ELECTRIC CURRENT

Different substances vary considerably in their electrical properties. It is useful to classify substances as conductors, semiconductors and insulators. In conductors, free charges can move freely under the influence of an electric field applied between the ends of the conductor, whereas, in insulators there are normally extremely few mobile charge carries.

A flow of electric charge from one place to another is called an electric current. The magnitude of an electric current $I$ is the rate charge passing a given cross-section

$$I = \frac{\Delta q}{\Delta t}$$

where $\Delta q$ is the amount of charge passing a given cross-section in the time interval $\Delta t$.

**S.I. units**
- time $t$ [seconds s]
- charge $q$ [coulombs C]
- current $I$ [amperes A, $1\, \text{A} = \,1\, \text{C.s}^{-1}$]
Consider a current \( I \) through a cylinder as shown in figure 1.

![Diagram of current through a cylinder](image)

All charges \( q \) within the shaded volume \( V \) will move on average to the left with an average velocity \( v_{\text{drift}} \) (drift velocity) so that they will all pass through the cross-section \( A \) in the time interval \( \Delta t \).

Number density (charges/volume) \( n = N / V \)

Amount of charge passing through \( A \) in time \( \Delta t \)

\[ \Delta q = N \cdot q = (N/V) \cdot q \cdot V = n \cdot q \cdot A \cdot v_{\text{drift}} \cdot \Delta t \]

Current through cylinder

\[ I = \Delta q / \Delta t \]

\[ I = n \cdot q \cdot A \cdot v_{\text{drift}} \]

Fig. 1. Current through a cylinder.

From figure 1, the current \( I \) depends upon the **number density** \( n \) (number of moving charges per unit volume) of the material, the charge on each charge carrier \( q \), the cross-sectional area \( A \) of the material and the **drift velocity** \( v_{\text{drift}} \) (average velocity) of the mobile charge carriers. The direction of current is defined to be in the same direction as positive charges **would** move (if electrons move to the left, then the current would be directed to the right).

\[
I = n \cdot q \cdot A \cdot v_{\text{drift}}
\]

Nearly all materials fall into two categories, **conductors** through which currents can flow easily, and **insulators**, through which currents have great difficulty in flowing. Metals are good conductors of electric current due to the metallic bonding where the number density \( n \) is large because about one electron per atom is not tightly bound to any one atom. For insulators, the number density is low since most electrons are shared between atoms in covalent bonds. Several materials such as germanium and silicon are **semiconductors** because their ability to conduct a current lies between that of conductors and insulators. Nearly all actual current consists of the flow of electrons, which owing to their small mass, are able to move more rapidly than other more massive particles. However, in semiconductor materials, the charge carriers are electrons and **holes** ("missing electron" that acts like a positive charge with the mass of an electron).
The current between two points depends upon the potential difference between those two points and the medium separating the two points. For metals, this current \( I \) is directly proportional to the potential difference \( V \) and the constant of proportionality is called the resistance \( R \). This relationship is expressed as Ohm’s Law

\[
I = \frac{V}{R}
\]

**Ohm’s Law**

\( R \) = constant at constant temperature

**S.I. units**

- current \( I \) [amperes A, \( 1 \text{ A} = 1 \text{ C.s}^{-1} \)]
- potential difference (voltage) \( V \) [volts, \( V \)]
- resistance \( R \) [ohms \( \Omega \)]

The resistance \( R \) of a conductor depends upon:

1. The material of which it is composed which is specified by the materials

   - **resistivity** \( \rho \) [rho \( \Omega.m \)] or its **conductivity** \( \sigma \) [sigma \( \Omega^{-1}.m^{-1} \)] where \( \sigma = \frac{1}{\rho} \).

   The greater value for the resistivity of the material (or the lower the value of its conductivity), the lower its ability to conduct a current. The resistivity of metals varies widely, with silver and copper having low values compared to iron and lead.

2. The length \( L \) of the conductor. The greater \( L \) is, the greater the value of the resistance \( R \).

3. The cross-sectional area \( A \) of the conductor. The greater \( A \), the smaller the value of the resistance \( R \).

