5.11 OHMIC CONTACTS AND THERMOELECTRIC COOLERS

An **ohmic contact** is a junction between a metal and a semiconductor that does not limit the current flow. The current is essentially limited by the resistance of the semiconductor outside the contact region rather than the thermal emission rate of carriers across a potential barrier at the contact. In the Schottky diode, the *I–V* characteristics were determined by the thermal emission rate of carriers across the contact. It should be mentioned that, contrary to intuition, when we talk about an ohmic contact, we do not generally infer a linear *I–V* characteristic for the ohmic contact itself. We only imply that the contact does not limit the current flow.

Figure 5.44 shows the formation of an ohmic contact between a metal and an *n*-type semiconductor. The work function of the metal Φ_m is smaller than the work function Φ_n of the semiconductor. There are more energetic electrons in the metal than in the CB, which means that the electrons (around E_{Fm}) tunnel into the semiconductor in search of lower energy levels, which they find around E_c, as indicated in Figure 5.44. Consequently, many electrons pile in the CB of the semiconductor near the junction. Equilibrium is reached when the accumulated electrons in the CB of the semiconductor prevent further electrons tunneling from the metal. Put more rigorously, equilibrium is reached when the Fermi level is uniform across the whole system from one end to the other.

The semiconductor region near the junction in which there are excess electrons is called the **accumulation region.** To show the increase in n, we draw the semiconductor energy bands bending downward to decrease $E_c - E_{Fn}$, which increases n. Going from the far end of the metal to the far end of the semiconductor, there are always conduction electrons. In sharp contrast, the depletion region of the Schottky junction

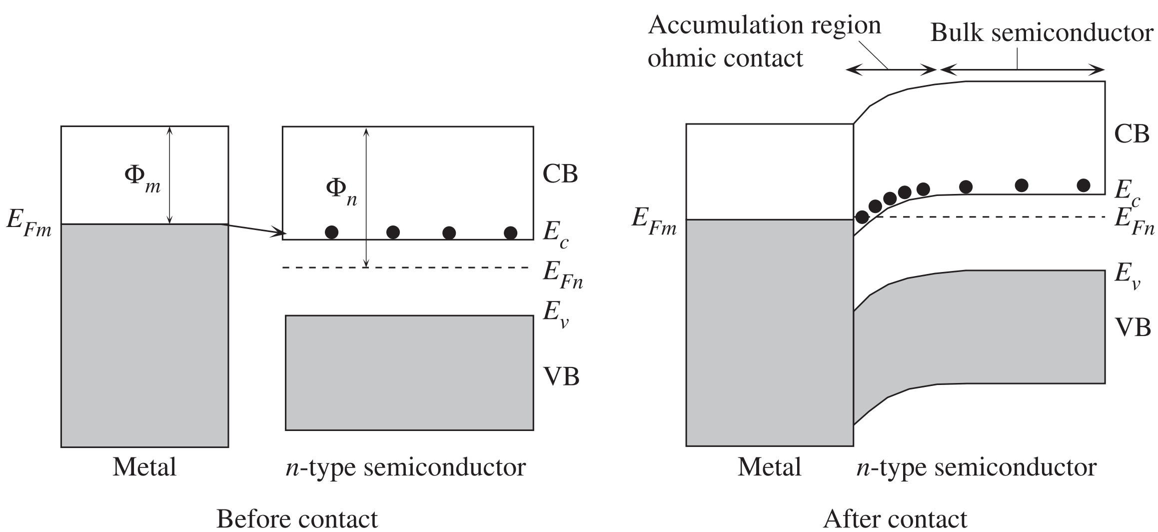

Figure 5.44 When a metal with a smaller work function than an *n*-type semiconductor is put into contact with the *n*-type semiconductor, the resulting junction is an ohmic contact in the sense that it does not limit the current flow.

separates the conduction electrons in the metal from those in the semiconductor. It can be seen from the contact in Figure 5.44 that the conduction electrons immediately on either side of the junction (at E_{Fm} and E_c) have about the same energy and therefore there is no barrier involved when they cross the junction in either direction under the influence of an applied field.

It is clear that the excess electrons in the accumulation region increase the conductivity of the semiconductor in this region. When a voltage is applied to the structure, the voltage drops across the higher resistance region, which is the bulk semiconductor region. Both the metal and the accumulation region have comparatively high concentrations of electrons compared with the bulk of the semiconductor. The current is therefore determined by the resistance of the bulk region. The current density is then simply $J = \sigma E$ where σ is the conductivity of the semiconductor in the bulk and E is the applied field in this region.

