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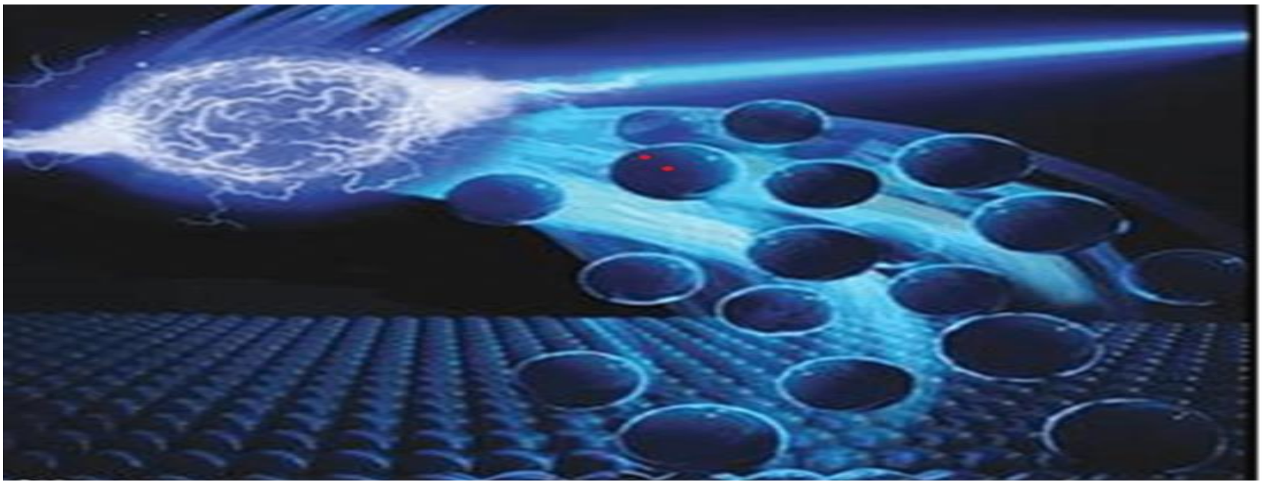
Department of Physics

Polycopy

Functional materials



Directed by:

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Destined for MASTER students

- University year 2024/2025

Preface

This work is designed for MASTER students, option: materials physics. Physics department.

. The content of this course corresponds to the official program of Functional materials taught in the second year master.

This course of Functional materials is constituted of about four chapters, its objective introduces students to understand Optical reflection is a physical phenomenon whereby a light wave thus to understand Properties of Functional Materials :

- the first chapter : Introduction
- The second chapter : Dielectric materials
- The third chapter : Electrical conductivity of solids
- The fourth chapter : Magnetic and optical properties of solids

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Questions

Chapter I: Introduction

Properties of Functional Materials

The main families of materials :

Characteristics of the materials required :

Specific applications :

a. Electronics and Computing

b. Energy

c. Medicine and Biomedicine

d. Environment and Sustainability

Definition :Functional materials

Functional materials are substances which, because of their chemical composition and structure, possess particular properties useful for specific applications.

Solid materials are divided into groups (this division is based essentially on the atomic structure and chemical composition of these solids):

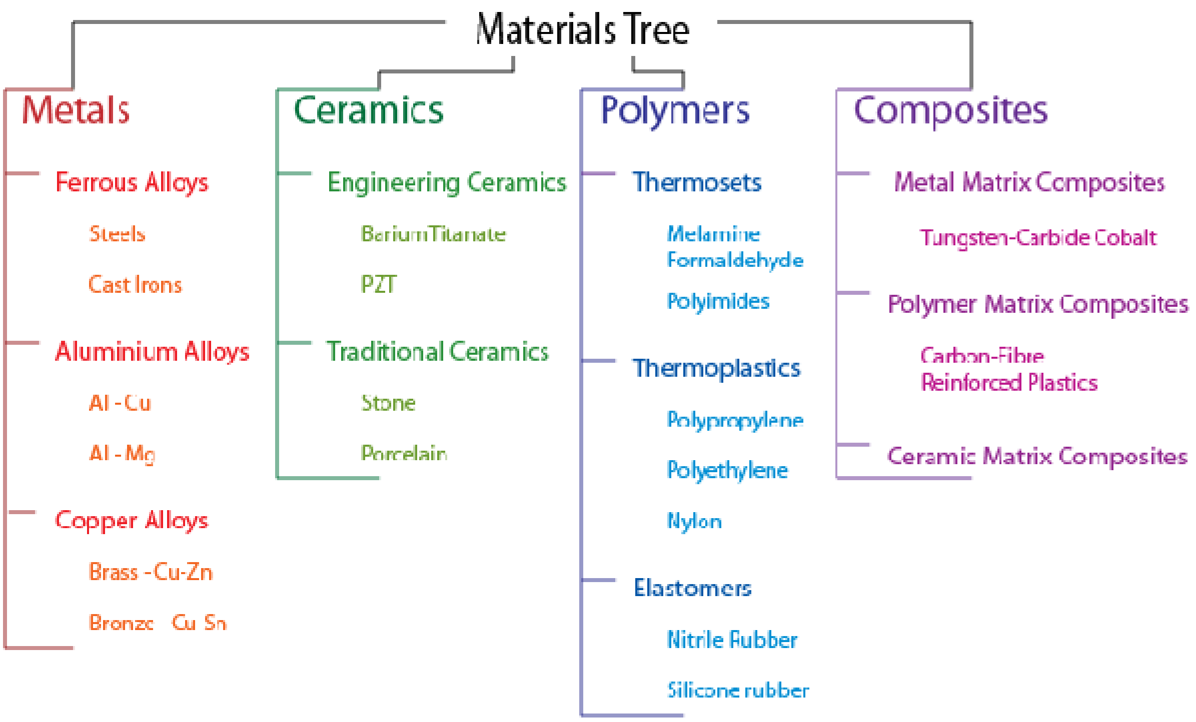
- metals

- ceramics

- polymers

- intermediate materials :

- synthetic materials (so-called intermediate materials): composites, semiconductors and biomaterials.



