band structure then depends upon the orientation of the atoms relative to one another in space (the crystal structure) and upon the atomic number, which determines the electrical constitution of each atom. Solutions of Schrödinger's equation are complicated and have been obtained approximately for only relatively few crystals. These solutions lead us to expect an energy-band diagram somewhat as pictured[1] in Fig. 1-3*b*. At the crystal-lattice spacing (the dashed vertical line), we find the valence band *filled* with $4N$ electrons separated by a forbidden band (no allowed energy states) of extent E_G from an *empty* band consisting of $4N$ additional states. This upper vacant band is called the *conduction band,* for reasons given in the next section.

1-8 INSULATORS, SEMICONDUCTORS, AND METALS

A very poor conductor of electricity is called an *insulator;* an excellent conductor is a *metal;* and a substance whose conductivity lies between these extremes is a *semiconductor.* A material may be placed in one of these three classes, depending upon its energy-band structure.

Insulator The energy-band structure of Fig. 1-3*b* at the normal lattice spacing is indicated schematically in Fig. 1-4*a*. For a diamond (carbon) crystal the region containing no quantum states is several electron volts high ($E_G \approx 6$ eV). This large forbidden band separates the filled valence region from the vacant conduction band. The energy which can be supplied to an electron from an applied field is too small to carry the particle from the filled into the vacant band. Since the electron cannot acquire sufficient applied energy, conduction is impossible, and hence diamond is an *insulator.*

Semiconductor A substance for which the width of the forbidden energy region is relatively small ($\sim$1 eV) is called a *semiconductor.* Graphite, a

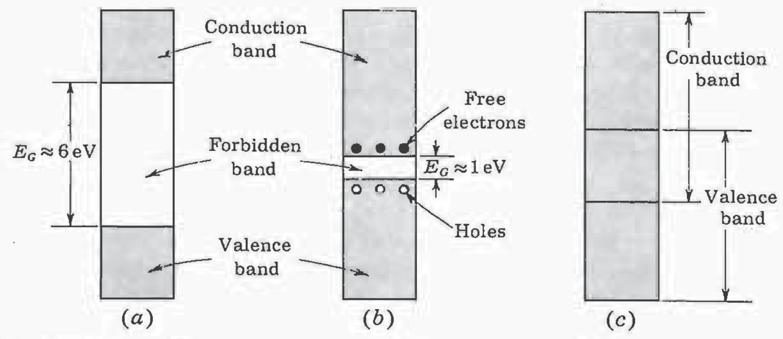

Fig. 1-4 Energy-band structure of (*a*) an insulator, (*b*) a semiconductor, and (*c*) a metal.

crystalline form of carbon but having a crystal symmetry which is different from diamond, has such a small value of E_G, and it is a semiconductor. The most important practical semiconductor materials are germanium and silicon, which have values of E_G of 0.785 and 1.21 eV, respectively, at 0°K. Energies of this magnitude normally cannot be acquired from an applied field. Hence the valence band remains full, the conduction band empty, and these materials are insulators at low temperatures. However, the conductivity increases with temperature, as we explain below. These substances are known as *intrinsic (pure) semiconductors*.

As the temperature is increased, some of these valence electrons acquire *thermal* energy greater than E_G, and hence move into the conduction band. These are now free electrons in the sense that they can move about under the influence of even a small applied field. These free, or conduction, electrons are indicated schematically by dots in Fig. 1-4*b*. The insulator has now become slightly conducting; it is a *semiconductor*. The absence of an electron in the valence band is represented by a small circle in Fig. 1-4*b*, and is called a *hole*. The phrase "holes in a semiconductor" therefore refers to the empty energy levels in an otherwise filled valence band.

The importance of the hole is that it may serve as a carrier of electricity, comparable in effectiveness with the free electron. The mechanism by which a hole contributes to conductivity is explained in Sec. 2-2. We also show in Chap. 2 that if certain impurity atoms are introduced into the crystal, these result in allowable energy states which lie in the forbidden energy gap. We find that these impurity levels also contribute to the conduction. A semiconductor material where this conduction mechanism predominates is called an *extrinsic (impurity) semiconductor*.

Since the band-gap energy of a crystal is a function of interatomic spacing (Fig. 1-3), it is not surprising that E_G depends somewhat on temperature. It has been determined experimentally that E_G decreases with temperature, and this dependence is given in Sec. 2-5.

Metal A solid which contains a partly filled band structure is called a *metal*. Under the influence of an applied electric field the electrons may acquire additional energy and move into higher states. Since these mobile electrons constitute a current, this substance is a conductor and the partly filled region is the conduction band. One example of the band structure of a metal is given in Fig. 1-4*c*, which shows overlapping valence and conduction bands.

REFERENCES

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