One of the interesting and important applications of semiconductors is in **thermoelectric,** or **Peltier,** devices, which enable small volumes to be cooled by direct currents. Whenever a dc current flows through a contact between two dissimilar materials, heat is either released or absorbed in the contact region, depending on the direction of the current. Suppose that there is a dc current flowing from an n-type semiconductor to a metal through an ohmic contact, as depicted in Figure 5.45a. Then electrons are flowing from the metal to the CB of the semiconductor. We only consider the contact region where the Peltier effect occurs. Current is carried by electrons near the Fermi level E_{Fm} in the metal. These electrons then cross over into

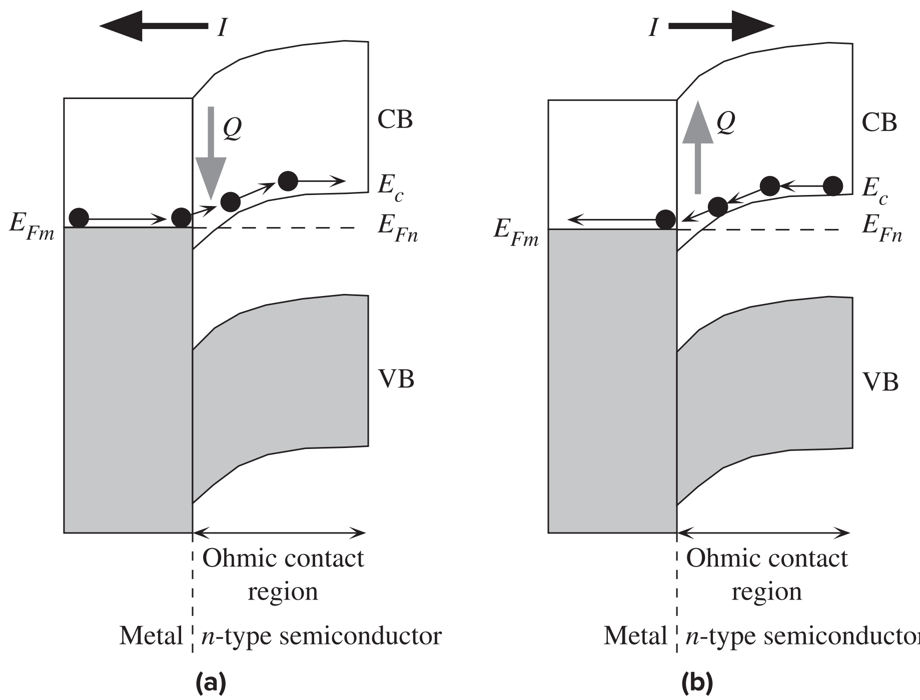

Figure 5.45 (a) Current from an n-type semiconductor to the metal results in heat absorption at the junction. (b) Current from the metal to an n-type semiconductor results in heat release at the junction.

the CB of the semiconductor and when they reach the end of the contact region, their energy is E_c plus average KE (which is $\frac{3}{2}kT$). There is therefore an increase in the average energy ($PE + KE$) per electron in the contact region. The electron must therefore absorb heat from the environment (lattice vibrations) to gain this energy as it drifts through the junction. Thus, the passage of an electron from the metal to the CB of an n-type semiconductor involves the absorption of heat at the junction.

When the current direction is from the metal to the n-type semiconductor, the electrons flow from the CB of the semiconductor to the Fermi level of the metal as they pass through the contact. Since E_{Fm} is lower than E_c, the passing electron has to lose energy, which it does to lattice vibrations as heat. Thus, the passage of a CB electron from the n-type semiconductor to the metal involves the release of heat at the junction, as indicated in Figure 5.45b.

It is apparent that depending on the direction of the current flow through a junction between a metal and an n-type semiconductor, heat is either absorbed or released at the junction. Although we considered current flow between a metal and an n-type semiconductor through an ohmic contact, this thermoelectric effect is a general phenomenon that occurs at a junction between any two dissimilar materials. It is called the **Peltier effect** after its discoverer. In the case of metal–p-type semiconductor junctions, heat is absorbed for current flowing from the metal to the p-type semiconductor and heat is released in the other direction. Thermoelectric effects occurring at metal–semiconductor junctions are summarized in Figure 5.46. It is important not to confuse the Peltier effect with the Joule heating of the semiconductor and the metal. Joule heating, which we simply call I^2R (or $J^2\rho$) heating, arises from the finite resistivity of the material. It is due to the conduction electrons losing their energy gained from the field to lattice vibrations when they become scattered by such vibrations, as discussed in Chapter 2.