Properties of Functional Materials

The properties that make these materials functional include :

- Electrical Conductivity: A measure of the material's ability to carry electricity.
- Magnetic Properties: Ability to react to magnetic fields.
- Mechanical Properties: Resilience, hardness and flexibility.

- Chemical Reactivity: How the material interacts with other substances.

- Thermal Behaviour: Ability to conduct or insulate heat.

The main families of materials :

1- Metals and metal alloys (Fe, Al, Cu, steels, etc.): Plasticity (ductility), mechanical strength and toughness, electrical and thermal conductivity.

2- Inorganics [Ceramics (Al2O3, Si3N4, SiC, etc.) and Glass]: Rigidity, hardness, mechanical strength, low toughness (brittleness), chemical and thermal resistance.

3- Organics [Polymers (Thermoplastics, Elastomers etc.)]: Ease of shaping, elasticity (flexibility)

Characteristics of the materials required :

a-Physical: density, electrical, thermal and ionic conductivity, surface energy, thermal expansion coefficients, etc.

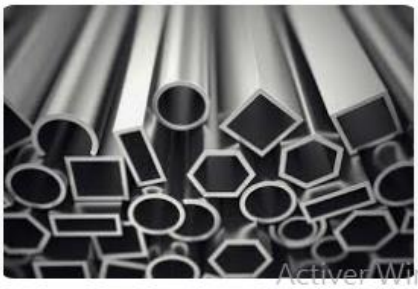
b-Chemical: resistance to oxidation and corrosion, stability, reactivity, etc.

c-Mechanics: elasticity, plasticity, fracture resistance, toughness, hardness, wear resistance, fatigue resistance, etc.

Example of materials :

- Metals: Antimony, Arsenic, Ismuth, Calcium, Cobalt, Copper, Tin, Indium, Lead.

Copper



Aluminium

- Metal alloys: Calcium-Aluminium, Tin-Silver, Tin-Copper, Tin-Indium, Tin-Lead, Tin-Zinc, Lead-Arsenic.

Bronze
Copper + tin

Brass
Copper + zinc

Specific applications :

a. Electronics and Computing

- Transistors and integrated circuits: Use of semiconductors for miniaturisation and energy efficiency.
- Sensors and Displays: Piezoelectric materials and photopolymers in pressure sensors and touch screens.

b. Energy

- Solar panels: Use of semiconductors such as silicon to convert light into electricity.
- Batteries: Hostile materials to create efficient chemistry for energy storage in lithium-ion batteries.

c. Medicine and Biomedicine

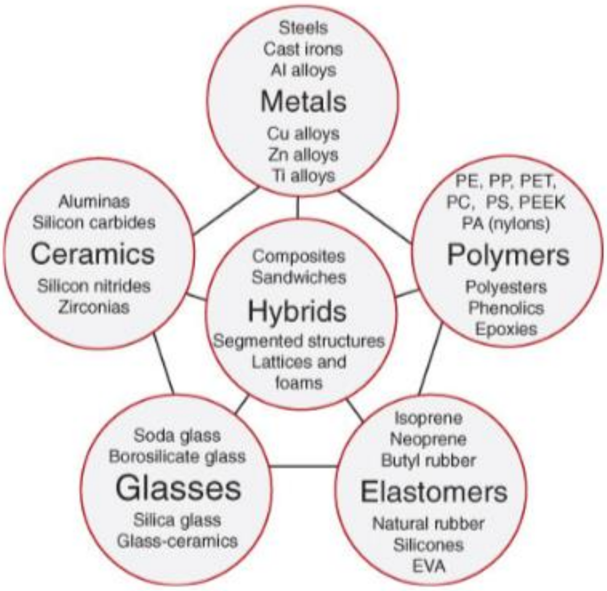
- Implants: Biocompatible materials for successful integration with biological tissues.
- Drug delivery devices: Use of hydrogels to control the rate and timing of drug release.

d. Environment and Sustainability

- Filtration: Materials adapted to purify water or air.
- Degradation of pollutants: Use of photocatalytic materials to degrade organic pollutants.

Summary :

Chemical composition largely defines the materials family.



Getting materials organized: the materials tree :

Metals: Relatively high stiffness, soft when pure but Harden able by alloying, working, and heat treatment, tough, good conductors,often reactive.

• Ceramics: Inorganic solids, stiff, hard, abrasion resistant, good high T bavoir, corrosion resistant, insulating, brittle.

• Glasses: Amorphous solids, hard, corrosion resistant, brittle,insulators, transparent.

• Polymers: Organic solids based on carbon chains, light, low modulus, strength to weight can be comparable to metals, low Tonly, easy to shape/snap together, near net shape, easily colored.

• Elastomers: Polymers with very low stiffness, very large recoverable shape change, can be strong and tough (tires).

• Hybrids: Combination of two or more of the other materials classes to get properties unattainable in a single material. Often difficult to process and join. CFRP, laminates, wood, bone (=polymer/ceramic) Modern, high-performance materials**.**

Chapter II: Dielectric materials

Dielectric materials

Characteristics of dielectric materials

Examples of dielectric materials

Maxwell's equations in a dielectric medium

II- Piezoelectricity

III- Polar Crystals

IV- Insulating ceramics

V Dielectric ceramics

Dielectric materials :

Dielectric materials are electrical insulators that can be polarised by an electric field. When an electric field is applied to a dielectric, the positive and negative charges within the material move slightly, creating an electric dipole. This property is used in many applications, including capacitors, electrical insulators and other electronic devices.

