

Introduction to Electrical Properties

Electrical properties include the response of a material for an applied electric field.

Resistivity

Measure of how strongly a material opposes the flow of electric current.

Resistance

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

Not a property of a material.

Conductivity

Reciprocal of the electrical resistivity.

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

Depends on:

- Number of available charge carriers
- Material's composition
- Material's structure
- Temperature
- Impurities

Electron Mobility

When an electrical field is applied, the free electron in a solid can be accelerated under force applied by electric field.

Force acting on a single electron is $-e\mathbf{E}$. Here:

- e - charge of electron
- \mathbf{E} - electric field strength

In a solid, the electrons are scattered by obstacles such as atom cores/imperfections etc. The electrons have a net drift at the direction opposite to the electric field

Drift Velocity

Average velocity attained by charge carriers accelerated in an electric field.

Note

In a conductor, such as a wire, the charge carriers are typically electrons. Due to thermal motion, electrons in a conductor have random velocities in all different directions.

Carrier Concentration

Number of charge carriers per unit volume. Usually denoted by n .

Current Density

Amount of electric current flows through a unit area.

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

Here:

- n - carrier concentration
- q - charge on a single charge carrier
- \bar{v} - drift velocity
- σ - conductivity
- E - applied electric field

Carrier Mobility

Denoted by μ .

$$\mu = \frac{\bar{v}}{E} \text{ and } \sigma = nq\mu$$

Energy Band Theory

In every atom, electrons occupy discrete energy levels in atomic orbitals, arranged into shells and subshells. In an isolated atom, electrons occupy well-defined energy states.

When N atoms are brought together in a solid, each discrete energy levels will split to N levels, which are closely spaced. The closely spaced energy levels form energy bands.

Energy bands in a solid

- **Valence band**: The highest energy band that can be occupied by electrons at $0K$.
- **Conduction band**: The empty band just above the valence band.

At higher temperatures, electrons which have sufficient energy can jump to conduction band. At this energy level, electrons can move freely through the material.

Fermi Energy

The energy level which is occupied by the highest electron orbital at $0K$.

In absolute zero temperature, electrons settle into lowest available energy states and build a *Fermi Sea* of electron energy states. Fermi energy is the surface of this sea and no electron has energy to rise above this surface.

Fermi Level

The energy level where Fermi-Dirac distribution equals to 0.5.

The closer the Fermi level is to the conduction band energy, the easier it will be for electrons in the valence band to transition into the conduction band.

For an electron to become free, it must be excited or promoted into one of the empty and available energy states above E_f . In metals, this energy is very small. In semiconductors and insulators, this energy is high.

Fermi-Dirac Distribution

In a system which is in thermodynamic equilibrium, the probability of finding an electron in a single energy state E_i at temperature T is given by the Fermi-Dirac (F- D) distribution.

$$f(E_i) = \frac{1}{e^{\frac{E_i - E_f}{k_B T}} + 1}$$

Here:

- E_f - Fermi level
- E_i - Energy of the i th energy state
- K_B - Boltzmann constant
- T - Absolute temperature

At $T=0$

- $E > E_f \implies f(E) = 0$: No electrons above fermi level
- $E < E_f \implies f(E) = 1$: All electrons are below fermi level

At $T>0$

There is more chance that the electrons can be available in conduction band. The chance increases with increasing temperature.

Semiconductivity

Materials with band gap of less than **2.5 eV**.

Holes

When electrons jump into conduction band, it leaves a hole in the valence band. The hole can be treated as a positive charge, having an equal and opposite charge value as an electron.

Under the influence of an electric field, an electron in valence band can jump into a hole, creating new hole in the electron's original position.

Both electrons and holes contribute to the current flow of a semiconductor.

Types of Semiconductors

2 types based on the crystal structure.

- Intrinsic: Made of a pure compound (no dopants)
- Extrinsic: Made of a pure compound and a dopant

Intrinsic Semiconductors

Fermi level lies in between conduction and valence bands. At higher temperatures some electrons can be thermally excited and jump to conduction band.

Conductivity of Intrinsic Semiconductors

Because holes and electrons are equal in count:

$$\sigma = n|e|(\mu_e + \mu_h)$$

Here:

- σ - conductivity
- n - carrier concentration
- e - electron's charge
- μ_e - carrier mobility of electrons
- μ_h - carrier mobility of holes

Note

Hole mobility is generally lower than electron mobility.

In intrinsic semiconductors, conductivity is low due to small number of charge carriers.

Extrinsic Semiconductors

A doped semiconductor. Has more conductivity compared to intrinsic semiconductors.

Doping

Introduction of a foreign atom (impurities) into a intrinsic semiconductor. The foreign atoms are usually either pentavalent (i.e. Sb, P, As) or trivalent (i.e. B, Ga, In).

2 types based on the dopant.

- n-type: When dopant is a pentavalent atom.
- p-type: When dopant is a trivalent atom.

n-type

Increased number of electrons. Fermi level is shifted upwards, due to extra electron energy states (**donor state**).

At room temperature, thermal energy is sufficient to excite the electrons from donor states.

$$\sigma \approx n|e|\mu_e \text{ because } (n_e \gg n_h)$$

p-type

Increased number of holes. Extra hole energy levels are introduced above valence band (**acceptor state**).

At room temperature, electrons in valence band can jump into acceptor state, facilitating movement of holes

$$\sigma \approx n_h|e|\mu_h \text{ because } (n_h \gg n_e)$$

Dielectric behavior

Dielectric material

A material that is electrically insulating (non-metallic) and exhibits (or be made to) exhibit an electric dipole structure.

Electric Dipole Structure

Electric Dipole Structure is the separation of positive and negative electrically charged entities on a molecular or atomic level.

Note

One of the common use cases of dielectric materials is in capacitors.

Electric Polarization

In dielectric materials, the electric dipoles are aligned in one direction due to the presence of the electric field. This process of alignment is called polarization.

Piezoelectricity

Piezoelectric Materials

When a piece of piezoelectric material is mechanically deformed, a current will flow and charge its faces. and vice versa, it will be deformed when exerted to an electrical field.

$$Q = d \times F$$

Here:

- Q - charge stored
- d - charge sensitivity (a material property)
- F - applied force

$$C = \epsilon \frac{A}{t} \implies V = \frac{d}{\epsilon} \sigma t$$

Here:

- V - applied voltage
- d - charge sensitivity
- ϵ - permittivity
- σ - applied stress
- t - thickness

Piezoelectric Transducer

Can be used to measure changes in pressure, force, acceleration, strain by converting them into an electrical signal. The applied force (or pressure) to piezoelectric crystal would generate a voltage.

Conductive Polymers

A class of polymers that conduct electricity. aka. intrinsically conducting polymers.

Unlike traditional polymers, conductive polymers have a conjugated system of double bonds which allows them to conduct electrical charge.

Conjugated polymers

Organic macromolecules that are characterized by a backbone chain of alternating double- and single-bonds.

Their overlapping p-orbitals create a system of delocalized π -electrons, which can result in interesting and useful optical and electronic properties.

Doping can be used to further enhance electrical conductivity of these polymers.

Examples

- Polyaniline (PANI)
- Polypyrrole (PPy)
- Poly(3,4-ethylenedioxythiophene) (PEDOT)
- Polythiophene (PT)