It is self-evident that when a current flows through a semiconductor sample with metal contacts at its ends, as depicted in Figure 5.46, one of the contacts will always absorb heat and the other will always release heat. The contact where heat is absorbed will be cooled and is called the cold junction, whereas the other contact, where heat

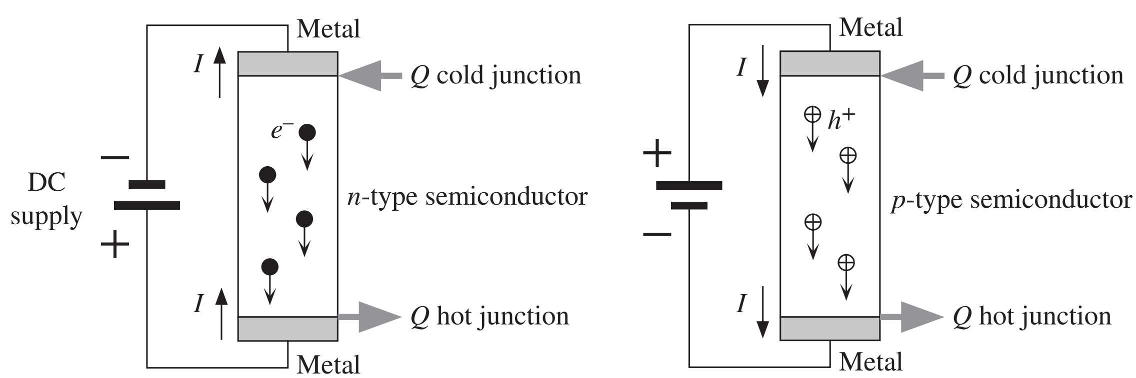

Figure 5.46 When a dc current is passed through a semiconductor to which metal contacts have been made, one junction absorbs heat and cools (the cold junction) and the other releases heat and warms (the hot junction).

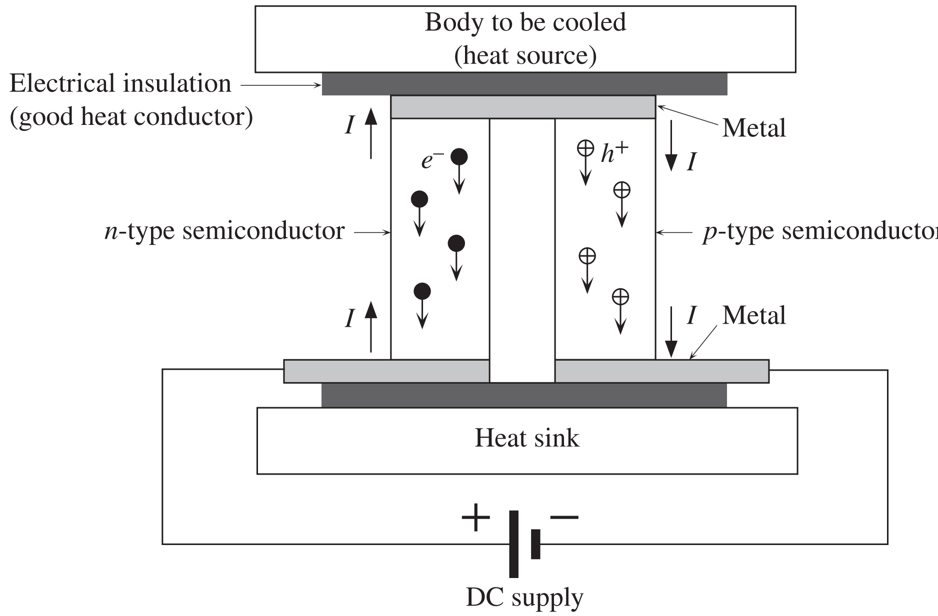

Figure 5.47 Cross section of a typical thermoelectric cooler.

is released, will warm up and is called the hot junction. One can use the cold junction to cool another body, providing that the heat generated at the hot junction can be removed from the semiconductor sufficiently quickly to reduce its conduction through the semiconductor to the cold junction. Furthermore, there will always be the Joule heating (I^2R) of the whole semiconductor sample since the bulk will always have a finite resistance.

A simplified schematic diagram of a practical single-element thermoelectric cooling device is shown in Figure 5.47. It uses two semiconductors, one n-type and the other p-type, each with ohmic contacts. The current direction therefore has opposite thermoelectric effects. On one side, the semiconductors share the same metal electrode. Effectively, the structure is an n-type and a p-type semiconductor connected in series through a common metal electrode. Typically, either Bi_2Te_3, Bi_2Se_3, or Sb_2Te_3 is used as the semiconductor material with copper usually as the metal electrode.

