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## Electrical conduction

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**Electrical conduction** is the movement of electrically charged particles through a transmission medium. The movement can form an electric current in response to an electric field. The underlying mechanism for this movement depends on the material.

Conduction in metals and resistors is well described by Ohm's Law, which states that the current is proportional to the applied electric field. The ease with which current density (current per area)  $j$  appears in a material is measured by the conductivity  $\sigma$ , defined as:

$$\mathbf{j} = \sigma \mathbf{E}$$

or its reciprocal resistivity  $\rho$ :

$$\mathbf{j} = \mathbf{E} / \rho$$

In linear anisotropic materials,  $\sigma$  and  $\rho$  are tensors.

### ***Solids (including insulating solids)***

In crystalline solids, **atoms** interact with their neighbors, and the energy levels of the electrons in isolated atoms turn into **bands**. Whether a material conducts or not is determined by its band structure. Electrons, being fermions, follow the Pauli exclusion principle, meaning that two electrons in the same interacting system cannot occupy the same state, which further means that their four quantum numbers have to be different. Thus electrons in a solid fill up the energy bands up to a certain level, called the Fermi energy. Bands which are completely full of electrons cannot conduct electricity, because there is no state of nearby energy to which the electrons can jump. Materials in which all bands are full (i.e. the Fermi energy is between two bands) are insulators. In some cases, however, the band theory breaks down and materials that are predicted to be conductors by band theory turn out to be insulators. Mott insulators and charge transfer insulators are two such classes of insulators.

### **Metals**

Metals are good conductors because they have unfilled space in the valence energy band. In the absence of an electric field, there exist electrons travelling in all directions and many different velocities up to the Fermi velocity (the velocity of electrons at the Fermi energy). When an electric field is applied, a slight imbalance develops and mobile electrons flow. Electrons in this band can be accelerated by the *field* because there are plenty of nearby unfilled states in the band.

Resistance comes about in a metal because of the scattering of electrons from defects in the lattice or by phonons. A crude theory of conduction in simple metals is the Drude model, in which scattering is characterized by a relaxation time  $\tau$ . The conductivity is then given by the formula

$$\sigma = \frac{ne^2\tau}{m}$$

where  $n$  is the density of conduction electrons,  $e$  is the electron charge, and  $m$  is the electron mass. A better model is the so-called semiclassical theory, in which the effect of the periodic potential of the lattice on the electrons gives them an **effective mass**.

## Semiconductors

A solid with filled bands is an insulator, but at finite temperature, electrons can be thermally excited from the valence band to the next highest, the conduction band. The fraction of electrons excited in this way depends on the temperature and the band gap, the energy difference between the two bands. Exciting these electrons into the conduction band leaves behind positively charged holes in the valence band, which can also conduct electricity. See semiconductor for more details.

In semiconductors, impurities greatly affect the concentration and type of charge carriers. Donor (n-type) impurities have extra valence electrons with energies very close to the conduction band which can be easily thermally excited to the conduction band. Acceptor (p-type) impurities capture electrons from the valence band, allowing the easy formation of holes. If an insulator is doped with enough impurities, a Mott transition can occur, and the insulator turns into a conductor.

## Superconductors

Superconductors are those materials which are neither conductors nor insulators. They are totally dependent on the temperature. As the temperature changes their properties also change. In metals and certain other materials, a transition to the superconducting state occurs at low (sub-cryogenic) temperature. By an interaction mediated by some other part of the system (in metals, phonons), the electrons pair up into **Cooper pairs**. The bosonic Cooper pairs form a superfluid which has zero resistance.

## Electrolytes

Electric currents in electrolytes are flows of electrically charged atoms (ions). For example, if an electric field is placed across a solution of  $\text{Na}^+$  and  $\text{Cl}^-$ , the sodium ions will move constantly towards the negative electrode (anode), while the chlorine ions will move towards the positive electrode (cathode). If the conditions are right, redox reactions will take place at the electrode surfaces, releasing electrons from the chlorine, and allow electrons to be absorbed into the sodium.

Water-ice and certain solid electrolytes called proton conductors contain positive hydrogen ions which are free to move. In these materials, currents of electricity are composed of moving protons (as opposed to the moving electrons found in metals).

In certain electrolyte mixtures, populations of brightly-colored ions form the moving electric charges. The slow migration of these ions during an electric current is one example of a situation where a current is directly visible to human eyes.

## ***Gases and plasmas***

In air, and other ordinary gases below the breakdown field, the dominant source of electrical conduction is via a relatively small number of mobile ions produced by radioactive gases, ultraviolet light, or cosmic rays. Since the electrical conductivity is extremely low, gases are dielectrics or insulators. However, once the applied electric field approaches the breakdown value, free electrons become sufficiently accelerated by the electric field to create additional free electrons by colliding, and ionizing, neutral gas atoms or molecules in a process called avalanche breakdown. The breakdown process forms a plasma that contains a significant number of mobile electrons and positive ions, causing it to behave as an electrical conductor. In the process, it forms a light emitting conductive path, such as a spark, arc or lightning.

**Plasma** is the state of matter where some of the electrons in a gas are stripped or "ionized" from their molecules or atoms. A plasma can be formed by high temperature, or by application of a high electric or alternating magnetic field as noted above. Due to their lower mass, the electrons in a plasma accelerate more quickly in response to an electric field than the heavier positive ions, and hence carry the bulk of the current.

## ***Vacuum***

Since a "perfect vacuum" contains no charged particles, vacuums normally behave as very good insulators. However, metal electrode surfaces can cause a region of the vacuum to become conductive by injecting free electrons or ions through either field emission or thermionic emission. Thermionic emission occurs when the thermal energy exceeds the metal's work function, while field emission occurs when the electric field at the surface of the metal is high enough to cause tunneling, which results in the ejection of free electrons from the metal into the vacuum. Externally heated electrodes are often used to generate an electron cloud as in the filament or indirectly heated cathode of vacuum tubes. Cold electrodes can also spontaneously produce electron clouds via thermionic emission when small incandescent regions (called **cathode spots** or **anode spots**) are formed. These are incandescent regions of the electrode surface that are created by a localized high current flow. These regions may be initiated by field emission, but are then sustained by localized thermionic emission once a vacuum arc forms. These small electron-emitting regions can form quite rapidly, even explosively, on a metal surface subjected to a high electrical field. Vacuum tubes and sphytrons are some of the electronic switching and amplifying devices based on vacuum conductivity.