

Electronics Materials-Conductors and insulators

Conduction mechanisms

Conduction of electricity in materials is by means of 'charge carriers', of which there are three types:

- The best-known example is the electron, with a negative charge of 1.6×10^{-19} C. Electron conduction is the mechanism seen in metals, which have an 'electron cloud'
- A concept that is less easy to understand is the lack of an electron in an electron cloud, which is referred to as a 'hole'. Hole conduction is very important in semiconductors. Each missing electron is equivalent to a positive charge of 1.6×10^{-19} C.
- In ionic materials, the ions can take part in conduction. Each ion will be associated with one or more charges of 1.6×10^{-19} C: 'anions' carry negative charge; 'cations' carry positive charge.

The conductivity of a material depends on three factors:

- How many charge carriers there are
- How much charge each carries
- How mobile the charge carriers are, which will depend on the strength of the local electric field and the structure of the material.

1 In an ionic material, both types of ion make separate contributions to the overall conductivity.

It is clear from Figure 1 that, as regards conductivity, different types of material fall into three radically different categories:

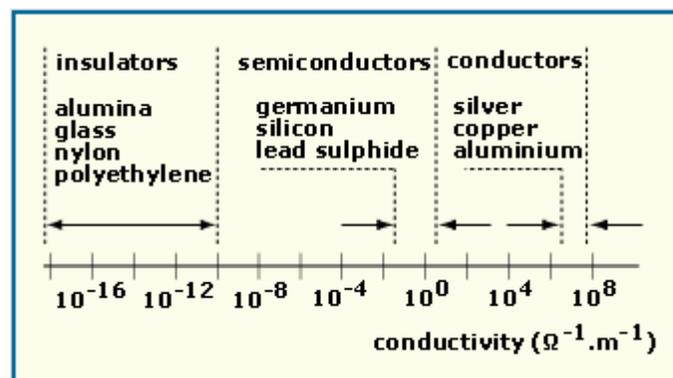


Figure 1: Electrical conductivity ranges for typical materials

These three groups of materials, with their vastly different properties, are very important in electronics. Whilst detailed consideration of the physics behind their conductivity behaviour is beyond the scope and needs of this module, a simple summary is that:

Conductors are metallic materials with loosely attached valence electrons, which can drift freely between the atoms.

Insulators have structures in which all the electrons are tightly bound to atoms by ionic or covalent bonds, so that almost no current flows.

Semiconductors are a class of insulating materials where little energy is needed for the bonds to be broken. This can be supplied by a small applied voltage, releasing valence electrons and creating conductivity as electrons move from one vacated valence site to another.

With semiconductor materials, the intrinsic conductivity is altered greatly by the presence of very small amounts (parts per thousand million) of foreign atoms. During the semiconductor 'doping' process, impurities are added intentionally, either to make more electrons available for conduction (creating an 'n-type' semiconductor) or to create holes into which electrons can move (a 'p-type' semiconductor).

2 You will find more detail in Chapter 8 in Bolton, Engineering Materials Technology and Chapter 15 in Shackelford, Materials Science for Engineers.

Current density

Without an applied electric field, the charge carriers move randomly, at a rate dictated by the temperature. However, when an electric field is applied to a conductor, a gradual drift is superimposed on this random movement.

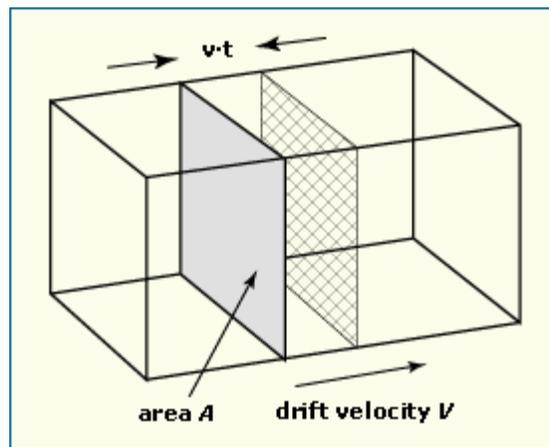


Figure 2: Current flow in a conductor

Figure 2 is a simplification of the situation in a conductor – to start with, there is no indication of any random movement. The current flowing is the rate of movement of charge, so, if there are n free charge carriers in unit volume, the amount of charge moved through the cross section in the conductor during time t is given by the equation

$$I = vAnq$$

where:

q = charge of the charge carrier

v = drift velocity³

This equation is often converted into the form

$$J = \frac{I}{A} = vng$$

where J is called the 'current density'.

This current density concept is very important for the designer, because there are limitations on the achievable current density – what may seem a small current in a cable is an extremely high current density in a fine track. You know what happens to fuses!

