Lecture 3
Electrical Properties

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1. Electrical Conduction

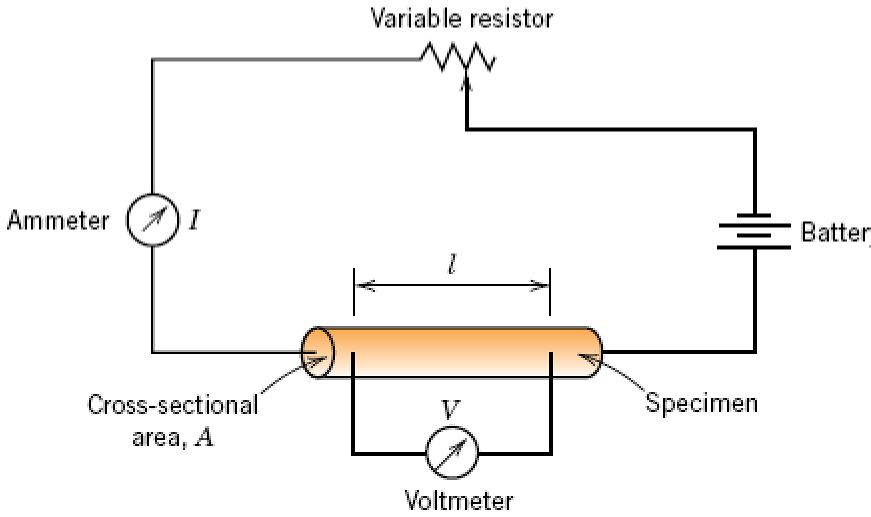
OHM'S LAW relates the current *I*—or time rate of charge passage—to the applied voltage *V* as follows:

$$V = IR$$

✓ where R is the resistance of the material through which the current is passing. The units for V, I, and R are, respectively, volts (J/C), amperes (C/s), and ohms (V/A)

✓ The electrical resistivity r is independent of specimen geometry but related to R through the expression

$$\rho = \frac{RA}{L} = \frac{VA}{IL} \qquad \Omega.\mathrm{m}$$



1. Electrical Conduction

ELECTRICAL CONDUCTIVITY

- ✓ Reciprocal relationship between electrical conductivity and resistivity

$$\sigma = \frac{1}{\rho} \qquad (\Omega.\mathrm{m})^{-1}$$

- ✓ Ohm's law expression—in terms of current density, conductivity, and applied electric field

$$J = \sigma E$$

- ✓ in which *J* is the current density—the current per unit of specimen area *I*/*A*—and is the electric field intensity, or the voltage difference between two points divided by the distance separating them.,
- ✓ Electric field intensity is given as follows

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

1. Electrical Conduction

Material	$\rho\,(\Omega - m)$ resistivity at 20° C
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.24×10^{-8}
Aluminium	2.82×10^{-8}
Calcium	3.36×10^{-8}
Tungsten	5.60×10^{-8}
Zinc	5.90×10^{-8}
Nickel	6.99×10^{-8}
Iron	1.00×10^{-7}
Lead	2.20×10^{-7}

Material	$\rho\,(\Omega - m)$ resistivity at 20° C
Nichrome	1.10×10^{-6}
Carbon (Graphite)	2.50×10^{-6}
Germanium	4.60×10^{-1}
Drinking water	2.00×10^{-1}
Silicon	6.40×10^{2}
Wet wood	1.00×10^{3}
Glass	10.0×10^{10}
Rubber	1.00×10^{13}
Air	1.30×10^{16}

1. Electrical Conduction

- In fact, one way of classifying solid materials is according to the ease with which they conduct an electric current; within this classification scheme there are three groupings:

1) ***Conductors.***
2) ***Semiconductors.***
3) ***insulators***.

