

Electrical Properties Of Materials

Ohm's Law :

Ohm's law relates the current I to the applied voltage V as follows:

$$V = IR$$

Where R is the resistance of the material through which the current is passing. The units for V , I , and R are, respectively, volts, amperes, and ohms. The value of R is influenced by specimen configuration and for many materials is independent of current. The **electrical resistivity** ρ is independent of specimen geometry but related to R through the expression:

$$\rho = \frac{RA}{l}$$

where l is the distance between the two points at which the voltage is measured and A is the cross-sectional area perpendicular to the direction of the current. The units for ρ are ohm-meters ($\Omega \cdot m$).

Sometimes, electrical **conductivity** σ is used to specify the electrical character of a material. It is simply the reciprocal of the resistivity:

$$\rho = \frac{1}{\sigma}$$

and is indicative of the ease with which a material is capable of conducting an electric current. The units for σ are reciprocal ohm-meters [$(\Omega \cdot m)^{-1}$].

In addition to the equation above, Ohm's law may be expressed as:

$$J = \sigma E$$

in which J is the **current density** the current per unit of area I/A —and E is the **electric field intensity**, or the voltage difference between two points divided by the distance separating them:

$$E = \frac{V}{l}$$

There are three groupings of solid materials: conductors, semiconductors, and insulators. Metals are good conductors, typically having conductivities on the order of $10^7 (\Omega \cdot m)^{-1}$.

At the other extreme are materials with very low conductivities, ranging between 10^{-10} and $10^{-20} (\Omega \cdot m)^{-1}$; these are electrical insulators. Materials with intermediate conductivities, generally from 10^{-6} to $10^4 (\Omega \cdot m)^{-1}$, are termed semiconductors.

Electronic and ionic conduction

An electric current result from the motion of electrically charged particles in response to forces that act on them from an externally applied electric field. Positively charged particles are accelerated in the field direction, negatively charged particles in the direction opposite.

Energy band structures in solids

In all conductors, semiconductors, and many insulating materials, only electronic conduction exists, and the magnitude of the electrical conductivity is strongly dependent on the number of electrons available to participate in the conduction process. However, not all electrons in every atom accelerate in the presence of an electric field. The number of electrons available for electrical conduction in a particular material is related to the arrangement of electron states or levels with respect to energy and the manner in which these states are occupied by electrons.

For each individual atom there exist discrete energy levels that may be occupied by electrons, arranged into shells and subshells. Shells are designated by integers (1, 2, 3, etc.) and subshells by letters (s, p, d, and f). For each of s, p, d, and f subshells, there exist, respectively, one, three, five, and seven states. The electrons in most atoms fill only the states having the lowest energies: two electrons of opposite spin per state. As the atoms come within close proximity of one another, electrons are acted upon, or perturbed, by the electrons and nuclei of adjacent atoms. This influence is such that each atomic state may split into a series of closely spaced electron states in the solid to form what is termed an electron energy band.

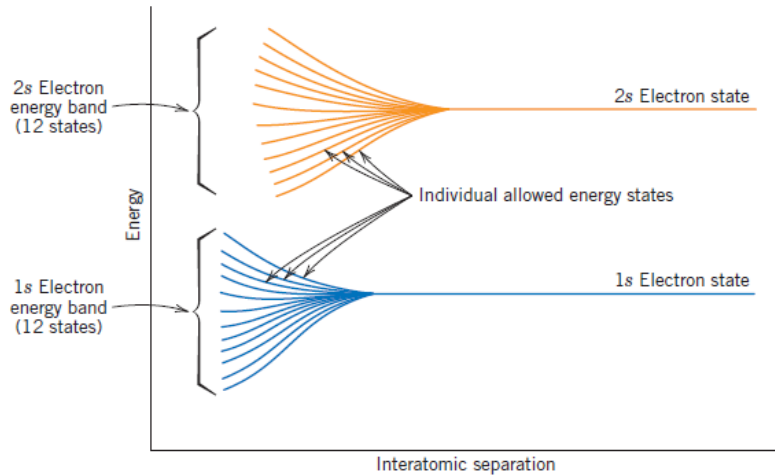


Figure 1

The extent of splitting depends on interatomic separation (Figure 2) and begins with the outermost electron shells because they are the first to be perturbed as the atoms coalesce. Within each band, the energy states are discrete, yet the difference between adjacent states is exceedingly small. At the equilibrium spacing, band formation may not occur for the electron subshells nearest the nucleus, as illustrated in Figure 2.b. Furthermore, gaps may exist between adjacent bands, as also indicated in the figure; normally, energies lying within these band gaps are not available for electron occupancy. The conventional way of representing electron band structures in solids is shown in Figure 2.a.

