

Lecture 1: Electrical properties of materials

1 Introduction

Stone Age—Bronze Age—Iron Age—what's next? Some individuals have called the present era the *space age* or the *atomic age*. However, space exploration and nuclear reactors, to mention only two major examples, have only little impact on our everyday lives. Instead, electrical and electronic devices (such as radio, television, telephone, refrigerator, computers, electric light, CD players, electromotor, etc.) permeate our daily life to a large extent. Life without electronics would be nearly unthinkable in many parts of the world. The present era could, therefore, be called the age of electricity. However, electricity needs a medium in which to manifest it and to be placed in service. For this reason, and because previous eras have been named after the material that had the largest impact on the lives of mankind, the present time may best be characterized by the name **Electronic Materials Age**.

Therefore, electronic materials have played a key role in the development of all devices and information – related technologies. Figure (1) gives a broad classification of some of the different electronic materials

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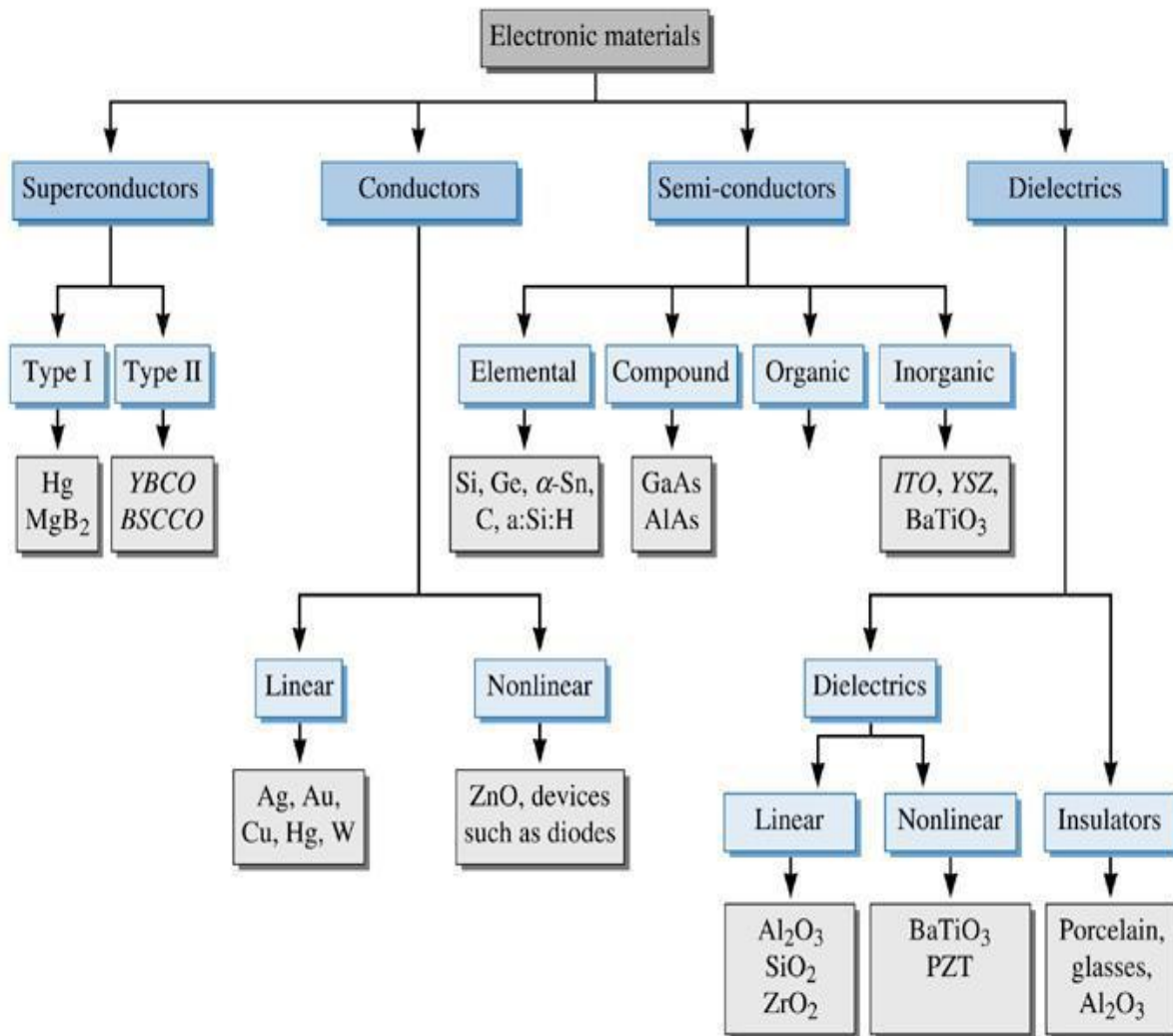