The current flowing through the n-type semiconductor to the common metal electrode causes heat absorption, which cools this junction and hence the metal. The same current then enters the p-type semiconductor and causes heat absorption at this junction, which cools the same metal electrode. Thus, the common metal electrode is cooled at both ends. The other ends of the semiconductors are hot junctions. They are connected to a large heat sink to remove the heat and thus prevent heat conduction through the semiconductors toward the cold junctions. The other face of the common metal electrode is in contact, through a thin ceramic plate (electrical insulator but thermal conductor), with the body to be cooled. In commercial Peltier devices, many of these elements are connected in series, as illustrated in Figure 5.48, to increase the cooling efficiency.

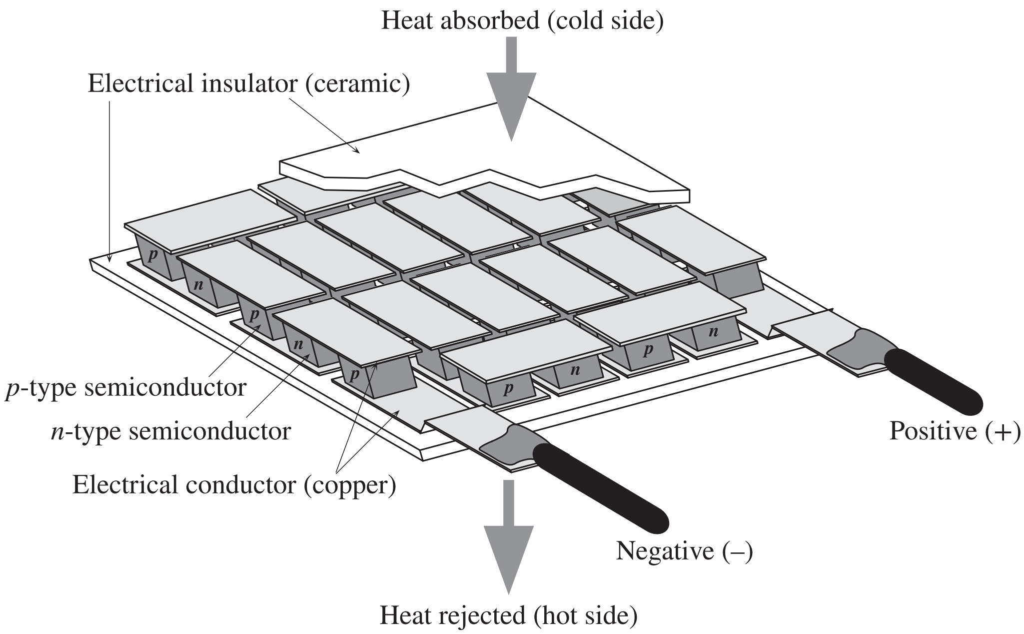

Figure 5.48 Typical structure of a commercial thermoelectric cooler.

EXAMPLE 5.24

THE PELTIER COEFFICIENT Consider the motion of electrons across an ohmic contact between a metal and an n–type semiconductor and hence show that the rate of heat generation Q' at the contact is approximately

Definition of Peltier coefficient

$$Q' = \pm \Pi I \quad [5.71]$$

where Π, called the **Peltier coefficient** between the two materials. Consider the motion of electrons across the junction in Figure 5.45a and show that

Peltier coefficient

$$\Pi = \frac{1}{e}\left[(E_c - E_{Fn}) + \frac{3}{2}kT\right] \quad [5.72]$$

where $E_c - E_{Fn}$ is the energy separation of E_c from the Fermi level in the n-type semiconductor. The sign depends on the convention used for heat liberation or absorption. What is the Peltier cofficient for between a metal and an n-type Si doped with 10^{16} cm^{-3} donors?

