Analog Electronics

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Lecture1:

Physics of Semiconductor

Outline

- **Introduction**
    - Electrical resistivity
    - Electrical conductivity
    - Cause of conductivity
        - In metals
        - In semiconductors and insulators
- **Electrical properties of:**
    - Insulator
    - Semiconductor
    - Conductor

Introduction

Electrical resistivity (also called specific electrical resistance or volume resistivity) is a fundamental property of a material that measures how strongly it resists electric current. A low resistivity indicates a material that readily allows electric current. Resistivity is commonly represented by the Greek letter ρ (rho). The SI unit of electrical resistivity is the **ohm-meter (Ω·m)**.

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

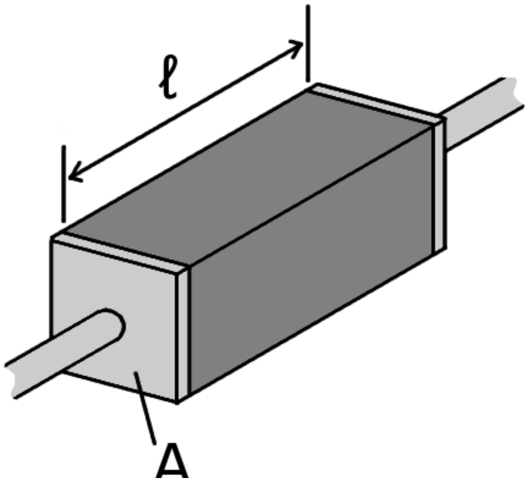


Figure 1: Resistive material with electrical contacts on both ends.:

Where:

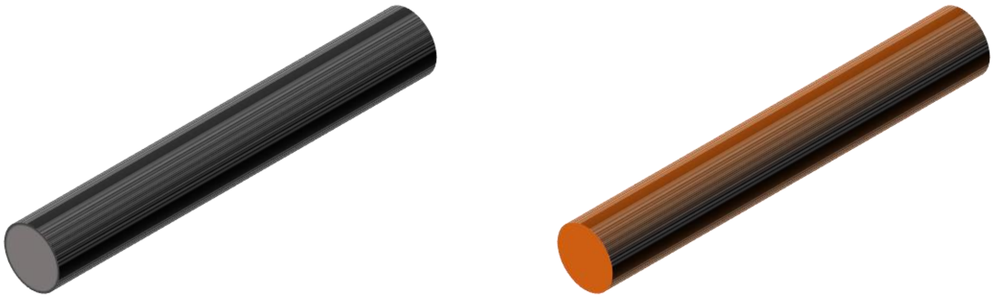
R is the electrical resistance of a uniform specimen of the material

l is the length of the specimen

A is the cross-sectional area of the specimen

Both resistance *R* and resistivity *ρ* describe how difficult it is to make electrical current flow through a material, but unlike resistance, resistivity is an intrinsic property. This means that all pure copper wires (which have not been subjected to distortion of their crystalline structure etc.), irrespective of their shape and size, have the same resistivity, but a long, thin copper wire has a much larger resistance than a thick, short copper wire. Every material has its own characteristic resistivity.

For example, rubber has a far larger resistivity than copper.



$\rho_{Rubber} = 10^{13}\ \Omega\text{-}m$ $\rho_{Copper} = 1.72 \times 10^{-8}\ \Omega\text{-}m$

Figure 2: Resistivity of rubber and copper

Electrical conductivity or specific conductance is the reciprocal of electrical resistivity. It represents a material's ability to conduct electric current. It is commonly signified by the Greek letter σ (sigma). The SI unit of electrical conductivity is **siemens per meter (S/m)**.

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

Where:

σ is the electrical conductivity

ρ is the electrical resistivity

Causes of conductivity

In Metal: A metal consists of a lattice of atoms, each with an outer shell of electrons that freely dissociate from their parent atoms and travel through the lattice. This is also known as a positive ionic lattice. This 'sea' of dissociable electrons allows the metal to conduct electric current. When an electrical potential difference (a voltage) is applied across the metal, the resulting electric field causes electrons to drift towards the positive terminal.

Like balls in a Newton's cradle, electrons in a metal quickly transfer energy from one terminal to another, despite their own negligible movement.