Characteristics of dielectric materials

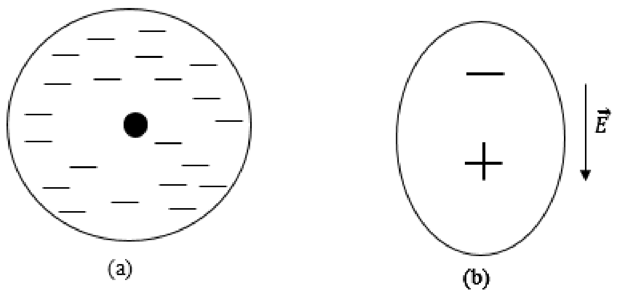
1. Permittivity: This is a measure of a material's ability to polarise in response to an electric field. It determines the amount of electric charge that can be stored in the material.
2. Dielectric strength: The ability of a material to withstand high electric fields without decomposing or conducting electricity.
3. Energy dissipation: Some materials are better than others at minimising the loss of energy in the form of heat when alternating current is passed through them.

Examples of dielectric materials

- Ceramics (such as titanium dioxide)
- Plastics (such as polyethylene, polystyrene)
- glass

Polarisation:

The atom is an electrically neutral object made up of a nucleus and a cloud of electrons.



(a): in the absence of an external electric field, the atom retains its symmetry.

(b): in the presence of an external electric field: the electric force moves the centres of mass in opposite directions, the field creates an internal dipole.

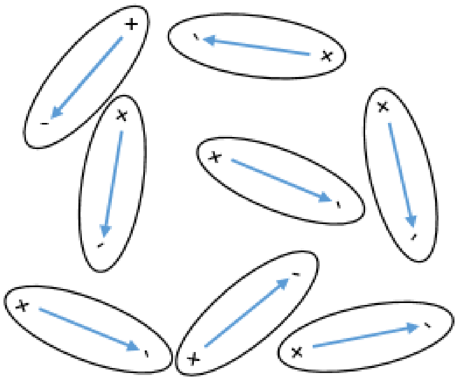
Each atom placed in an electric field $\vec{E}$ carries a dipole moment.

$$\vec{P} = \alpha \varepsilon_0 \vec{E}, \qquad \text{(II-1)}$$

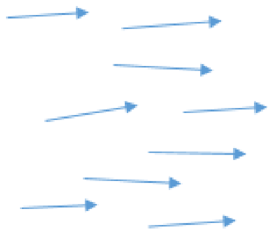
$\alpha = 4\pi r_0^3$: is the electrical polarisation.

r_0 : the radius of the atom.

The orientation of polar molecules :



(c)



(d)

(c): in the absence of an external electric field, the distribution of dipole moments is random. The sum of the dipole moments is zero.

A polar molecule has a dipole moment even in the absence of an external electric field.

(d) : When an electric field is applied, polar molecules tend to orient their dipole moment parallel to the electric field.

Each of these dipoles contributes to the creation of an electric field of polarisation $\overrightarrow{E_p}$. The number of dipoles per unit volume defines the polarisation vector $\vec{P}$.

$$\vec{P} = \varepsilon_0 \chi_e \vec{E} \qquad \text{(II-2)}$$

The polarisation electric field :

$$\vec{E}_P = \frac{1}{\varepsilon_0} \vec{P} = \chi_e \vec{E} \qquad \text{(II-3)}$$

Gauss's theorem :

$$div\left(\vec{E} + \vec{E}_P\right) = \frac{\rho}{\varepsilon_0} \qquad \text{(II-4)}$$

$$div[\vec{E}(1 + \chi_e)] = \frac{\rho}{\varepsilon_0}$$

Relative permittivity :

$$\varepsilon_r = 1 + \chi_e \qquad \text{(II-5)}$$

La permittivité absolue du milieu :

$$\varepsilon = \varepsilon_0 \varepsilon_r \qquad \text{(II-6)}$$

Gauss's theorem becomes as follows:

$$div(\vec{E}\varepsilon_0) = \rho \qquad \text{(II-7)}$$

The electrical excitation vector $\vec{D}$:

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = \varepsilon_0 (1 + \chi_e)\vec{E} = \varepsilon_0 \varepsilon_r \vec{E}$$

$$\Rightarrow \quad \vec{D} = \varepsilon \vec{E} \qquad \text{(II-8)}$$

Gauss's theorem :

$$div\vec{D} = \rho \qquad \text{(II-9)}$$

Maxwell's equations in a dielectric medium :

Maxwell-Gauss equation: $div\vec{D} = \rho$ (II-10)

Maxwell-magnetic flux equation: $div\vec{B} = 0$ (II-11)

Maxwell-Faraday equation: $\overrightarrow{rot D} = -\varepsilon \frac{d\vec{B}}{dt}$ (II-12)

Maxwell-Ampere equation: $\overrightarrow{rot B} = \mu_0 \vec{j} + \mu_0 \frac{\partial \vec{D}}{\partial t}$ (II-13)

II- Piezoelectricity :

Piezoelectricity (from the Greek 'piézein', to press, to press) is the property of certain bodies to become electrically polarised under the action of a force: charges appear on the faces of the crystal.

Piezoelectricity is the property of certain bodies to polarise electrically under the action of mechanical forces (direct effect) and conversely to deform when an electric field is applied to them (inverse effect).

The piezoelectricity of quartz was discovered in 1880 by the brothers Pierre and Jacques Curie, who observed that certain crystals, such as quartz, produced an electric charge when subjected to mechanical stress. This phenomenon is known as the direct piezoelectric effect.