³ Metals have very high numbers of free electrons, so drift velocities are actually very small, of the order of microns (μm) per second.

Sheet and volume resistivity

The volume resistivity of a material, symbol ρ (Greek letter rho), is the resistance between opposite faces of a 'unit cube'. For a test piece, the relationship between resistance and resistivity is given by the equation:

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

where

ρ = volume resistivity in ohm.cm

R = resistance in ohms between faces

A = area of the faces

l = distance between faces

Note that this is not resistance per unit volume, which would be ohm/cm³, although this term is sometimes incorrectly used.

The surface resistivity, symbol σ (Greek letter sigma), is the resistance between two opposite edges of a square of film. Using the equation above, where l is the length of each side, and t the thickness of the film:

$$\sigma = R \cdot \frac{A}{l} = R \cdot \frac{(l \cdot t)}{l} = R \cdot t$$

For a constant film thickness, the resistance is independent of the length of the path. The units of surface resistivity are actually ohms, but are more frequently quoted in 'ohms per square' ($\Omega/\text{sq.}$) to avoid confusion with usual resistance values.

The electrical resistance of an insulating material, like that of a conductor, is the resistance offered by the conducting path to the passage of current. Insulating materials are very poor conductors when dry, so that resistance values tend to be in Megohms, rather than ohms. However, the concept of surface resistivity is equally applicable, and you will find this concept when you read about ESD. In the case of insulators, the thickness of the film may be constant, but it is poorly defined – typically conduction takes place in the top layers of the surface and in any contamination or moisture on top of it.

You will also come across the term insulation resistance, which is a measurement of ohmic resistance for a given configuration, rather than a specific resistivity test. For example, insulation resistance is often measured at high voltage, in order to check for electrical safety. In that case, the term 'proof test' is also used.

Resistance changes with environment

Whether we are referring to volume resistivity, surface resistivity or insulation resistance, the values we obtain will depend on a number of factors, including temperature, humidity, moisture content, applied voltage, and the duration of voltage application. Comparing or interpreting data is difficult unless the test is controlled and defined, especially when a specimen is drying out after being subjected to moist or humid conditions. Results can be particularly affected by surface wetting or contamination, which greatly reduce surface resistivity.

Some general points can, however, be made about the likely changes in resistivity and insulation resistance as temperature rises:

- For conductors, increased movement of the atoms interferes more with the electron drift, resulting in an increase in resistance.
- Whilst a very large temperature increase would be necessary to free electrons within their tightly-bound structure, insulators have some slight conductivity, which is caused by the diffusion of ions in the applied field. As the temperature increases, so does the chance of an ion having enough energy to break free, so high temperatures increase diffusion and hence conductivity⁴.
- With semiconductors, an increase in temperature will enable electrons to break free, in the same way as will a small applied voltage. Though the mobility of the electrons decreases with temperature in the same way as for metals, a much larger contribution comes from their greatly increased number, which depends exponentially⁵ on the absolute temperature.

⁴ A particular case of an insulator which becomes a conductor of electricity when heated is soda-silica glass, which contains enough sodium ions for the resistivity at 300°C to be six orders of magnitude lower than at room temperature

⁵ The rate of change of temperature gives useful information about the basic physics of the device

Dielectric properties

Dielectric strength

All insulating materials fail at some level of applied voltage, and 'dielectric strength' is the voltage a material can withstand before breakdown occurs. Dielectric strength is measured through the thickness of the material (taking care to avoid surface effects) and is normally expressed as a voltage gradient (volts per unit length). Note that the voltage gradient at breakdown is much higher for very thin test pieces (<100µm thick) than for thicker sections.

The value of dielectric strength for a specimen is also influenced by its temperature and ambient humidity, by any voids or foreign materials in the specimen, and by the conditions of test, so that it is often difficult to compare data from different sources.

Test variables include electrode configuration and specimen geometry, and the frequency and rate of application of the test voltage. Standard strategies include:

- The 'short-time' test, increasing the voltage from zero at a predetermined rate (usually between 100 and 3,000V/sec) until breakdown occurs
- The 'step-by-step' test, initially applying half the short-time breakdown voltage, and then increasing this in equal increments, holding each level for a set period of time.

Intrinsic dielectric strength

Another test term sometimes used is 'intrinsic dielectric strength', which is the maximum voltage gradient a homogeneous substance will withstand in a uniform electric field. This shows the ability of an insulating material to resist breakdown, but practical tests produce lower values for a number of reasons:

- Defects, voids, and foreign particles introduced during manufacture which lower the dielectric strength locally, having the effect of reducing the test values as the area tested is increased
- The presence of a stress concentration at the electrode edges or points where the electric field is higher than average
- Due to the damaging effect of an electric discharge during testing
- Because of dielectric heating, which raises the temperature and lowers the breakdown strength.