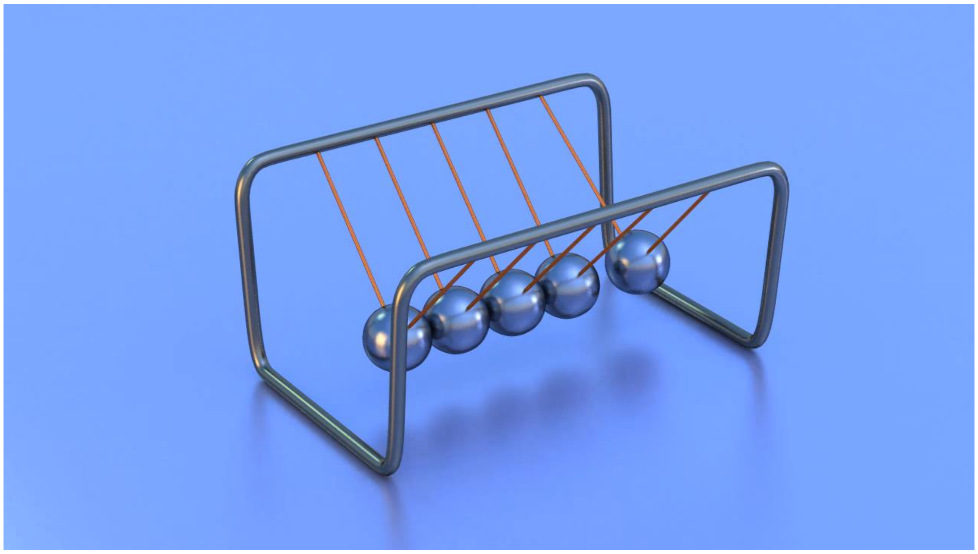


Figure 3: Balls in a Newton's cradle

Most metals have electrical resistance. In simpler models (non quantum mechanical models) this can be explained by replacing electrons and the crystal . by a wave-like structure. When the electron wave travels through the lattice, the waves interfere, which causes resistance. The more regular the lattice is, the less disturbance happens and thus the less resistance. **The amount of resistance is thus mainly caused by two factors:**

First, it is caused by the temperature and thus amount of vibration of the crystal lattice. Higher temperatures cause bigger vibrations, which act as irregularities in the lattice.
Second, the purity of the metal is relevant as a mixture of different ions is also an irregularity.

In semiconductors and insulators

In metals, the Fermi level lies in the conduction band giving rise to free conduction electrons. However, in semiconductors the position of the Fermi level is within the band gap, about halfway between the conduction band minimum (the bottom of the first band of unfilled electron energy levels) and the valence band maximum (the top of the band below the conduction band, of filled electron energy levels). That applies for intrinsic (undoped) semiconductors. This means that at absolute zero temperature, there would be no free conduction electrons, and the resistance is infinite. However, the resistance decreases as the charge carrier density (i.e., without introducing further complications, the density of electrons) in the conduction band increases. In extrinsic (doped) semiconductors, dopant atoms increase the majority charge carrier concentration by donating electrons to the conduction band or producing holes in the valence band. (A "hole" is a position where an electron is missing; such holes can behave in a similar way to electrons.) For both types of donor or acceptor atoms, increasing dopant density reduces resistance. Hence, highly doped semiconductors behave metallically. At very high temperatures, the contribution of thermally generated carriers dominates over the contribution from dopant atoms, and the resistance decreases exponentially with temperature.

Electrical properties of Insulators, Semiconductors and Conductors

Based on the electrical conductivity all the materials in nature are classified as insulators, semiconductors, and conductors