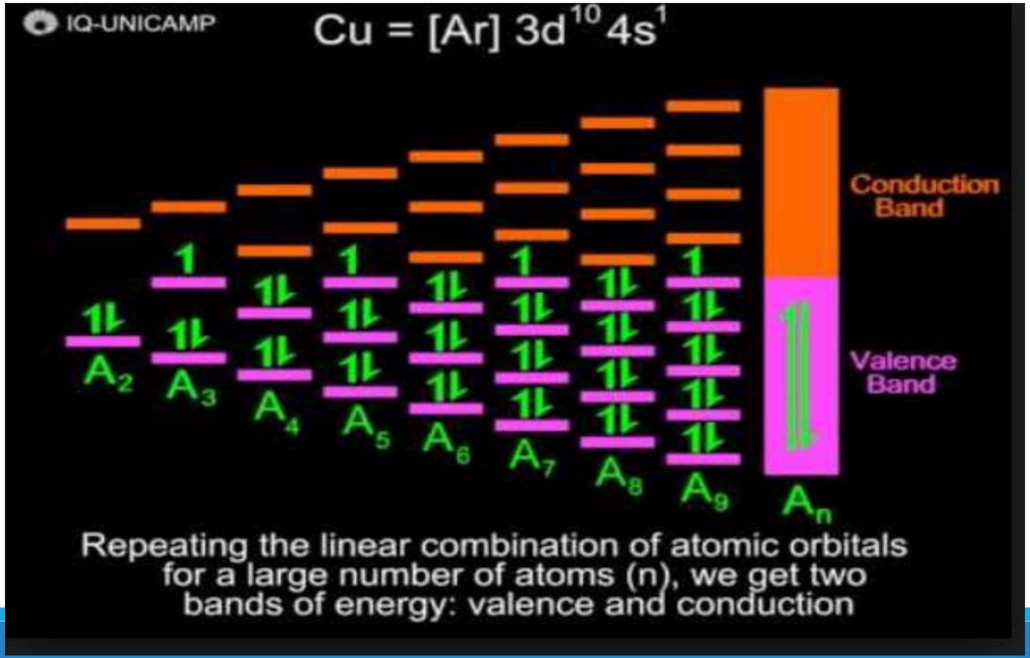
- **Metals** are good conductors, typically having conductivities on the order of 10^7 $(\Omega.m)^{-1}$.
- At the other extreme are materials with very low conductivities, ranging between **10^{-10} and 10^{-20}** $(\Omega.m)^{-1}$; these are electrical **insulators.**
- Materials with intermediate conductivities, generally from 10^6 to 10^4 $(\Omega.m)^{-1}$, are termed **semiconductors.**

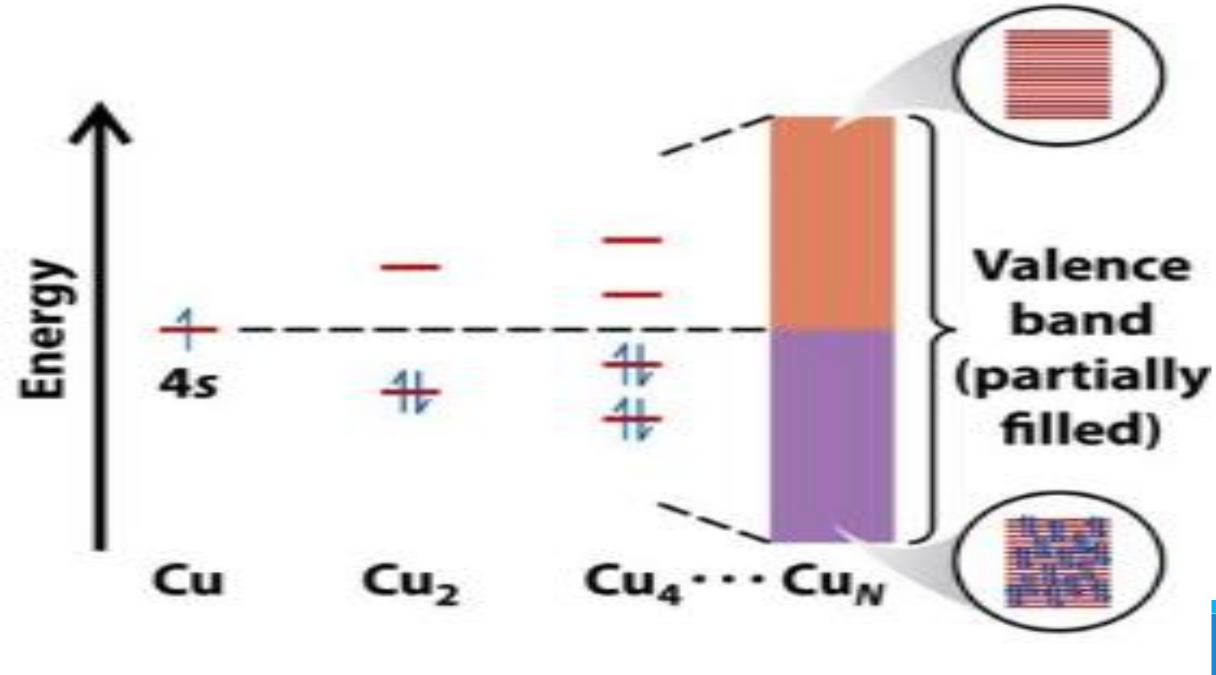
2.Energy Band Structures In Solids

- ✓ The electrons of a single, isolated atom occupy atomic orbitals each of which has a discrete energy level.
- ✓ When two or more atoms join together to form into a molecule, their atomic orbitals overlap. The Pauli exclusion principle مبدأ بولي للاستبعاد dictates that no two electrons can have the same quantum numbers in a molecule. So if two identical atoms combine to form a molecule, each atomic orbital splits into two molecular orbitals of different energy, allowing the electrons in the former atomic orbitals to occupy the new orbital structure without any having the same energy.
- ✓ This influence is such that each distinct atomic state may split into a series of closely spaced electron states in the solid to form what is termed an *electron energy band.*