Figure (1): Classification of technologically useful electronic materials.

2- Electrical Properties of Materials

- Engineering materials are important in everyday life because of their versatile structural properties.

Other than these properties, they do play an important role because of their physical properties.

- Prime physical properties of materials include: electrical properties; thermal properties; magnetic properties; and optical properties.
- The electrical behaviors of engineering materials are diverse, and so are their uses in electrical applications.

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Materials are classified based on their electrical properties as conductors, semiconductors, insulators and superconductors.

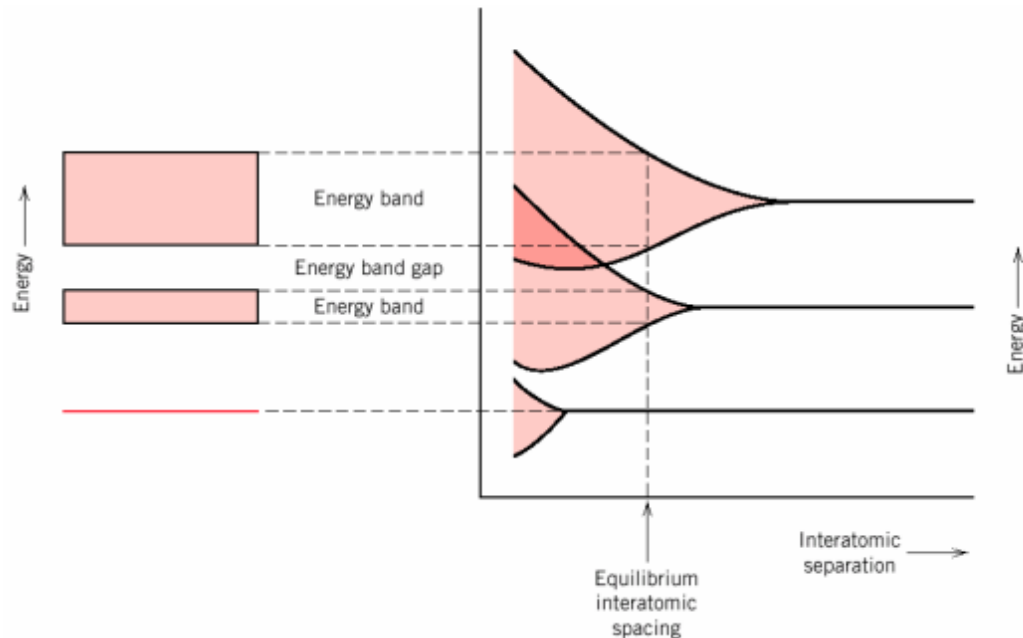
Thus, the prime objective of this chapter is to explore the electrical properties of materials, that is, their responses to an applied electric field. We begin with the phenomenon of electrical conduction: the parameters by which it is expressed, the mechanism of conduction by electrons, and how the electron energy band structure of a material influences its ability to conduct. These principles are extended to metals, semiconductors, and insulators. Particular attention is given to the characteristics of semiconductors and then to semiconducting devices. Also treated are the dielectric characteristics of insulating materials.

3- Electronic And Ionic Conduction: An electric current results 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. Within most solid materials a current arises from the flow of electrons, which is termed electronic conduction. In addition, for ionic materials a net motion of charged ions is possible that produces a current; such is termed ionic conduction.