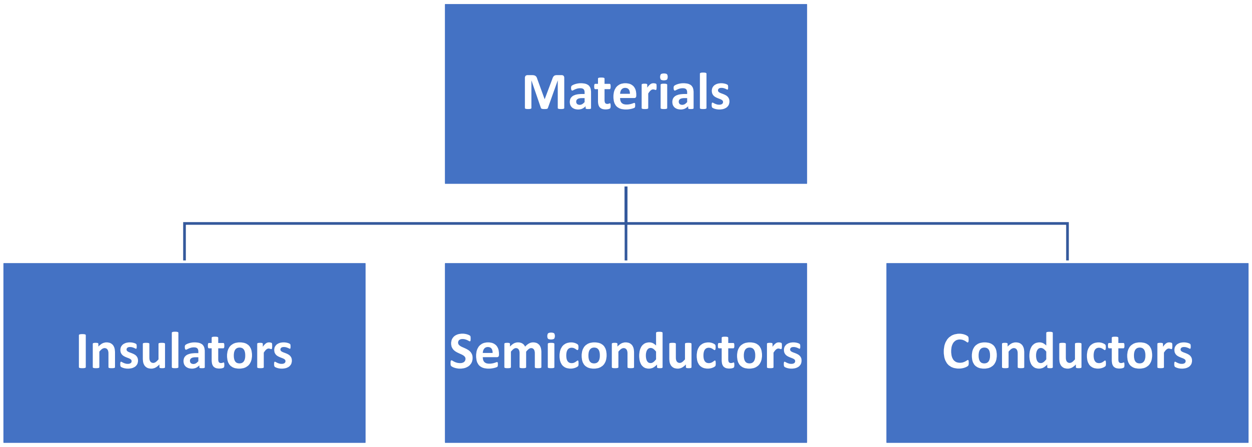


Figure 4: Metrial Electrical classification

Insulators

An insulator is a material that offers a very low level (negligible) of conductivity when voltage is applied. ***Paper, Mica, Glass, Quartz. Plastic, Rubber, ….***

Typical resistivity level of an insulator is of the order of 10^{10} to 10^{12} Ω-cm.

Band structure of a material defines the band of energy levels that an electron can occupy.

Valence band VB: is the range of electron energy where the electron remain bended to the atom and do not contribute to the electric current.

Conduction bend CB: is the range of electron energies higher than valance band where electrons are free to accelerate under the influence of external voltage source resulting in the flow of charge.

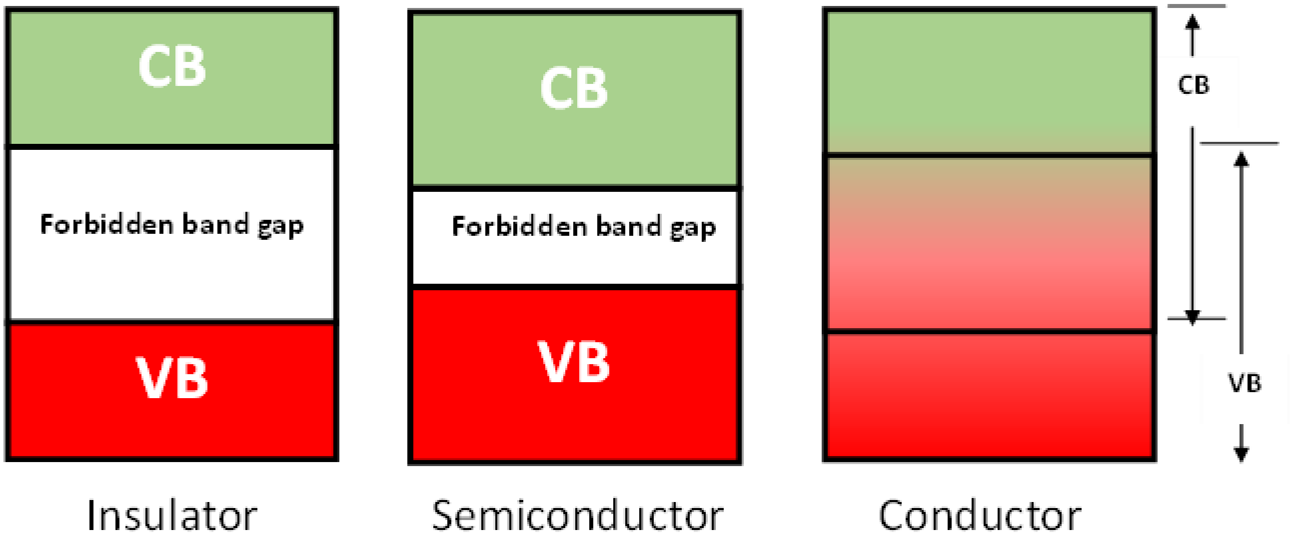


Figure 5: Energy band diagrams insulator, semiconductor and conductor

The energy band between the valance band and conduction band is called as:

Forbidden band gap. It is the energy required by an electron to move from balance band to conduction band i.e. the energy required for a valance electron to become a free electron is:

$$1\ \mathrm{eV} = 1.6 \times 10^{-19}\ \mathrm{J}$$

For an insulator, there is a large forbidden band gap of greater than 5Ev.