Piezoelectric materials produce an electrical voltage when subjected to mechanical stress, for example when they are in motion or compressed, they can also deform when subjected to an electric current.

Direct effect :

A mechanical action causes an electric dipole to appear in each mesh of the material by shifting the centres of the positive and negative charges.

Reverse effect:

Conversely, the application of an electric field induces a mechanical deformation of the material. geometrical deformation)

- Material has a centre of symmetry:

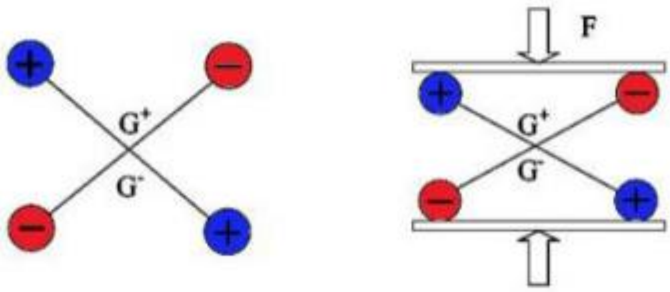


Figure 1. 3: Cristal possédant un centre de symétrie [

If a material has a centre of symmetry, as shown in Figure 1.3, the application of mechanical stress does not cause the positive and negative charge centres, also known as barycentres (G+ and G-), to move. As a result, no electrical polarisation occurs, even if the mechanical stress causes the material to deform.

- Material does not have a centre of symmetry :

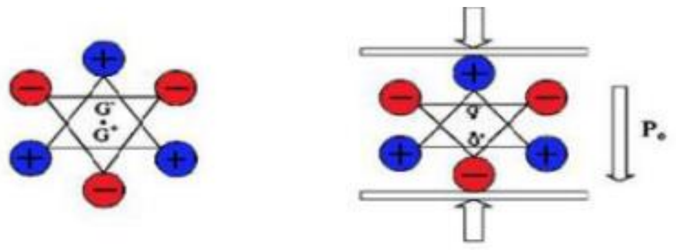
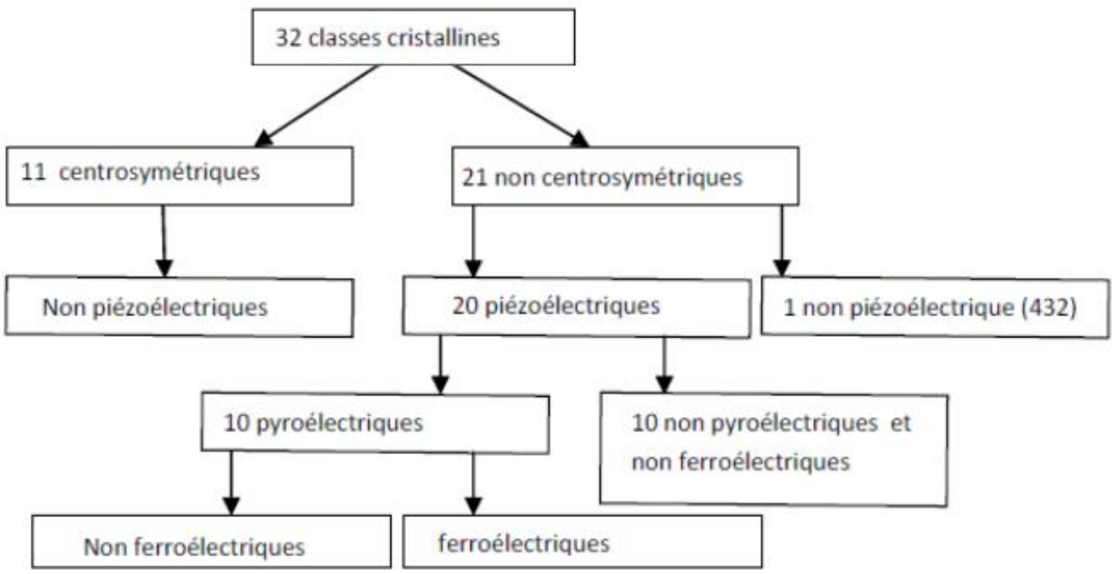


Figure 1. 4 : Cristal ne possédant pas de centre de symétrie, le barycentre des charges Déplace, créant une polarisation Po [6]

In the case of a crystal with no centre of symmetry, as shown in Figure (1.3), deformation induces a displacement of the positive and negative charge centres (G+ and G-). This displacement leads to the appearance of an electrical polarisation, noted P0, which is proportional to the deformation undergone by the material.

Of the 32 crystalline classes, 21 are non-centrosymmetrical (lacking a centre of inversion) and exhibit the piezoelectric effect



Ten of the 20 piezoelectric crystal classes have spontaneous polarisation in the absence of an electric field or external stress. Crystals belonging to these 10 classes are said to be pyroelectric because their polarisation varies as a function of temperature.

Matériaux piezoelectric materials :

There are around 200 piezoelectric materials used in energy harvesting applications, divided into four main categories:

- Single crystals (Rochelle salt, lithium niobite, quartz crystals).

- Ceramics (barium titanate ($BaTiO_3$), lead zirconate titanate (PZT), potassium niobate ($KNbO_3$)).

- Polymers (polylactic acid (PLA), polyvinylidene fluoride (PVDF), co-polymers, cellulose and derivatives).

- Polymer composites or nanocomposites (polyvinylidene fluoride-zinc oxide (PVDF-ZnO), $BaTiO_3$ cellulose, polyimides-PZT). Another classification of piezoelectric materials is : - Natural: Quartz, Rochelle salt, Topaz, tourmaline group

- Synthetic: Barium titanate, lead titanate, lithium niobite, lead zirconate titanate. The applications of piezoelectricity include the following:

The piezoelectric effect has a large number of applications in everyday life and in industry:

- Piezoelectric motors.