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. 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. In an isolated atom electrons occupy well defined energy states. When atoms come together to form a solid, their valence electrons interact with each other and with nuclei due to Coulomb forces. In addition, two specific quantum

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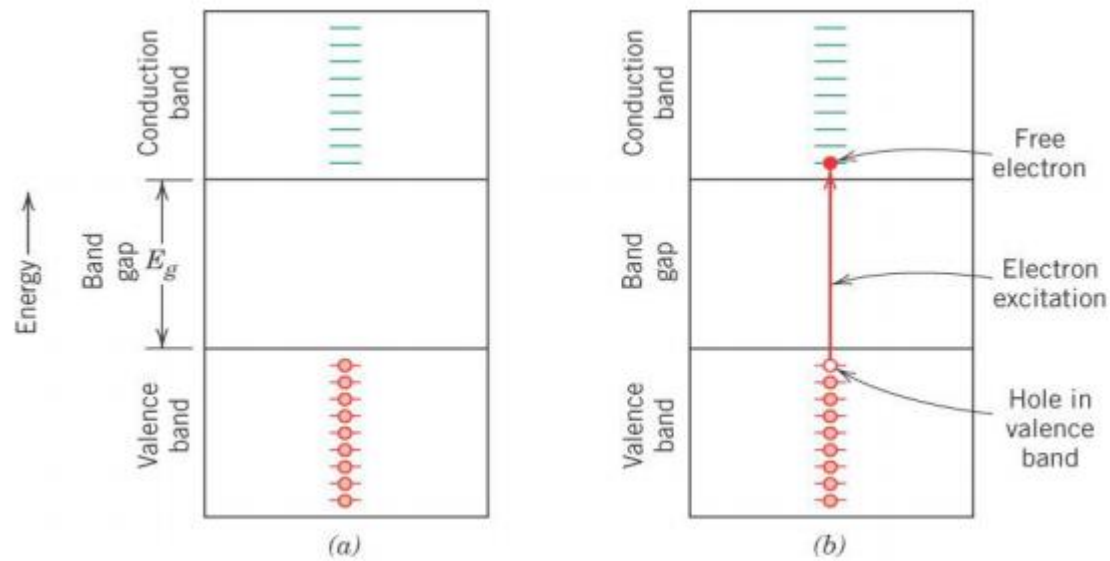
mechanical effects happen. As a result of these effects, the valence electrons of atoms form wide electron energy bands when they form a solid. The bands are separated by gaps, where electrons cannot exist.



Energy Band Structures and Conductivity: The highest filled state at 0 K Fermi Energy (E_f) Fermi level : energy level in solids at which the Fermi-Dirac distribution function is equal to 0.5. The two highest energy bands are:

- *Valence band – the highest band where the electrons are present at 0 K
- *Conduction band - a partially filled or empty energy band where the electrons can increase their energies by going to higher energy levels within the band when an electric field is applied

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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.

4.1 Ohm's Law

One of the most important electrical characteristics of a solid material is the ease with which it transmits an electric current. **Ohm's law** relates the potential difference, V (in volts (J/C)), with the electrical resistance, R (in ohms i.e. Ω (V/A)), and the electrical current, I (in amp or A (C/s)). as follows:

$$V = IR$$

This law is applicable to most but not all materials. The resistance R is the resistance of the material through which the current is passing. The value of R is influenced by specimen configuration (size, shape); materials properties; and for many materials is independent of current.

$$R = \rho \frac{l}{A}$$

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where l is the length (cm) of the resistor, A is the cross-sectional area (cm²) of the resistor. The ρ is the **resistivity or Electrical resistivity** (Ohm.cm or Ω .cm). From the expression for Ohm's law and Eq. (2)

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

Therefore, resistivity ρ ; either dependence on *resistance, specimen cross-sectional area, and distance between measuring points*; or dependence on *applied voltage, current, specimen cross-sectional area, and distance between measuring point*. Figure (2) is a schematic diagram of an experimental arrangement for measuring electrical resistivity.