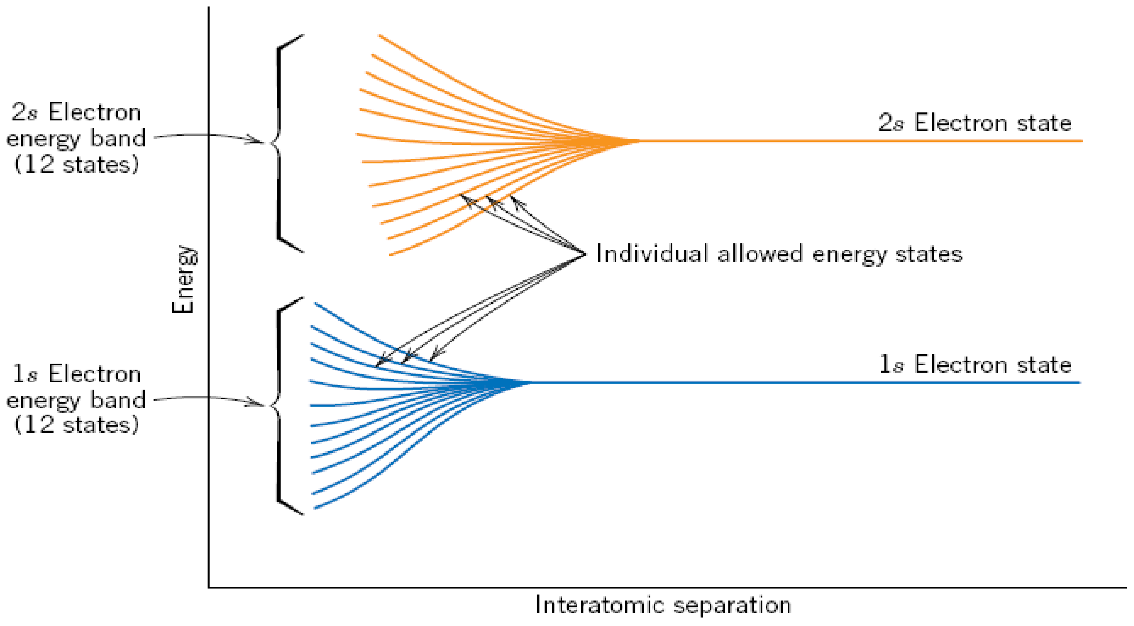
2.Energy Band Structures In Solids

- ✓ **Band theory** is an extension of molecular orbital theory that describes bonding in solids.
- ✓ Bands of orbitals that are filled or partially filled by valence electrons are called **valence bands**.
- ✓ Higher-energy unoccupied bands in which electrons are free to migrate are called **conduction bands**.
- ✓ The energy corresponding to المقابل ل the highest filled state at 0 K is called the **Fermi energy** *Ef*,