- Actuators in the industrial sector.

- Sensors in the medical sector.

- Actuators in consumer electronics (printers, loudspeakers, etc.).

- Piezoelectric buzzers.

- Instrument sensors.

- Microphones.

- Piezoelectric igniters.

- Nanopositioning in AFM, STM.

- Micro-robotics (defence).

III- Polar Crystals :

A crystal is a solid in which the atoms or molecules are organised in a regular, periodic pattern.

- **Asymmetry:** In polar crystals, the absence of central symmetry creates electric dipoles.

- **Types of structure:** Polar crystals can belong to different crystal systems, such as trigonal, tetrahedral and orthorhombic.

IntroductionPolar crystals are materials that exhibit a permanent dipole moment due to their asymmetric structure. This means that they have a separation of electrical charges, which gives them unique properties compared with non-polar crystals.

What is a polar crystal?

In crystalline physics, a crystalline class is considered to be polar if it allows the existence of a permanent dipole moment, i.e. if it is capable of pyroelectricity In crystallography, however, the term polar crystalline class is frequently used as a synonym for non-centrosymmetric crystalline class.

Elementary crystals are always non-polar. Polar crystals contain two or more non-equivalent elements with different electronegativity values

Crystal systems: Polar crystals can be found in different systems:

- Trigonal: Example: Quartz.

- Tetragonal: Example: PZT (lead zirconia).

- Orthorhombic: Example: Rochelle salt.

Properties of Polar Crystals :

- Dipole Moment: Polar crystals have a dipole moment which results from the asymmetric arrangement of their atoms.

The dipole moment P of a molecule is given by the following formula:

$$\vec{P} = -q\vec{r}$$

Where: q :is the charge

$\vec{r}$: is the distance between the positive and negative load centres

Electrical properties :

- Piezoelectricity: Ability to generate an electric current when subjected to pressure.

- Electrostrictivity: Ability to change shape when subjected to an electric field.

- Optical properties

  - **Birefringence:** Optical anisotropy, which means that the speed of light varies according to the direction of propagation within the crystal**.**
  - **Kerr and Pockels effect:** Changes in the refractive index under the influence of an electric field.

Examples of Polar Crystals:

- Quartz (SiO_2): Exhibits piezoelectric properties and is used in electronics and watchmaking.

- Tourmaline : Used in electronic devices for its piezoelectric and thermal properties(Tourmaline is a group of crystalline silicate minerals in which boron is associated with elements such as aluminium, iron, magnesium, sodium, lithium, etc.).

- crystalline (NH_4 H_2 PO_4) : An example of a polar crystal used in applications

Technological Applications :

- Electroelectric Devices: Used in microphones, loudspeakers, and sensors (such as pressure transducers).

- Non-linear optics: Used in lasers to generate harmonic frequencies.

- Piezoelectric Materials: Used in sensors, actuators and energy harvesting.

Characterisation of polar crystals:

- X-ray diffraction: Used to determine the crystalline structure and study the arrangement of atoms.

- Spectrometry: To analyse electronic and vibrational properties.

- Electron microscopy: to study the morphology of crystals.

IV- Insulating ceramics :

Insulating ceramics are materials widely used in various applications because of their properties. :Caractéristiques des céramiques isolantes

1. **Electrical insulation:** These ceramics have a high electrical resistivity, making them ideal for preventing short circuits and protecting electrical components.

2. **Thermal insulation:** They have low thermal conductivity, which helps minimise heat loss and improve energy efficiency in a variety of applications.

3. **Chemical stability:** Insulating ceramics are often resistant to corrosion and chemicals, making them suitable for many environments.

4. **High-temperature resilience:** They can maintain their insulating properties even at high temperatures, which is essential in industrial applications.

5. **Durability and longevity:** Ceramics have good resistance to wear and degradation, ensuring long-term performance.

Applications of insulating ceramics :

- **Electronics:** Used in capacitors, resistors and other components, they act as insulators in printed circuits and high-voltage devices.

- **Energy:** In the energy industry, they are used in devices such as power line insulators and energy production equipment, particularly in power stations.

- **Aerospace:** Insulating ceramics are used in applications requiring heat resistance and insulation, such as aircraft engines and propulsion systems.

- **Construction:** They can be incorporated into construction materials to improve the thermal insulation of buildings.

- **Medical:** Used in medical devices, they offer electrical insulation and resistance to sterilisation.

Examples of insulating ceramics:

- **Alumina (Al_2O_3):** Very common due to its high resistivity and thermal stability.

- **Zirconium silicate ($ZrSiO_4$):** Used for its thermal properties and chemical resistance.

- **Titanium-based ceramics:** Often used in advanced electronic applications for their low permittivity.

So; insulating ceramics are essential materials in many modern industries thanks to their unique properties and ability to operate in harsh conditions.

Types of insulating ceramics

a. Oxide ceramics :

- Alumina (Al_2O_3): Used for its excellent resistivity and high hardness. It is often used in electrical and electronic applications - Zirconia (ZrO_2): Prized for its dielectric capabilities and resistance to thermal shock, it is used in applications requiring increased robustness.

b. Silicate ceramics :

- Alumina silicate (SiO_2): Used in refractory ceramics, it can withstand high temperatures while displaying good mechanical strength.

- Zirconium silicates ($ZrSiO_4$): Offer good chemical resistance and are used in the oil and chemical industries.

c. Non-oxide ceramics :

- Carbides (e.g. SiC): Known for their durability at high temperatures as well as their good thermal conduction while offering electrical insulation.