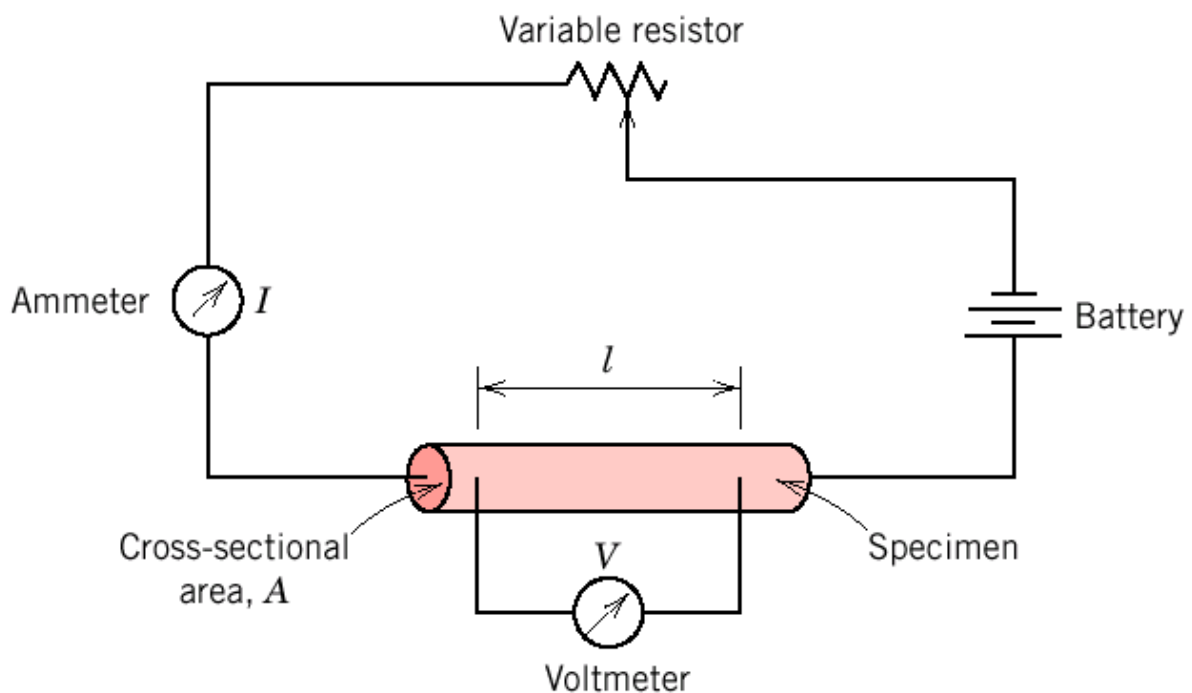


Figure (2): Schematic representation of the apparatus used to measure electrical

4.2 Electrical Conductivity

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

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

and is indicative of the ease of electric current flow through the material. The units for σ are reciprocal ohm.cm $[(\Omega \cdot \text{cm})^{-1}]$.

The following discussion on electric properties through other forms, as follows:

Power loss P (watts) due to conduction is given by

$$P = VI = I^2R$$

A second form of Ohm's law is obtained if combined Equations (1), (2) and (4) to give:

$$\frac{I}{A} = \sigma \frac{V}{l}$$

Since I/A is the **current density** J (A/cm^2), *the current per unit of specimen area* and V/l is the **electric field intensity** E (V/cm) or *the voltage difference between two points divided by the distance separating them*, then:

$$J = \sigma E$$

Eq. (5) is Ohm's law expression *in terms of current density, conductivity, and applied electric field*.

A third form is determine the electrical conductivity σ through carriers mobility, as follows:

The current density J can also determine by

$$J = nq\bar{v}$$

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Where n is the number of charge carriers (carries/cm³), q is the charge on each carrier (1.6×10^{-19} C), and \bar{v} is the average drift velocity (cm/s) at which the charge carriers move and $\bar{v} = \Delta x / \Delta t$ or λ_e / τ , where λ_e mean free bath of electron, τ the average time between collision or relaxation time .