3.Energy Band Structures In Solids



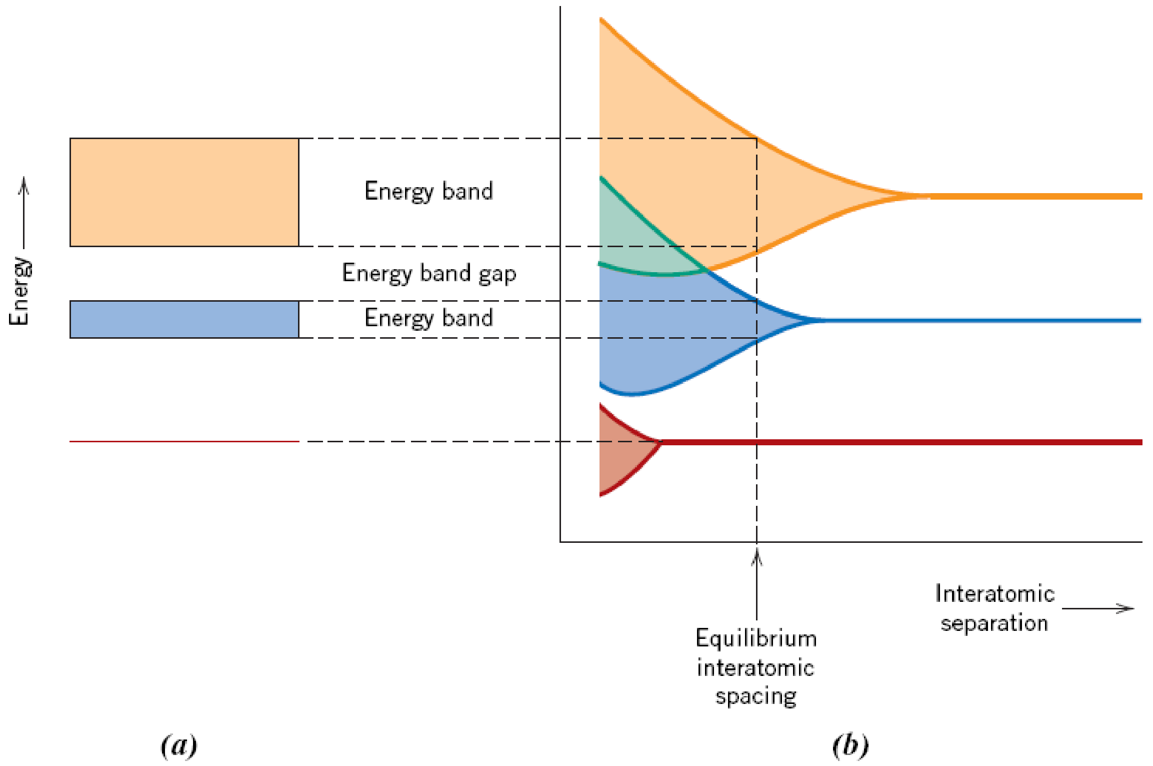


Figure 3

(*a*) The conventional representation of the electron energy band structure for a solid material at the equilibrium interatomic separation. (*b*) Electron energy versus interatomic separation for an aggregate of atoms

4.Conduction in terms of band and atomic bonding models

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.

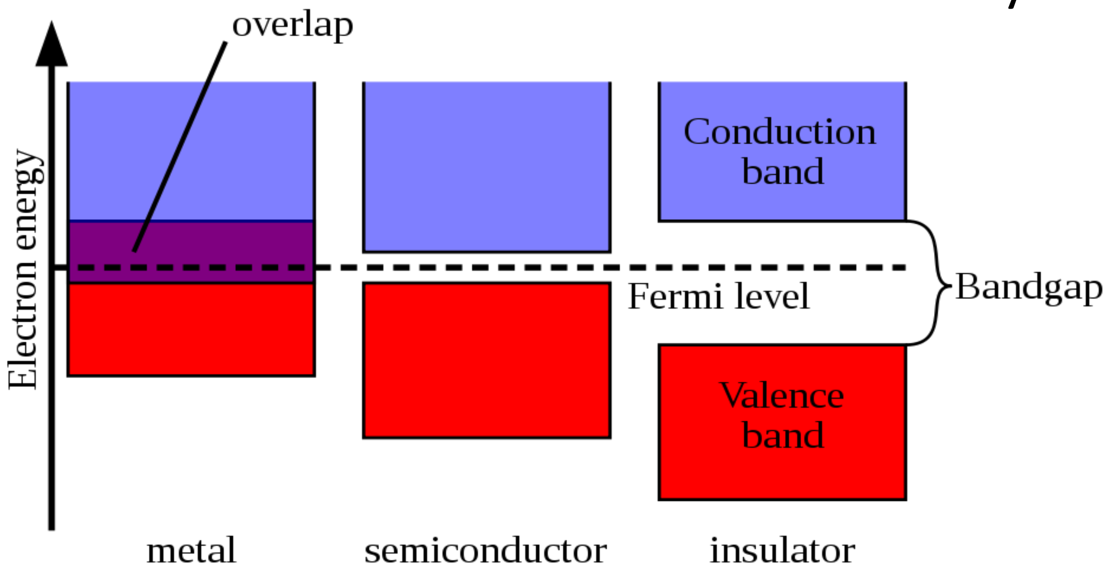


Figure 4

Figure 4 The various possible electron band structures in solids at 0 K. (*a*) The electron band structure found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. (*b*). The electron band structure characteristic of insulators; the filled valence band is separated fromthe empty conduction band by a relatively large band gap (2 eV). (*d*) The electron band structure found in the semiconductors, which is the same as for insulators except that the band gap is relatively narrow (2 eV).

4.Conduction In Terms Of Band And Atomic Bonding Models

- ✓ 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. Another charged electronic entity called a hole is found in semiconductors and insulators. Holes have energies less than *Ef* and also participate in electronic conduction.
- ✓ Electrical conductivity is a direct function of the numbers of free electrons and holes.
- ✓ For an electron to become free, it must be excited or promoted into one of the empty and available energy states above *Ef*. For metals having either of the band structures shown in Figures **5**, there are vacant energy states adjacent to the highest filled state at *Ef*. Thus, very little energy is required to promote electrons into the empty states

4.Conduction In Terms Of Band And Atomic Bonding Models

- ✓ For insulators and semiconductors, the conduction band are not adjacent to قريب من the top of the filled valence band. 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 *Eg*. This excitation process is demonstrated in Figure **6** For many materials, this band gap is several electron volts wide.