- Nitrides (e.g. Si_3N_4): Used for their extraordinary mechanical properties and heat resistance.

Manufacturing methods

a. Preparation of raw materials

- Raw materials often consist of pre-treated ceramic powders, mixed with additives to optimise the final properties (e.g. thickening agents or plasticisers).

b. Manufacture by moulding

- Injection moulding: Fairly common, this process involves melting a ceramic paste and injecting it into moulds. This allows complex shapes to be produced.

- Dry pressing: Ceramic powders are compacted under pressure to form a solid part.

c. Sintering

- Standard sintering: After moulding, the parts are heated to allow the particles to weld together without complete liquefaction.

- Flash sintering: A method that uses electrical pulses to locally heat the particles, creating a rapid bond and improving mechanical properties.

d. Advanced techniques

- Functional Gradient Ceramics (FGC): This technique involves variations in composition and structure throughout the material to adjust its mechanical and thermal properties.

- Multilayer ceramics: Made up of several layers of different materials, they optimise insulation while offering other functions.

Dielectric ceramics :

Dielectric ceramics are ceramic materials with dielectric properties, i.e. they can be polarised in an electric field and thus store electrical energy. They are widely used in a variety of fields, including electronics, telecommunications and electrical devices..

Properties of dielectric ceramics :

Dielectric permittivity: This is a measure of a material's ability to store electrical energy in an electric field. Dielectric ceramics typically have a high permittivity.

- Dielectric Loss: This corresponds to the loss of energy when ceramics are subjected to an alternating electric field. A low loss factor is desirable for high-frequency applications.

- Thermal stability: Dielectric ceramics must maintain their electrical properties over a wide range of temperatures.

Types of dielectric ceramics :

Dielectric ceramics can be classified according to their chemical composition and properties:

- Titanium-based ceramics: For example, barium titanate ($BaTiO_3$) is a widely used ceramic due to its high permittivity and ease of incorporation into electronic devices.

- Zirconate-based ceramics: Titanium zirconate ($Pb(ZrTi)O_3$) is another example, known for its pyezoelectric and ferroelectric properties.

- Silicate-based ceramics: Used in certain types of capacitors and energy storage devices.

- ## Applications of dielectric ceramics :

- Capacitors: Dielectric ceramics are widely used in the manufacture of capacitors because of their ability to store electrical charges.

- RF and microwave components: Used in filters, resonators and high-frequency circuit foundations.

- Piezoelectric materials: Used in devices such as pressure sensors and actuators.

- Electrical insulation: They are also used in insulation applications for electrical equipment.

Fabrication :

The manufacture of dielectric ceramics generally involves the following steps:

1. Powder mixing: The raw materials are mixed to obtain the desired compositions.
2. Moulding: The mixture is shaped into blanks.
3. Sintering: The parts are fired at high temperature to densify the structure and obtain the desired properties.
4. Characterisation: The electrical, mechanical and thermal properties of the material are then tested.

So : Dielectric ceramics represent a constantly evolving area of research and application, with materials developed to meet specific needs in electronics and technology. Understanding the properties and applications of these materials is essential for engineers and scientists working in fields related to electronics and materials physics.Exemples Les céramiques diélectriques et leurs propriétés et applications :

1. Barium titanate ($BaTiO_3$)

- Properties :

- High permittivity (ε_r): Permittivity can reach up to 1000 or more, particularly at temperatures close to the ferroelectric transition.
- Ferroelectric character: Has a spontaneous electrical polarisation that can be modified by an external electric field.
- -Wide bandwidth: Excellent for high-frequency applications.

- Fabrication :

- Methods such as sol-gel, sintering and ceramic road technique are commonly used.

- $BaTiO_3$ powders are mixed with sintering agents and sintered at high temperatures to cause densification.

- Applications:

- Used in multilayer capacitors (MLCC) for energy storage in electronic devices.
- Also used in piezoelectric sensors and resonance devices for communication electronics.

- 2. Titanium zirconate ($Pb(ZrTi)O_3$ or PZT)

- Properties :

- Ferroelectric: Exhibits electrostrictive properties, resulting in deformation under the effect of an electric field.
- High permittivity: Depending on the concentration, permittivity can exceed 2000.
- Mechanical strength: Suitable for applications requiring impact resistance.

- Manufacture :

- Prepared using solid chemistry, sol-gel or co-precipitation techniques. The powders are then sintered to increase density and electrical properties.

- Applications :

- Used in piezoelectric devices, such as pressure sensors, piezoelectric loudspeakers, and actuators.
- Excellent option for acoustic resonators and frequency resonators for telecommunications.

- **3. Beryl (BeO)**

• Properties:

- Electrical insulator: Very good resistance to electricity, making it suitable for high voltage applications.
- Thermal conductivity: Excellent thermal conductivity, making it useful in applications requiring heat dissipation.
- Heat resistance: Can operate at high temperatures without degradation of properties.

• Manufacturing:

- Obtained by melting and recrystallization, using sintering techniques to produce solid forms.

• Applications:

- Used as an insulator in power electronic devices, such as diodes and field effect transistors.
- Used in laser devices and high frequency printed circuits.

the differences between insulating ceramic and dielectric ceramic:

The distinction between insulating ceramics and dielectric ceramics is mainly based on their electrical properties and applications. Here is a detailed overview of the differences:

Dielectric ceramics are widely used in various fields due to their unique properties. Applications of dielectric ceramics:

➢ **Insulating Ceramics:**

An insulating ceramic is a material that has a very high electrical resistivity, which means that it does not allow the passage of electric current under normal conditions. These ceramics are mainly used for their electrical insulation qualities.