SOLUTION

Consider Figure 5.45a, which shows only the ohmic contact region between a metal and an n-type semiconductor when a current is passing through it. The majority of the applied voltage drops across the bulk of the semiconductor because the contact region, or the accumulation region, has an accumulation of electrons in the CB. The current is limited by the bulk resistance of the semiconductor. Thus, in the contact region we can take the Fermi level to be almost undisturbed and hence uniform, $E_{Fm} \approx E_{Fn}$. In the bulk of the metal, a conduction electron is at around E_{Fm} (same as E_{Fn}), whereas just at the end of the contact region in the semiconductor it is at E_c plus an average KE of $\frac{3}{2}kT$. The energy difference is the heat absorbed per electron going through the contact region. Since I/e is the rate at which electrons are flowing through the contact,

$$\text{Rate of energy absorption} = \left[\left(E_c + \frac{3}{2}kT\right) - E_{Fm}\right]\left(\frac{I}{e}\right)$$

or

Peltier effect

$$Q' = \left[\frac{(E_c - E_{Fn}) + \frac{3}{2}kT}{e}\right] I = \Pi I \qquad [5.73]$$

so the Peltier coefficient is given by the term in the square brackets. For n type Si that has $N_d = 10^{16}$ cm^{-3}, from Equation 5.6 with $n = N_d$, $E_c - E_{Fn} = (kT/e)\ln(n/N_c) = 0.205$ eV, and Equation 5.72, gives $\Pi = 0.24$ W A^{-1}. Thus, a current of 1 A through this metal/n-Si junction as in Figure 5.45a will lead to the absorption of heat at a rate of 240 mW.

We can increase $(E_c - E_{Fn})$ and hence Π by decreasing the donor concentration N_d. But, we also need a reasonable amount of doping to increase the conductivity of the bulk to reduce the Joule heating arising from the current through the semiconductor; Joule heating per unit volume is ρJ^2, where ρ is the resistivity.

ADDITIONAL TOPICS

5.12 SEEBECK EFFECT IN SEMICONDUCTORS AND VOLTAGE DRIFT

Consider an n-type semiconductor that has a temperature gradient across it. The right end is hot and the left end is cold as depicted in Figure 5.49a. The majority carriers are electrons. We will ignore the few minority carriers. There are more energetic

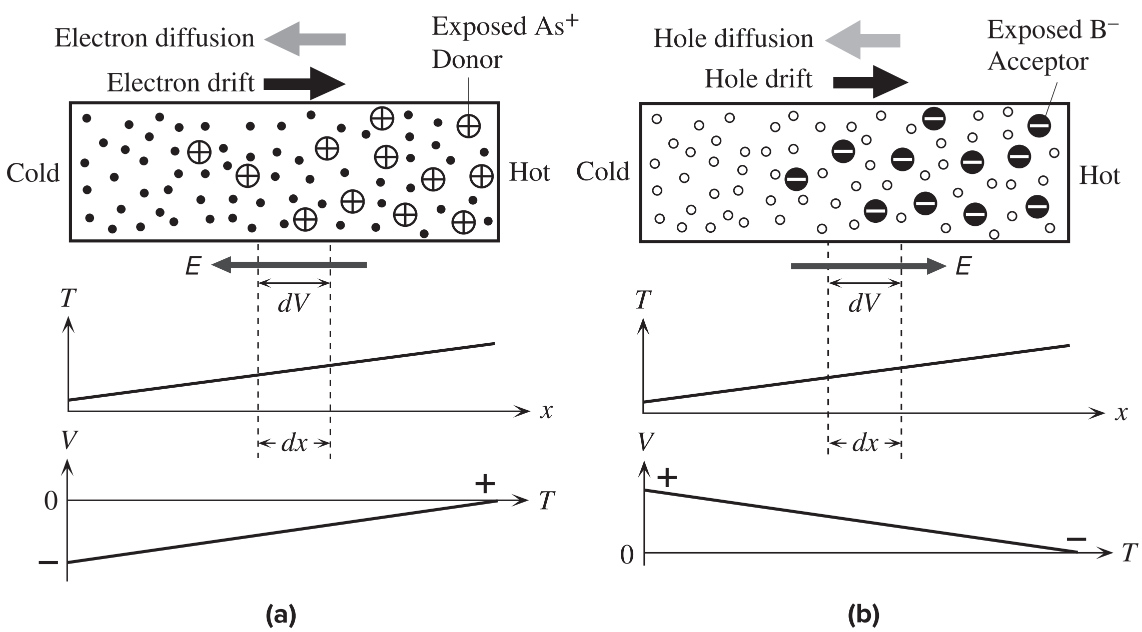

Figure 5.49 (a) In the presence of a temperature gradient in an n-type semiconductor, electrons diffuse from the hot to the cold region. The cold end is negative with respect to the hot end. There is an internal field and a voltage difference. The Seebeck coefficient is defined as dV/dT, potential difference per unit temperature difference. (b) In the presence of a temperature gradient in a p-type semiconductor, holes diffuse from the hot to cold region. The Seebeck coefficient is now positive; the cold end is positive with respect to the hot end.