4.Conduction In Terms Of Band And Atomic Bonding Models

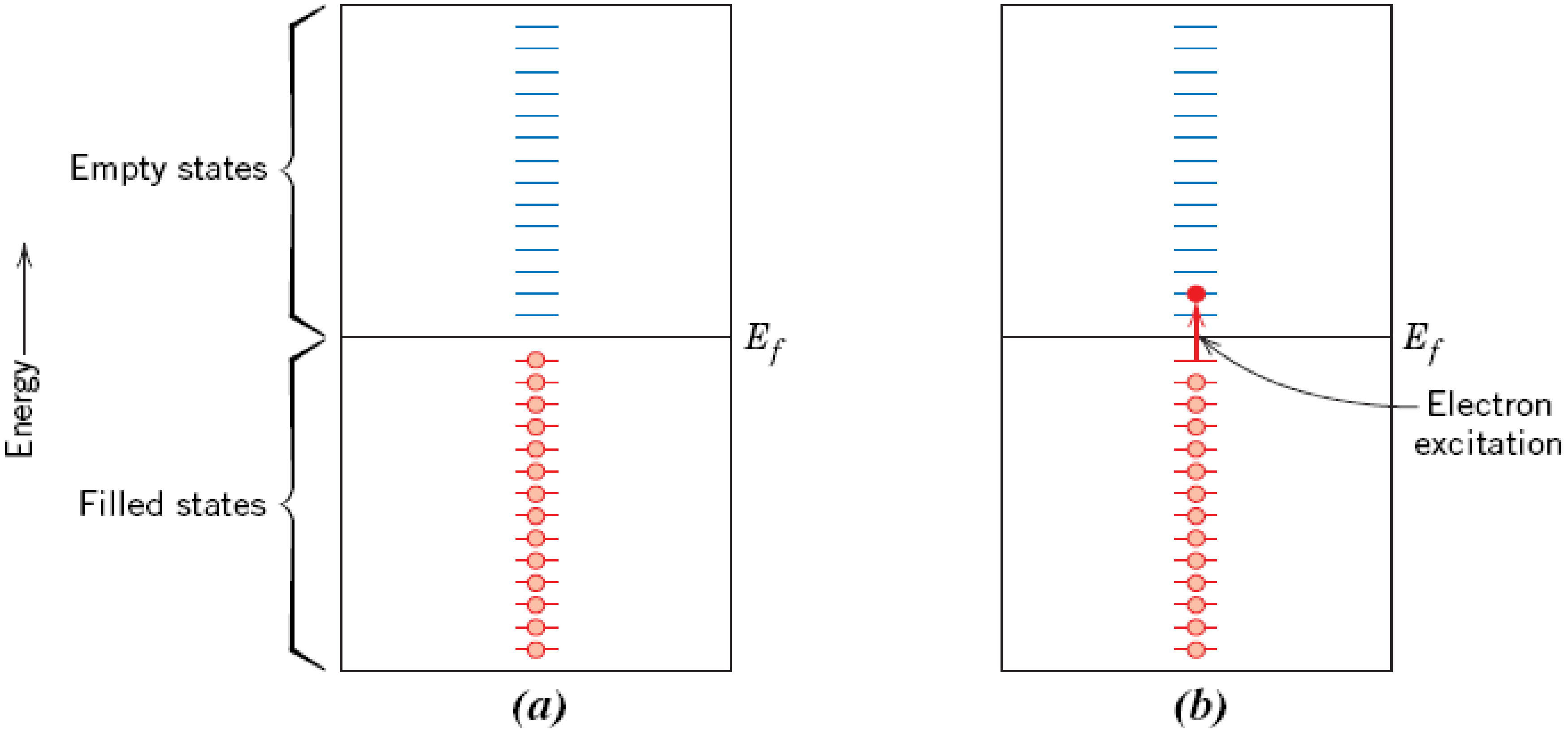
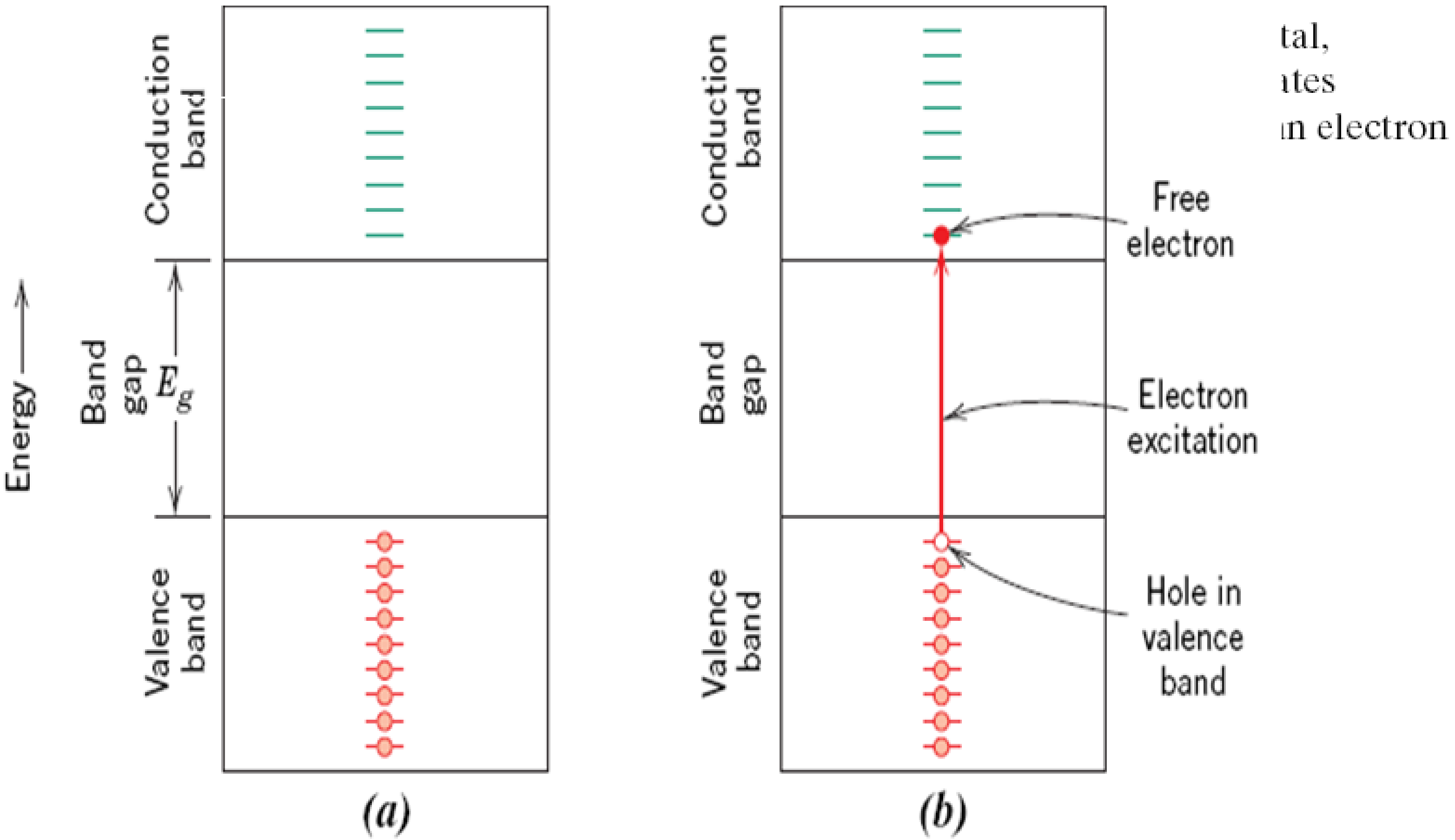