Because of this large gap where a very few electrons in the **CB** and hence the conductivity of insulator is poor. Even an increase in temperature or applied electric field is insufficient to transfer electrons from **VB** to **CB**.

Conductors

A conductor is a material which supports a generous flow of charge when a voltage is applied across its terminals. i.e. it has very high conductivity. Eg: ***Copper, Aluminum, Silver, Gold.***

The resistivity of a conductor is in the order of 10^{-4} and 10^{-6} **Ω-**cm. The Valance and conduction bands overlap and there is no energy gap for the electrons to move from valence band to conduction band. This implies that there are free electrons in CB even at absolute zero temperature (0K). Therefore, at room temperature when electric field is applied large current flows through the conductor.

Semiconductor

A semiconductor is a material that has its conductivity somewhere between the insulator and conductor. The resistivity level is in the range of 10 and 10^4 Ω-cm. Two of the most commonly used are ***Silicon (Si=14 atomic no.)*** *and* ***germanium (Ge=32 atomic no.)***. Both have 4 valance electrons. The forbidden band gap is in the order of 1eV. For eg., the band gap energy for Si, Ge and GaAs is 1.21, 0.785 and 1.42 eV, respectively at absolute zero temperature (0K).

A pure form of semiconductors is called as **intrinsic semiconductor**. Conduction in intrinsic SC. is either due to thermal excitation or crystal defects.

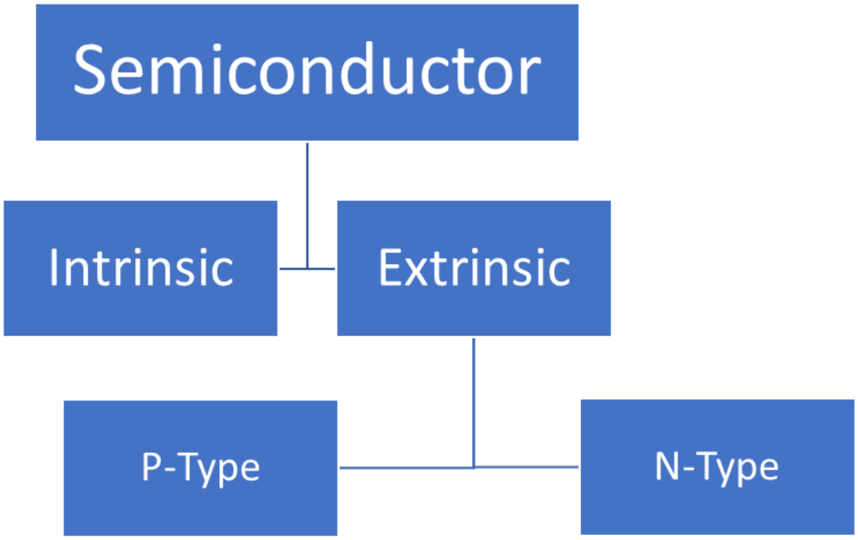


Figure 5: Types of Semiconductors

Si and Ge are the two most important semiconductors used in electronics. Other examples include **Gallium arsenide GaAs, Indium Antimonide (InSb) etc**. Let us consider the structure of Si. A Si atomic no. is 14 and it has 4 valance electrons. These 4 electrons are shared by four neighboring atoms in the crystal structure by means of covalent bond. Fig. 1.2a shows the crystal structure of Si at absolute zero temperature (0K). Hence a pure SC acts has poor conductivity (due to lack of free electrons) at low or absolute zero temperature. The absence of electrons in covalent bond is represented by a small circle usually referred to as hole which is of positive charge. Even a hole serves as carrier of electricity in a manner similar to that of free electron. In a pure semiconductor, the number of holes is equal to the number of free electrons