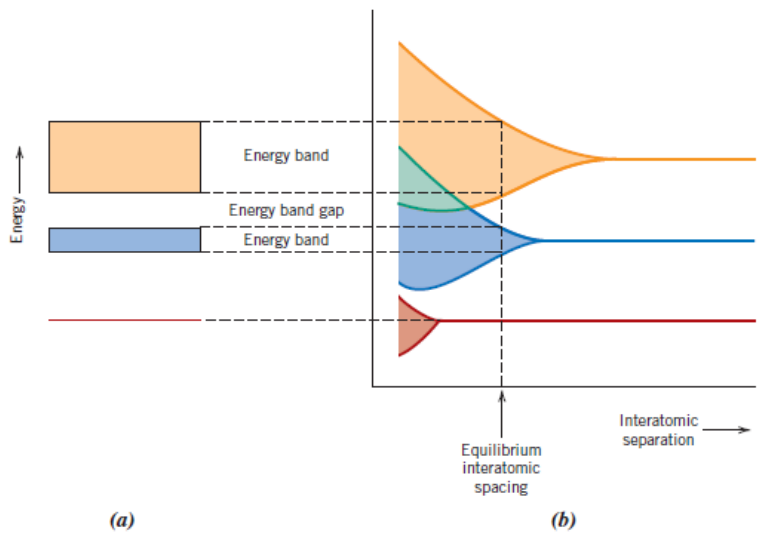


Figure 2

The number of states within each band is equal to the total of all states contributed by the N atoms. For example, an s band consists of N states and a p band of $3N$ states. With regard to occupancy, each energy state may accommodate two electrons that must have oppositely directed spins. Furthermore, bands contain the electrons that resided in the corresponding levels of the isolated atoms; for example, a $4s$ energy band in the solid contains those isolated atoms' $4s$ electrons. Of course, there are empty bands and, possibly, bands that are only partially filled.

The electrical properties of a solid material are a consequence of its electron band structure—that is, the arrangement of the outermost electron bands and the way in which they are filled with electrons.

Four different types of band structures are possible at 0 K . In the first (Figure 3.a), one outermost band is only partially filled with electrons. The energy corresponding to the highest filled state at 0 K is called **the Fermi energy E_f** , as indicated. This energy band structure is typified by some metals, in particular those that have a single s valence electron (e.g., copper). Each copper atom has one $4s$ electron; however, for a solid composed of N atoms, the $4s$ band is capable of accommodating $2N$ electrons. Thus, only half of the available electron positions within this $4s$ band are filled.

For the second band structure, also found in metals (Figure 3.b), there is an overlap of an empty band and a filled band. Magnesium has this band structure. Each isolated Mg atom has two $3s$ electrons. However, when a solid is formed, the $3s$ and $3p$ bands overlap. In this instance and at 0 K , the Fermi energy is taken as that energy below which, for N atoms, N states are filled, two electrons per state.

The final two band structures are similar; one band (**the valence band**) that is completely filled with electrons is separated from an empty **conduction band**, and an **energy band gap** lies between them. For very pure materials, electrons may not have energies within this gap. The difference between the two band structures lies in the magnitude of the energy gap; for materials that are insulators, the band gap is relatively wide (Figure 3.c), whereas for semiconductors it is narrow (Figure 3.d). The Fermi energy for these two band structures lies within the band gap—near its center.

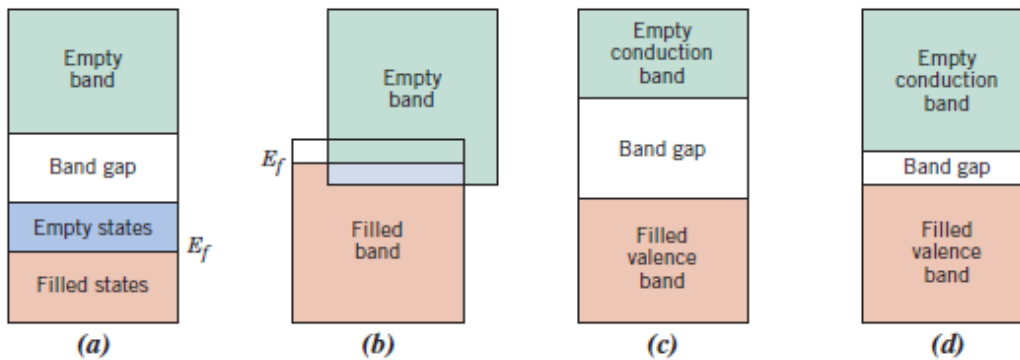


Figure 3

Conduction in terms of band and atomic bonding models

Only electrons with energies greater than the Fermi energy may be acted on and accelerated in the presence of an electric field. These are the electrons that participate in the conduction process, which are termed **free electrons**.