Figure 5 For a metal, occupancy of electron states (*a*) before and (*b*) after an electron excitation.

4. Conduction in terms of band and atomic bonding models

Figure 6. For an insulator or semiconductor, occupancy of electron states (*a*) before and (*b*) after an electron excitation from the valence band into the conduction band, in which both a free electron and a hole are generated.



5.Electron Mobility

- ✓ 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 ترتقي او تنتقل into the conduction band, which gives rise to an enhanced conductivity.
- ✓ The conductivity of insulators and semiconductors may also be viewed from the perspective of atomic bonding models. For electrically insulating materials, interatomic bonding is ionic or strongly covalent. Thus, 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 predominantlyفي الغالب 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.

5.Electron Mobility

- ✓ When an electric field is applied, a force is brought to bear on the free electrons; as a consequence, the **electrons** are accelerated in a direction opposite to that of the field, by virtue of their negative charge بحكم شحنتهم السالبة .
- ✓ all the free electrons should accelerate as long as the electric field is applied, which would give rise to an electric current that is continuously increasing with time until current reaches a constant
- ✓ frictional forces, which counter this acceleration from the external field. These frictional forces result from the scattering of electrons تشتت الالكترونات by imperfections in the crystal lattice عيوب البنية البلورية
- ✓ Each scattering event causes an electron to lose kinetic energy and to change its direction of motion, as represented schematically in Figure 7.
- ✓ The scattering phenomenon is manifested as تبرهن a resistance to the passage of an electric current.