➢ **Dielectric Ceramic:**

A dielectric ceramic is a type of insulating ceramic that also has some ability to store electrical energy due to its relative permittivity, which is often high. These materials are used in applications that require not only insulation but also the ability to interact with an electric field.

2. Electrical Properties

➢ **Insulating Ceramics:**

- **High Resistivity:** Insulating ceramics have a very high resistivity (can reach values of 10^10 Ω•m or more).
- **Zero Conductivity:** They practically do not allow the passage of current, which is crucial to avoid short circuits in electronic devices.Céramique Diélectrique :
- **High Permittivity:** These ceramics have a relative permittivity (ε_r) that can be significantly higher than a typical insulating ceramic, thus allowing energy storage.
- **Comparatively Lower Resistance:** Although they are also very insulating, some dielectric ceramics can conduct a small amount of current under high stress.

3. Applications

- **Insulating Ceramics**:

  Used for applications requiring insulation, such as:

- Insulators for electrical transmission lines.
- Supports and substrates in electronic equipment.
- Ceramics for vacuum devices and high-voltage systems.

- Dielectric Ceramics:

  Used in applications that require both insulation and the ability to respond to electric fields, such as:

- Dielectric capacitors (e.g., $BaTiO_3$, PZT ceramics).
- High-frequency cables and RF devices where energy storage is crucial.
- Piezoelectric elements in sensors and actuators.

4. Examples of Materials

- **Insulating Ceramics**:

- Alumina (Al_2O_3), zirconia (ZrO_2), and alumina silicate.

- **Dielectric Ceramics**:

- Barium titanate ($BaTiO_3$), lead zirconate titanate (PZT), lithium silicate (Li_2SiO_3).

Chapter III: Electrical conductivity of solids

The main categories

1. Conductors

2. Semiconductors

3. Insulators

I Conductivity of the most common metals :

Mechanism of conduction in metals :

1-Drude model :

2-Sumerfeld theory of metals:

3-Band theory

II. Semiconductor spectra

Types of Superconductors

Electrical conductivity of solids :

The electrical conductivity of solids depends on their ability to allow an electric current to pass through them. Conductive materials, such as metals, allow the movement of electrons, which facilitates the passage of current. On the other hand, other solids may be insulating and not conduct electricity. It is important to note that not all solids conduct electric current; only those described as conductive can do so effectively.

The electrical conductivity of solids depends mainly on their atomic structure and the mobility of electrical charges within their crystal lattice.

This means that when you melt a crystalline solid, its crystal lattice gets broken down and the molecules change into a liquid state. In case of metallic solids there is a large diversity of melting points. Although metallic solids usually have *high melting points*, some of them, such as the alkali metals (group 1), actually have low melting points.

ELECTRICAL CONDUCTIVITY: is referred to as the ability to conduct electricity. While you read this article on your computer' screen, you're probably not thinking about the wires your computer uses to get the electrical power it needs to run. Those wires are made of metal, most probably copper, simply because generally metals have good electrical conductivity.

The main categories :

1. Conductors

Examples:

Metals such as copper (Cu), aluminium (Al), gold (Au).

Characteristics:

In metals, the valence electrons are free to move, which facilitates the passage of electric current. Conductors have a high conductivity.

2. Semiconductors

Examples:

Silicon (Si), germanium (Ge).

Characteristics:

Semiconductors have an intermediate conductivity. Their conductivity can be modified by the addition of impurities (doping) or by temperature variations. At room temperature, semiconductors can conduct electricity, but their capacity is lower than that of conductors.

3. Insulators

Examples:

Glass, rubber, plastic.

Characteristics:

Insulators have no free mobile charges, which prevents electrical conduction. They have very low conductivity. They are often used to prevent the passage of electric current in circuits.

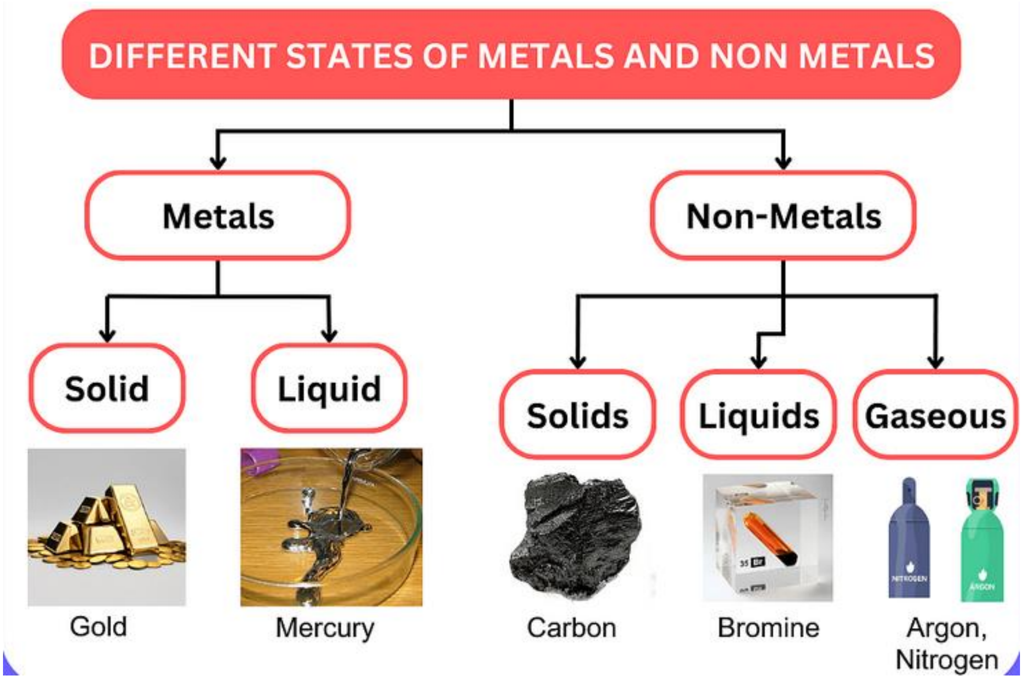
Factors influencing conductivity

Temperature:

For metals, conductivity decreases with increasing temperature due to the increased thermal agitation of the atoms. For semiconductors, conductivity often increases with temperature.