Metals

For an electron to become free, it must be excited or promoted into one of the empty and available energy states above E_f . For metals having either of the band structures shown in Figures 3.a and 3.b, there are vacant energy states adjacent to the highest filled state at E_f . Thus, very little energy is required to promote electrons into the low-lying empty states, as shown in Figure 4. Generally, the energy provided by an electric field is sufficient to excite large numbers of electrons into these conducting states.

For the metallic bonding model, it assumed that all the valence electrons have freedom of motion and form an electron gas that is uniformly distributed throughout the lattice of ion cores. Although these electrons are not locally bound to any particular atom, they must experience some excitation to become conducting electrons that are truly free. Thus, although only a fraction are excited, this still gives rise to a relatively large number of free electrons and, consequently, a high conductivity.

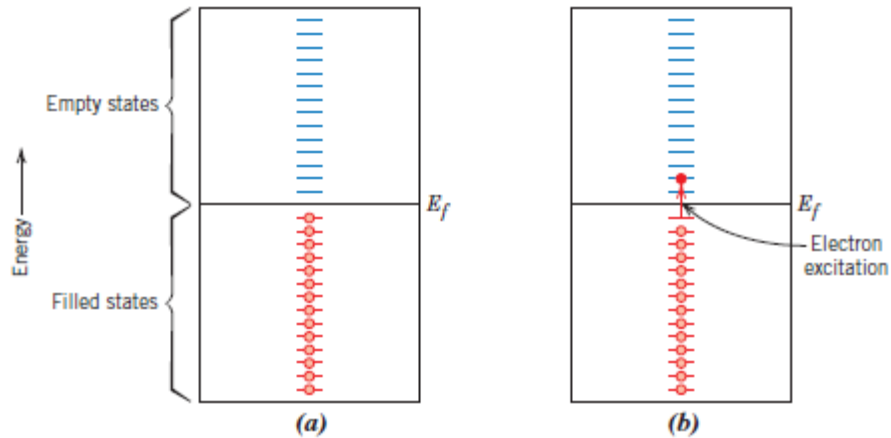


Figure 4

Insulators and Semiconductors

For insulators and semiconductors, empty states adjacent to the top of the filled valence band are not available. To become free, therefore, electrons must be promoted across the energy band gap and into empty states at the bottom of the conduction band. This is possible only by supplying to an electron the difference in energy between these two states, which is approximately equal to the band gap energy E_g . This excitation process is demonstrated in Figure 5. For many materials, this band gap is several electron volts wide. Most often the excitation energy is from a nonelectrical source such as heat or light, usually the former. The number of electrons excited thermally (by heat energy) into the conduction band depends on the energy band gap width and the temperature. At a given temperature, the larger the E_g , the lower the probability that a valence electron will be promoted into an energy state within the conduction band; this results in fewer conduction electrons. In other words, the larger the band gap, the lower the electrical conductivity at a given temperature. Thus, the distinction between semiconductors and insulators lies in the width of the band gap; for semiconductors, it is narrow, whereas for insulating materials, it is relatively wide.

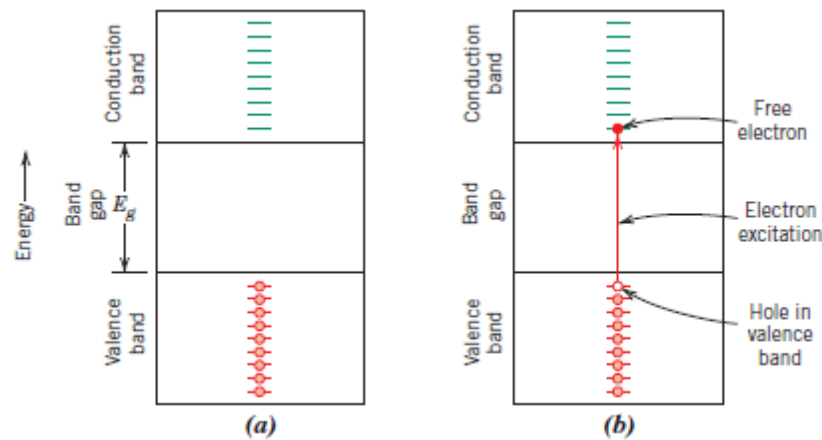


Figure 5

Increasing the temperature of either a semiconductor or an insulator results in an increase in the thermal energy that is available for electron excitation. Thus, more electrons are promoted into the conduction band, which gives rise to an enhanced conductivity. For electrically insulating materials, the valence electrons are tightly bound to or shared with the individual atoms. In other words, these electrons are highly localized and are not in any sense free to wander throughout the crystal. The bonding in semiconductors is covalent (or predominantly covalent) and relatively weak, which means that the valence electrons are not as strongly bound to the atoms. Consequently, these electrons are more easily removed by thermal excitation than they are for insulators.