5. Electron Mobility

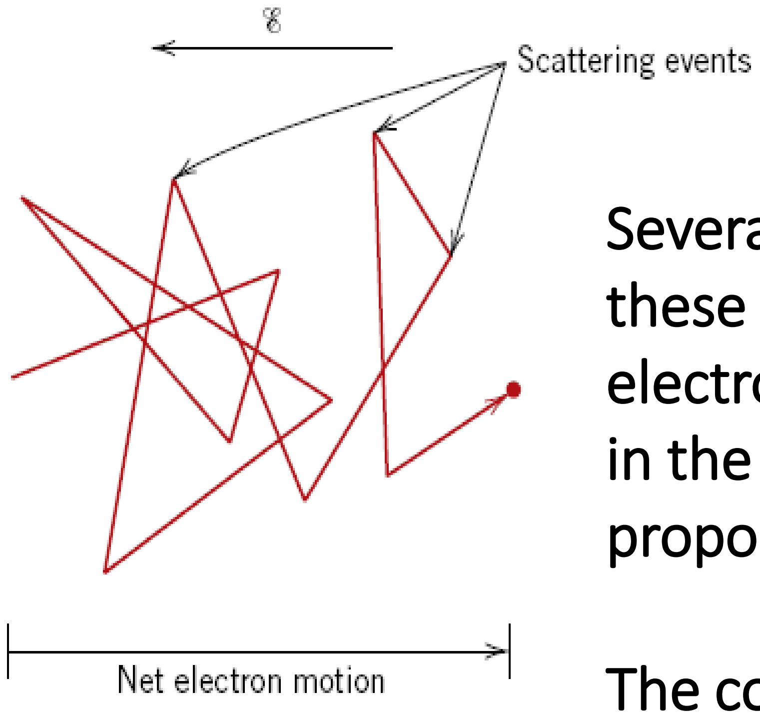


Figure 18.7 Schematic diagram showing the path of an electron that is deflected by scattering events.

Several parameters are used to describe the extent of this scattering; these include the *drift velocity* (V_d) and the electron mobility (μ_e) of an electron. The drift velocity V_d represents the average electron velocity in the direction of the force imposed by the applied field. It is directly proportional to the electric field as follows:

$$V_d = \mu_e E$$

The conductivity of most materials may be expressed as

$$\sigma = n|e|\mu_e$$

where *n* is the number of free or conducting electrons per unit volume $|e|$ is the absolute magnitude of the electrical charge on an electron ($1.6*10^{-19}$ C).

6. Electrical Resistivity Of Metals

As mentioned previously, most metals are extremely good conductors of electricity; room-temperature conductivities for several of the more common metals are given in Table.

Metal	*Electrical Conductivity* $[(\Omega \cdot m)^{-1}]$
Silver	6.8×10^7
Copper	6.0×10^7
Gold	4.3×10^7
Aluminum	3.8×10^7
Brass (70 Cu–30 Zn)	1.6×10^7
Iron	1.0×10^7
Platinum	0.94×10^7
Plain carbon steel	0.6×10^7
Stainless steel	0.2×10^7

6. Electrical Resistivity Of Metals

- ✓ The electrical resistivity versus temperature for copper and three copper–nickel alloys, one of which has been deformed. Thermal, impurity, and deformation contributions to the resistivity are indicated at 100C.
- ✓ Metals have high conductivities because of the large numbers of free electrons that have been excited into empty states above the Fermi energy. Thus n has a large value in the conductivity expression.
- ✓ Total resistivity of a metal is the sum of the contributions from thermal vibrations, impurities, and plastic deformation.
- ✓ Matthiessen's rule— for a metal, is the total electrical resistivity equals the sum of thermal vibrations, impurity, and deformation contributions

$$\rho_{total} = \rho_t + \rho_i + \rho_d$$

Where, ρ_t, ρ_i , and ρ_d represent the individual thermal, impurity, and deformation resistivity contributions,