Thus:

$$\sigma E = n \cdot q \cdot \bar{v} \quad \text{or} \quad \sigma = nq \frac{\bar{v}}{E}$$

The term \bar{v}/E is called the **mobility** μ (cm²/V.s) of the carriers (in the case of metals this is the mobility of electrons):

$$\mu = \frac{\bar{v}}{E}$$

Finally:

$$\sigma = n \cdot q \cdot \mu$$

From Eq. (6), electrical conductivity of a material can be controlled by (i) controlling number of charge carriers, n or (ii) controlling the mobility of the carriers, μ .

Mobility is important for metals or electrical conductors, whereas number of carriers is important for semiconductors and insulators. Thus Eq. (6) will be

1- for metals and alloys

$$\sigma = n_e \cdot q_e \cdot \mu_e$$

2- for semiconductors :

$$\sigma = n \cdot q \cdot \mu_n + p \cdot q \cdot \mu_p$$

3- for ionic materials:

$$\sigma_{total} = \sigma_{electronic} + \sigma_{ionic}$$

$$\sigma_{total} = n_e \cdot q_e \cdot \mu_e + n_{ion} \cdot q_{ion} \cdot \mu_{ion}$$



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Electrical conduction in metals and alloys occurs by the motion of electrons. It can be shown that the conductivity is proportional to the number of electrons per unit volume ne , the charge of electron qe , and the *electron mobility* μ_e , as in Eq. (6a).

In Eq. (6b), μ_n and μ_p are the mobilities of electrons and holes, respectively. The terms n and p represent the concentrations of free electrons and holes in the semiconductor.

In ionic materials, both cations and anions in ionic materials possess an electric charge and, as a consequence, are capable of migration or diffusion when an electric field is present. Thus an electric current will result from the net movement of these charged ions, which will be present in addition to current due to any electron motion. Of course, anion and cation migrations will be in opposite directions. The total conductivity of an ionic material σ_{total} is thus equal to the sum of both electronic and ionic contributions, as in Eq. (6c). Either contribution may predominate depending on the material, its purity, and temperature.

Mobility may be associated with each of the ionic species as follows:

$$\mu_{ion} = \frac{e \cdot D_{ion}}{k_B T}$$

where n_{ion} and D_{ion} represent, respectively, the valence and diffusion coefficient of a particular ion; e , k , and T are electron charge, Boltzmann's constant and temperature, respectively. Thus, the ionic contribution to the total conductivity increases with increasing temperature, as does the electronic component. However, in spite of the two conductivity contributions, most ionic materials remain insulated, even at elevated temperatures.

Solid materials exhibit an amazing range of electrical conductivities because of affected any of these three quantities (n , q , μ), extending over

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27 orders of magnitude, as show in Figure (4); probably no other physical property experiences this breadth of variation. 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: *conductors*, *semiconductors*, and *insulators*. **Metals** are good conductors, typically having conductivities on the order of 10^7 ($\Omega\text{-m}$)⁻¹. At the other extreme are materials with very low conductivities, ranging between 10^{-10} and 10^{-20} ($\Omega\text{-m}$)⁻¹; these are electrical **insulators**. Materials with intermediate conductivities, generally from 10^{-4} to 10^4 ($\Omega\text{-m}$)⁻¹, are termed **semiconductors**. Table (1), include electrical conductivity of selected materials. Table (2), include some useful units and relationships.