A simple equation summaries the above dependence

\[
R = \rho \frac{L}{A} = \frac{1}{\sigma} \frac{L}{A}
\]

**Table:**

<table>
<thead>
<tr>
<th>solid</th>
<th>Resistivity ( \rho ) ( [\Omega.m] \text{ at } 20^\circ \text{C} )</th>
<th>Conduction Electrons ( n ) ( [\text{m}^{-3}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>( \sim 1.60 \times 10^{-8} )</td>
<td>( \sim 10^{23} )</td>
</tr>
<tr>
<td>Copper</td>
<td>( \sim 1.7 \times 10^{-8} )</td>
<td>( \sim 10^{23} )</td>
</tr>
<tr>
<td>Iron</td>
<td>( \sim 10 \times 10^{-8} )</td>
<td>( \sim 10^{23} )</td>
</tr>
<tr>
<td>germanium</td>
<td>semiconductor</td>
<td>( \sim 5 \times 10^{14} )</td>
</tr>
<tr>
<td>silicon</td>
<td>semiconductor</td>
<td>( \sim 6 \times 10^{12} )</td>
</tr>
<tr>
<td>diamond</td>
<td>insulator</td>
<td>( \sim 10^{12} )</td>
</tr>
</tbody>
</table>

The electrical properties of solids can be explained fully by the concepts of quantum physics. When a large number of electrons are brought together to form a solid, the total number of quantum states available for the electrons remains the same as the number available in the isolated atoms. This means that the individual energy levels of an isolated atom are perturbed so that in the solid these energy levels are grouped into energy bands.
ENERGY BANDS

When atoms are brought as close together as those in a crystal, they interact with one another to such an extent that their outer electron shells constitute a single system of electrons common to the entire array of atoms that form the solid. The energy levels of the electrons are altered by the mutual interaction between the atoms. The shift in energy levels is greater for the outer most electron shells. For $N$ atoms comprising the solid, there are $N$ different energy levels for each individual energy level of an atom and these levels form energy bands. That is, these energy bands are actually composed of a multitude of individual levels, as many as there are atoms in the crystal, the energy levels being so close to one another as to form a continuous distribution. An electron in a crystal can only have an energy that falls within one of these energy bands.

The energy bands in a crystal may or may not overlap. If they do not overlap, the gaps between them represent energy values which electrons in the crystal can’t have. The gaps are known as **forbidden bands**. The energy bands contain all the possible energies that can be possessed by electrons. The electrical properties of crystalline solids depend upon its energy band structure and the way in which these bands are normally occupied by electrons.

The first empty energy band is referred to as the **conduction band**. The highest energy band that is occupied by electrons is referred to as the **valence band**. For a current to flow through the solid, it is necessary for electrons to gain extra energy and move from the valance band to the conduction band. These electrons must gain sufficient energy to jump across any energy gap.
Diamond is an insulator at room temperatures because there is a large energy gap (~6 eV) between the conduction band and the valence band. That is, a minimum of 6 eV of additional energy must be given to an electron in a diamond crystal if it is capable of free motion, since it can’t have an energy lying in the forbidden band. Such an energy increment can’t be given readily to an electron in a crystal by an electric field (figure 3).

Germanium and silicon are semiconductors and have a similar structure to diamond, and, as in diamond, an energy gap separates the conduction and valence bands. The energy gap for diamond is 5.2 eV, however it much small in germanium (0.67 eV) and silicon (1.12 eV). At very low temperatures germanium and silicon are hardly better than diamond as a conductor. But, at room temperatures, a small proportion of electrons can possess enough kinetic energy of thermal origin to migrate from the valence band into the conduction band. These few electrons are sufficient to permit a limited amount of current to flow when an electric field is applied. Thus germanium and silicon have a resistivity intermediate between those of conductors and insulators and hence they are classified as semiconductors.

Germanium was the first semiconductor to be used (because it could be obtained in a pure form at that time, but silicon could not), but, today silicon is the most used semiconductor material. The band gap in germanium is only about half the value for silicon. Devices made from germanium suffered from thermal effects much more so than silicon devices because variations in temperature affects the number of electrons in the conduction band of germanium (smaller band gap) more than in silicon.
Metals are conductors because there is no energy gap \( E_{gap} = 0 \) between the conduction and valence bands. The higher energy bands can overlap or the valence band is not completely filled with electrons. Consider the metal sodium with the electron configuration \( 1s^2 \, 2s^2 \, 2p^6 \, 3s^1 \). Sodium atoms have one electron in its outer 3s subshell but this subshell can possess two electrons. This means that the upper energy band in a sodium crystal is only half filled with electrons. When an electric field is applied across a sodium crystal, electrons readily acquire additional energy they need to move up in the band. This additional energy is in the form of kinetic energy of the moving electrons that constitute the electric current through the sodium crystal. The current through a metal is due to the movement of electrons (negative charges) in the conduction band.

![Energy bands in a conductor](image)

**Fig. 5.** Energy bands in a conductor.

![Energy levels for sodium atom and energy bands for sodium crystal](image)

**Fig. 6.** Energy levels for sodium atom and energy bands for sodium crystal.