6. Electrical Resistivity Of Metals

Figure.8 The electrical resistivity versus temperature for copper and three copper–nickel alloys, one of which has been deformed. Thermal, impurity, and deformation contributions to the resistivity are indicated at 100C.
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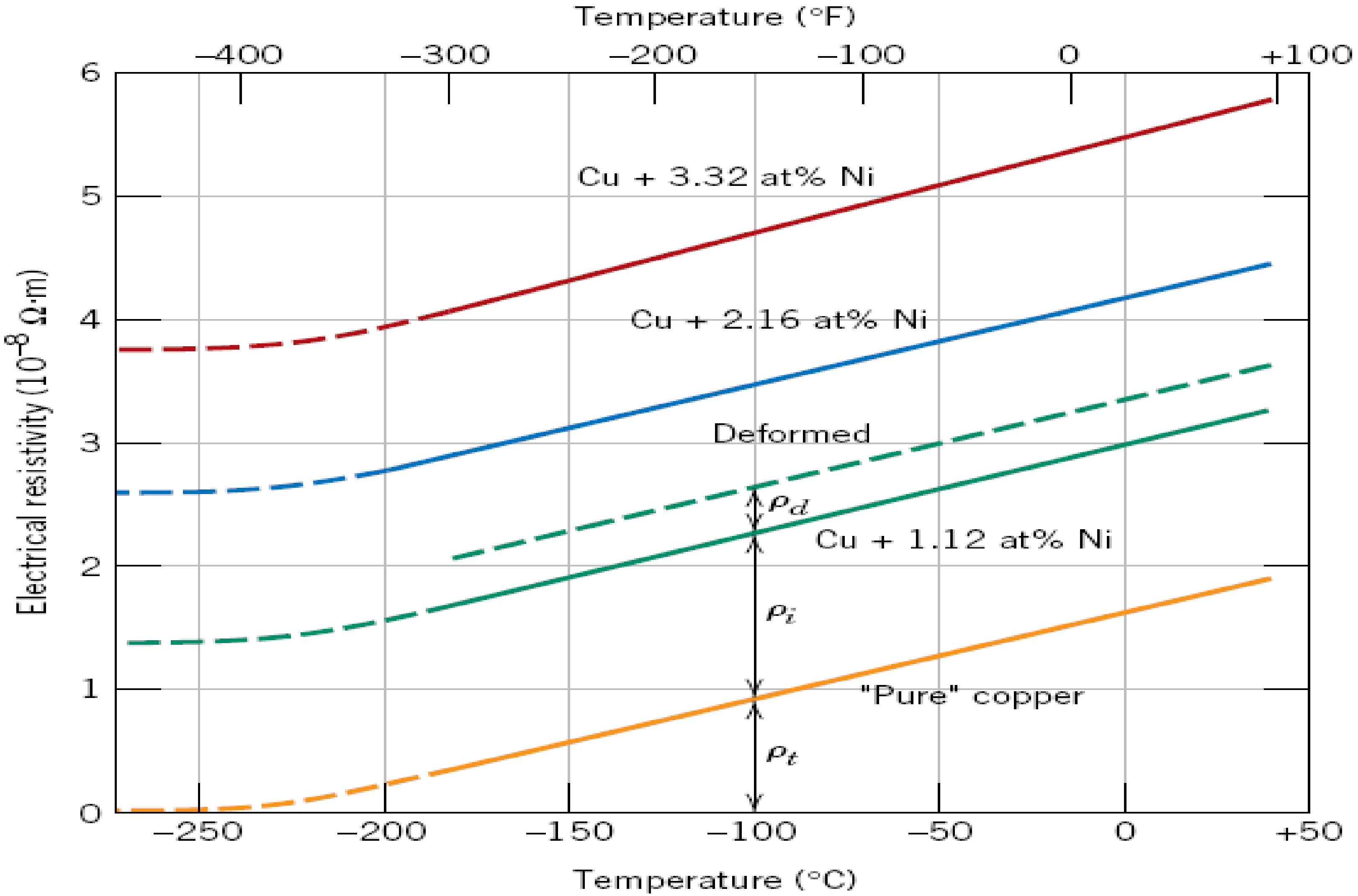

6. Electrical Resistivity Of Metals

1-Influence of Temperature

For the pure metal the resistivity rises linearly with temperature

$$\rho_t = \rho_0 + a\,T$$

Where ρ_0 and *a* are constants for each particular metal. This dependence of the thermal resistivity component on temperature is due to the increase with temperature in thermal vibrations and other lattice irregularities (e.g., vacancies), which serve as electrons scattering centers.

2- Influence of Impurities

The impurity resistivity ρ_i is related to the impurity concentration C_i in terms of the atom fraction (at% /100) as follows:

$$\rho_i = A \times C_i \times (1 - C_i)$$

where A is a composition-independent constant that is a function of both the impurity and host metals.

For a two-phase alloy consisting of α and β phases, a rule-of-mixtures. Impurity resistivity contribution (for two-phase alloy)— dependence on volume fractions and resistivities of two phases

$$\rho_i = \rho_\alpha V_\alpha + \rho_\beta V_\beta$$

6. Electrical Resistivity Of Metals

3. Influence of Deformation

Deformation also raises the electrical resistivity as a result of increased numbers of electron-scattering dislocations. The effect of deformation is much weaker than that of increasing temperature or the presence of impurities.