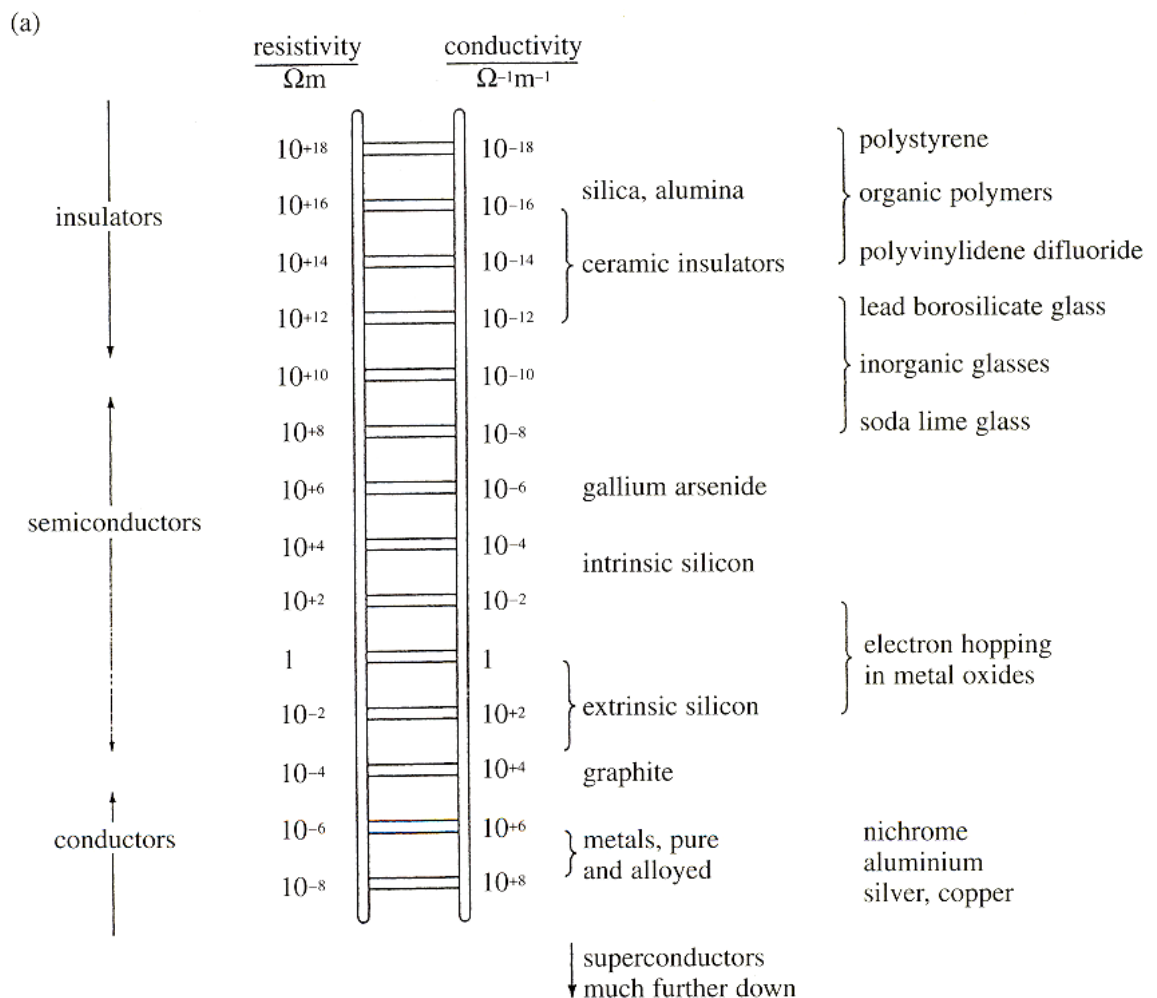


Figure (4): Room-temperature conductivity of various materials.

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Example 1 : (a) Compute the electrical conductivity of a 7.0mm (0.28in.) diameter cylindrical silicon specimen 57 mm long in which a current of 0.25 A passes in an axial direction. A voltage of 24 V is measured across two probes that are separated by 45 mm. (b) Compute the resistance over the entire 57 mm of the specimen.

Sol :

(a) $\sigma = 1/\rho = I L / VA = I l / V\pi(d/2)^2$ And, incorporating values for the several parameters provided in the problem statement, leads to

$$\sigma = (0.25A)(45 \times 10^{-3}m) / (24V)(\pi)(7.0 \times 10^{-3}m/2)^2 = 12.2 (\Omega\text{-m})^{-1}$$

(b) $R = L / \sigma A = L / \sigma\pi(d/2)^2 = 57 \times 10^{-3}m / [12.2(\Omega\text{-m})^{-1}] (\pi)(7.0 \times 10^{-3}m/2)^2 = 121.4 \Omega$.

