Electrical Properties

Introduction

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.

Temperature coefficient of resistivity

$$\rho = \rho_0 \Big[1 + \alpha(T - T_0) \Big]$$

Here:

- ρ - resistivity at temperature T
- ρ_0 - resistivity at temperature T_0
- α - temperature coefficient of resistivity

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 $-eE$. Here:

- e - charge of electron

- 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.

> (i) **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 flowing through a unit area.

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

Here:

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

Carrier Mobility

Denoted by μ.

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

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. A set of closely spaced energy levels form an energy band. Multiple energy bands are created.

Energy bands in a solid

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

At higher temperatures, electrons which have sufficient energy can jump to conduction band. Electrons can move freely through the material when they are in the conduction band.

Fermi Energy

The energy of the highest electron orbital occupied at $0\,\mathrm{K}$.

In $0\,\mathrm{K}$, 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 at which has 50% probablity for electron occupancy. Fermi level is located at the center between valence band and conduction band for pure elements.

Fermi level of a material affects its electrical properties.

If the Fermi level is close to conduction band, it will be easier 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 (or negative). 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.

$$f(E_i) = \frac{1}{\exp\left(\frac{E_i - E_f}{K_B T}\right) + 1}$$

Here:

- E_f - Fermi level
- E_i - Energy of the i th energy state
- K_B - Boltzmann constant
- T - Absolute temperature
- $\exp()$ - exponent function

Fermi-Dirac distribution of Fermi level is 0.5. From this equation, all materials are insulators at $T = 0$.

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.

Band gap

The energy gap between conduction band and valence band. Aka. forbidden energy gap.

Semiconductivity

Materials with band gap of less than $2.5\,\text{eV}$.

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

Electrons

If the number of electrons is increased, fermi level move towards the conduction band.

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.

If the number of holes is increased, fermi level move towards the valence band.

Types of Semiconductors

2 types based on the crystal structure.

- Intrinsic: Made of a pure compound
- 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 an 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. Extra electron energy states are called as **donor states** and they are formed closer to conduction band.

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 called as **acceptor state**, and they are formed closer to valance band.

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) an electric dipole structure. One of the common use cases of dielectric materials is in capacitors.

Electric Dipole Structure

A structure where the positive and negative charges are separated on atomic or molecular level.

Electric Polarization

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

Uses

- Converting mechanical stresses into electrical signals
- Producing ultrasonic sounds
- Producing X-rays
- Converting sounds to electrical signals
- In nano-precision actuators

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.

Uses

- Organic solar cells
- Microwave-absorbent coatings
- Electroluminescence

Examples

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