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.

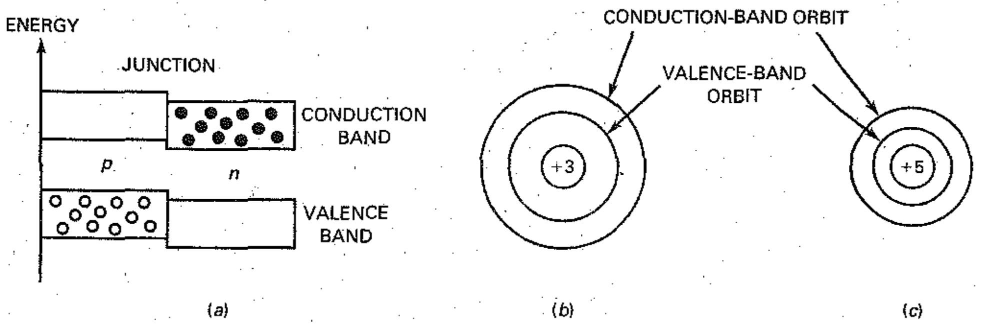
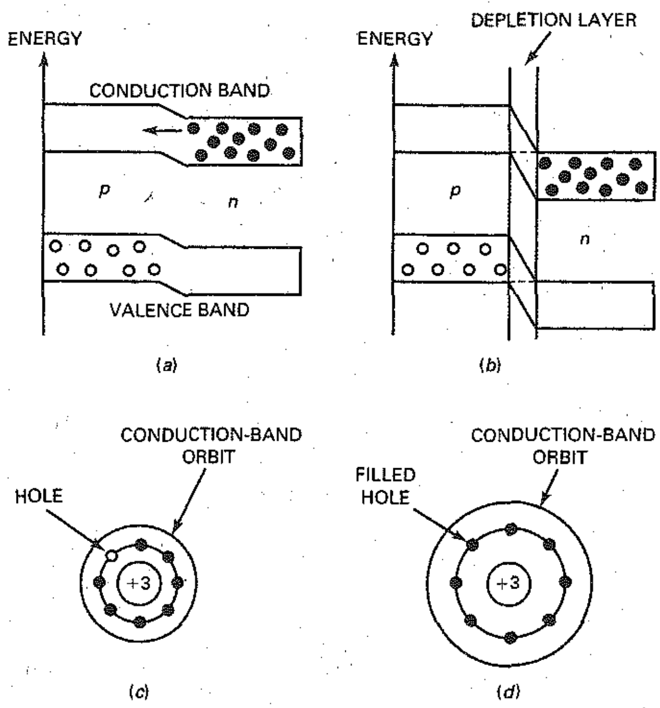


Figure 2-25 (*a*) Energy bands before diffusion; (*b*) energy bands after depletion layer is formed; (*c*) *p*-type atom before diffusion has smaller orbit; (*d*) *p*-type atom after diffusion has larger orbit, equivalent to higher energy level.



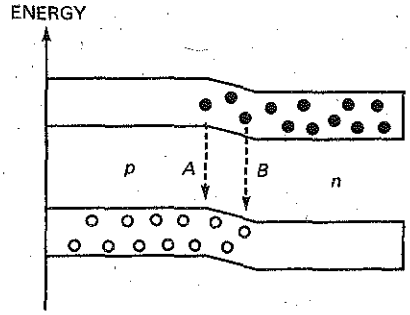
energy levels at the junction by increasing the energy level difference between the *p* and *n* bands.

Figure 2-25*b* shows the energy diagram after the depletion layer is created. The *p* bands have moved up with respect to the *n* bands. As you can see, the bottom of each *p* band is level with the top of the corresponding *n* band. This means that electrons on the *n* side no longer have enough energy to get across the junction. What follows is a simplified explanation of why the *p* band moves up.

Figure 2-25*c* shows a conduction-band orbit around one of the trivalent atoms before diffusion has occurred. When an electron diffuses across the junction, it falls into the hole of a trivalent atom (Fig. 2-25*d*). This extra electron in the valence orbit will push the conduction-band orbit farther away from the trivalent atom, as shown in Fig. 2-25*d*. Therefore, any new electrons coming into this area will need more energy than before to travel in a conduction-band orbit. Stated another way, the larger conduction-band orbit means that the energy level has increased. This is equivalent to saying that the *p* bands move up with respect to the *n* bands after the depletion layer has built up.

At equilibrium, conduction-band electrons on the *n* side travel in orbits not quite large enough to match the *p* side orbits (Fig. 2-25*b*). In other words, electrons on the *n* side do not have enough energy to get across the junction. To an electron trying to diffuse across the junction, the path it must travel looks like a hill, an energy hill (see Fig. 2-25*b*). The electron cannot climb this hill unless it receives energy from an outside source. This energy source may be a voltage source, but it can also be heat, light, or other radiation. Do not think of the energy

Figure 2-26 Forward bias gives free electrons more energy, equivalent to higher energy level.



hill as a "physical" hill. Instead, think of it as the necessary higher energy level for the valence electrons to "rise" to before they can cross the depletion layer.

Forward Bias

Forward bias lowers the energy hill (see Fig. 2-26). In other words, the battery increases the energy level of the free electrons; this is equivalent to forcing the *n* band upward. Because of this, free electrons have enough energy to enter the *p* region. Soon after entering the *p* region, they fall into holes (path *A*). As valence electrons, they continue moving toward the left end of the crystal; this is equivalent to holes moving toward the junction.

Some holes penetrate the *n* region as shown in Fig. 2-26. In this case, conduction-band electrons can follow recombination path *B*. Regardless of where the recombination takes place, the result is the same. A steady stream of free electrons moves toward the junction and falls into holes near the junction. The captured electrons (now valence electrons) move left in a steady stream through the holes in the *p* region. In this way, we get a continuous flow of electrons through the diode.

Incidentally, when free electrons fall from the conduction band to the valence band, they radiate their excess energy in the form of heat and light. With an ordinary diode, the radiation is heat energy, which serves no useful purpose. But with an LED, the radiation can be light such as red, green, blue, or orange. LEDs are widely used as visual indicators on electronic instruments, computer keyboards, and consumer equipment.

2-14 Barrier Potential and Temperature

The **junction temperature** is the temperature inside a diode, right at the *pn* junction. The *ambient temperature* is different. It is the temperature of the air outside the diode, the air that surrounds the diode. When the diode is conducting, the junction temperature is higher than the ambient temperature because of the heat created by recombination.

The barrier potential depends on the junction temperature. An increase in junction temperature creates more free electrons and holes in the doped regions. As these charges diffuse into the depletion layer, it becomes narrower. This means that there is *less barrier potential at higher junction temperatures.*