Example 2: (a) Calculate the drift velocity of electrons in silicon at room temperature and when the magnitude of the electric field is 500 V/m. (b) Under these circumstances, how long does it take an electron to traverse a 25mm length of crystal? Since the room temperature mobility of electrons is 0.14 m²/V-s

Sol :

(a) $V^- = \mu E = (0.14 \text{ m}^2 / \text{V}\cdot\text{s})(500 \text{ V/m}) = 70 \text{ m/s}$

(b) The time, t, required to traverse a given length, L (= 25 mm), is just

$$V^- = L / t \text{ when } t = L / V^- = 25 \times 10^{-3}m / 70 \text{ m/s} = 3.6 \times 10^{-4} \text{ s} .$$

Example 3 : At room temperature the electrical conductivity and the electron mobility for aluminum are $3.8 \times 10^7 (\Omega\text{-m})^{-1}$ and $0.0012 \text{ m}^2 / \text{V}\cdot\text{s}$ respectively.

Compute the number of free electrons per cubic meter for aluminum at room temperature.

Sol :

$$n = \sigma / nq\mu = 3.8 \times 10^7 (\Omega\text{-m})^{-1} / (1.602 \times 10^{-19} \text{ C})(0.0012 \text{ m}^2 / \text{V}\cdot\text{s}) = 1.98 \times 10^{29} \text{ m}^{-3} .$$

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Example4: Calculation of Drift velocity of electrons in copper (valence =1)

Assuming that all of the valence electrons contribute to current flow,

(a) calculate the mobility of an electron in copper and

(b) calculate the average drift velocity for electrons in a 100cm copper wire when 10V are applied.

Data: conductivity of copper = $5.98 \times 10^5 (\Omega \cdot \text{cm})^{-1}$; $q = 1.6 \times 10^{-19} \text{C}$; lattice parameter of copper = $0.36151 \times 10^{-7} \text{cm}$; copper has a FCC structure

The equation that we need to apply is:

$$\sigma = nq\mu$$

n is the number of carriers. q is the charge . μ is the mobility

Number of carriers (n): The valence of copper is 1. Therefore, the number of valence electrons equals the number of copper atoms in the material.

$$n = \frac{(\text{atoms / cell})(\text{electrons / atoms})}{\text{cell_volume}} = \frac{4 \times 1}{(0.36151 \times 10^{-7} \text{cm})^3} = 8.466 \times 10^{22} \text{ electrons / cm}^3$$

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Part (a)

$$\mu = \frac{\sigma}{nq} = \frac{5.98 \times 10^5 \Omega^{-1} \cdot \text{cm}^{-1}}{(8.466 \times 10^{22} \text{ electrons/cm}^3)(1.6 \times 10^{-19} \text{ C})} = 44.2 \frac{\text{cm}^2}{\Omega \cdot \text{C}} = 44.2 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}$$

Note : 1amp = 1Coulomb / second

Part (b)

The electric field intensity is: $\xi = \frac{V}{L} = \frac{10\text{V}}{100\text{cm}} = 0.1\text{V} \cdot \text{cm}^{-1}$

The equation we need to use is

$$\bar{v} = \mu \xi$$

$$\bar{v} = \left(44.2 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}\right) \left(0.1 \frac{\text{V}}{\text{cm}}\right) = 4.42 \text{cm/s}$$

H.W1: The power lost in a 2-mm-diameter copper wire is to be less than 250 W when a 5-A current is flowing in the circuit. What is the maximum length of the wire? (conductivity of copper = $5.98 \times 10^5 (\Omega \cdot \text{cm})^{-1}$).

H.W2 : In a welding process, a current of 400 A flows through the arc when the voltage is 35 V. The length of the arc is about 0.1 in. and the average diameter of the arc is about 0.18 in. Calculate the current density in the arc, the electric field across the arc, and the electrical conductivity of the hot gases in the arc during welding.

H.W3: We apply a voltage of 10 V to an aluminum wire 2 mm in diameter and 20 m long. If 10% of the valence electrons carry the electrical charge, calculate the average drift velocity of the electrons. Data: conductivity of Aluminum = $3.77 \times 10^5 (\Omega \cdot \text{cm})^{-1}$; lattice parameter of Aluminum = $4.04958 \times 10^{-8} \text{ cm}$; Aluminum has a FCC structure.