Corona

Another failure mode related to voltage stress failure is 'corona', which is ionisation under voltage stress of air inside or at the interfaces of insulating materials. Breakdown occurs at edges, points, interfaces, voids or gaps at voltages which depend on the materials and part geometries.

Corona erodes the insulator surface by electron bombardment, associated heat, and sometimes secondary effects from the formation of chemical oxidising agents such as ozone and oxides of nitrogen. This effect begins immediately, and even fractions of a second of exposure at AC voltages near to breakdown will significantly reduce the breakdown strength. Corona-induced breakdown will also occur at lower voltages, but the time required will be longer.

Dielectric constant and permittivity

The simplest capacitor structure is a pair of parallel conducting plates separated by a medium called the 'dielectric'. The value of the capacitance between the plates is given by the equation:

$$C = \epsilon \times \frac{A}{t}$$

where:

A = the area of the plates

t = the separation between the plates

and ϵ (Greek letter epsilon) is the absolute permittivity of the dielectric, which is a measure of the electrostatic energy stored within it and therefore dependent on the material.

A more usual way of writing the equation is to replace the absolute permittivity of the dielectric by the product term $\epsilon_0\epsilon_r$, where ϵ_0 is the permittivity of free space (that is, of a vacuum), which has a value of $8.85 \times 10^{-12} \text{ Fm}^{-1}$, and ϵ_r is the relative permittivity, more usually called the 'dielectric constant'. In some literature, you will also find this dimensionless quantity (it is a ratio) referred to as κ (Greek letter kappa).

The dielectric constant of an insulating material is therefore numerically the ratio of the capacitance of a capacitor containing that material to the capacitance of the same electrode system with vacuum replacing the insulation as the dielectric medium.

Nothing is going to have a relative permittivity less than that of a vacuum! All materials will therefore have a dielectric constant greater than 1. Dielectric constants of polymers at room temperature are normally in the range 2 to 10, the lower values generally being associated with the lowest electrical loss characteristics.

The dielectric constant of any given material varies with temperature, and for polymers a rapid increase begins near their glass transition temperature. Dielectric constants also vary as a function of frequency, and this aspect will be important when you look at high frequency designs.

Most materials used for capacitors have substantially higher dielectric constants than polymers, sometimes many tens of thousands. However, this is often achieved at the expense of stability. Most of these high-permittivity dielectrics are ceramics, such as barium titanate and these can be used as fillers in polymers to increase the dielectric constant if this is required.

Dielectric loss

As well as dielectrics breaking down, as described above, most capacitors lose a fraction of the energy when an alternating current is applied. In other words, the dielectric is less than perfect. The simplest model for a capacitor with a lossy dielectric is as a capacitor with a perfect dielectric in parallel with a resistor giving the power dissipation. The current now leads the voltage by a very little less than 90° , where the difference δ (Greek letter delta) is termed the dielectric loss angle, as seen in Figure 3.

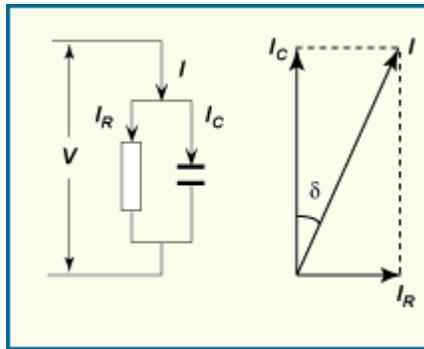


Figure 3: Equivalent circuit for a lossy

Without bothering about the equations, the fraction of the maximum energy lost each cycle, divided by 2π is termed the 'loss factor' and its value is given by $\tan \delta$ ('tan delta'): typically it is values of $\tan \delta$ that you will find quoted in reference material.

Make sure that you understand the difference between losses in the dielectric which happen when alternating current is applied, and for which $\tan \delta$ is the measure, and insulation resistance, which is a function of the direct current that flows when a voltage is applied.

Table 1 shows some typical values of dielectric constant, loss factor, and dielectric strength. The AC values are measured at 1MHz.

Table 1: Some typical values of dielectric parameters

material	ϵ_r	$\tan \delta$	MVm^{-1}
air	1.0006	0	3
polycarbonate	2.3	0.0012	275
FR-4	4.4	0.035	70
alumina	8.8	0.00033	12
barium titanate	1200+	0.01	2

Author: Martin Tarr

Source: http://www.ami.ac.uk/courses/topics/0115_cai/index.html