for a *p*-type semiconductor. Here you see a reversal of the carrier roles. Now, the majority carriers are the holes in the valence

Figure 2-22 *n*-type semiconductor and its energy bands.

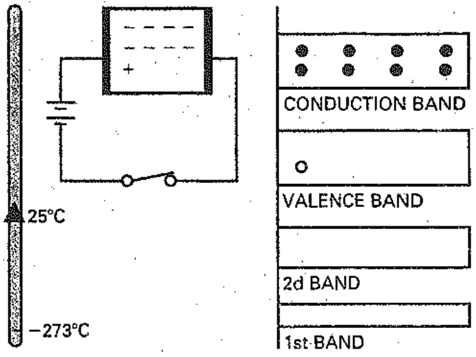
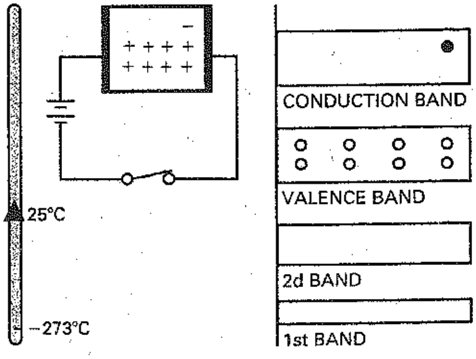


Figure 2-23 *p*-type semiconductor and its energy bands.



band, and the minority carriers are the free electrons in the conduction band. Since the switch is closed in Fig. 2-23, the majority carriers flow to the right, and the minority carriers flow to the left.

2-13 The Energy Hill

To understand more advanced types of semiconductor devices, you will need to know how energy levels control the action of a *pn* junction.

Before Diffusion

Assuming an abrupt junction (one that suddenly changes from *p* to *n* material), what does the energy diagram look like? Figure 2-24*a* shows the energy bands before electrons have diffused across the junction. The *p* side has many holes in the valence band, and the *n* side has many electrons in the conduction band. But why are the *p* bands slightly higher than the *n* bands?

The *p* side has trivalent atoms with a core charge of +3, shown in Fig. 2-24*b*. On the other hand, the *n* side has pentavalent atoms with a core charge of +5 (Fig. 2-24*c*). A +3 core attracts an electron less than a +5 core does. Therefore, the orbits of a trivalent atom (*p* side) are slightly larger than those of a pentavalent atom (*n* side). This is why the *p* bands of Fig. 2-24a are slightly higher than the *n* bands.

An abrupt junction like that of Fig. 2-24*a* is an idealization because the *p* side cannot suddenly end where the *n* side begins. A manufactured diode has a gradual change from one material to the other. For this reason, Fig. 2-25*a* is a more realistic energy diagram of a junction diode.

At Equilibrium

When the diode is first formed, there is no depletion layer (Fig. 2-25*a*). In this case, free electrons will diffuse across the junction. In terms of energy levels, this means that the electrons near the top of the *n* conduction band move across the junction, as previously described. Soon after crossing the junction, a free electron will recombine with a hole. In other words, the electron will fall from the conduction band to the valence band. As it does, it emits heat, light, and other radiation. This recombination not only creates the depletion layer, it also changes the

Figure 2-24 (*a*) Energy bands of abrupt junction before diffusion; (*b*) *p*-type atom has larger orbits, equivalent to higher energy level; (*c*) *n*-type atom has smaller orbits, equivalent to lower energy level.