Impurities: In semiconductors, the introduction of impurities can increase or decrease conductivity, a crucial phenomenon in the manufacture of electronic devices.

In short, the electrical conductivity of solids varies according to their type of material, their atomic structure and environmental conditions.



Conductivity of the most common metals :

Material	Resistivity	Conductivity
Silver	1.59×10^{-8}	6.30×10^{7}
Copper	1.68×10^{-8}	5.96×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.5×10^{7}
Calcium	3.36×10^{-8}	2.98×10^{7}
Tungsten	5.60×10^{-8}	1.79×10^{7}
Zinc	5.90×10^{-8}	1.69×10^{7}
Nickel	6.99×10^{-8}	1.43×10^{7}
Lithium	9.28×10^{-8}	1.08×10^{7}
Iron	1.0×10^{-7}	1.00×10^{7}
Platinum	1.06×10^{-7}	9.43×10^{6}
Tin	1.09×10^{-7}	9.17×10^{6}
Stainless steel	6.9×10^{-7}	1.45×10^{6}
Mercury	9.8×10^{-7}	1.02×10^{6}
Sea water	2×10^{-1}	4.8
Drinking water	2×10^{1} to 2×10^{3}	5×10^{-4} to 5×10^{-2}
Silicon	6.40×10^{2}	1.56×10^{-3}
Wood (damp)	1×10^{3} to 4	10^{-4} to 10^{-3}
Deionized water	1.8×10^{5}	5.5×10^{-6}
Glass	10×10^{10} to 10×10^{14}	10^{-11} to 10^{-15}
Hard rubber	1×10^{13}	10^{-14}
Wood (oven dry)	1×10^{14} to 16	10^{-16} to 10^{-14}
Sulfur	1×10^{15}	10^{-16}

Some of the most common examples of metallic alloys are presented in the following table:

Alloy	Composition	Use
Brass	Cu + Zn	Machine bearings, jewellery, electrical objects, metallic parts of door furniture, water pipes
Bronze	Cu + Sn	Machine parts, ornaments e.g. necklaces, castin etc.
Solder	Pb+ Sn	Connecting electrical wiring.
Duralumin	Al + Cu + Mg	Aircraft construction, bicycle parts and small boats.
Magnalium	Al +Mg	Aircraft construction, small boats.
Alnico (feromagnetic)	Al + Ni + Co	Generators, electric motors, mass spectometer.
Pewter	Pb + Sn + small amount of Sb	Plates, ornaments and drinking mugs.
Stainless steel	Fe + Cr + Ni	Cutlery, kitchen sinks, surgical instruments.
Hard steel	Fe + C	Cutting tools, razor blades, chisels.
Tungsten steel	Fe + W	Edges of high speed cutting tools.

Difference between metals and non-metals on the basis of their physical properties.

Physical Properties	Metals	Non-metals
1. Malleability	Metals are malleable, *i.e.*, they can be beaten into thin sheets. Exception: Mercury	Non-metals are non- malleable. They are broken into pieces when hammered. Hence they are also called brittle.
2. Sonority	Metals are sonorous, *i.e.*, they produce ringing sound when struck.	Non-metals are non-sonorous.
3. Ductility	Metals are ductile, *i.e.*, they can be drawn into wires. Exception: Mercury	Non-metals are non-ductile.
4. Lustre	Metals are lustrous, *i.e.*, they are shiny.	Non-metals are non-lustrous, *i.e.*, they are dull in appearance. Exception: Graphite and iodine.
5. Hardness or solidness	Metals are hard except sodium and potassium.	Non-metals are soft except diamond.
6. Conductivity	Metals are good conductor of heat and electricity.	Non-metals are poor conductor of heat and electricity. Exception: Graphite is a non-conductor of heat and electricity.
7. Density	Metals are of high density except lithium.	Non-metals are of low density.
8. Melting and boiling points.	Metals have high melting and boiling points.	Non-metals have low melting and boiling points except graphite.

Difference between metals and non-metals on the basis of their chemical properties.

Chemical Properties	Metals	Non-metals
1. Reaction with oxygen	Metals react with oxygen to form basic oxides which form bases when dissolve in water.	Non-metals react with oxygen to form acidic oxides which form acids when dissolve in water.
2. Reaction with water	Metals react with water to form their oxides or hydroxides.	Non-metals do not react with water.
3. Reaction with acids	Metals react with acids to produce respective salts along with evolution of hydrogen gas. Some metals like Cu, Ag, Au, etc., do not liberate hydrogen gas.	Non-metals do not react with acids except sulphur which react with hot, concentrated acid.
4. Reaction with bases	Most of the metals do not react with bases. However, some metals like Al, Pb, Zn react with strong bases like NaOH to form complex salts and hydrogen gas.	Generally, non-metals do not react with bases. Sometimes, some complex reactions take place between non-metals and bases.

Conduction in solids (metals, semiconductors) has a very wide range of applications in microelectronics, thermometry and metallurgy. Understanding the mechanisms (microscopic or macroscopic in origin) responsible for electrical transport in these solids and the associated physical properties is an essential prerequisite for optimising the use of these materials at all temperatures.

Mechanism of conduction in metals :

Drude model :

The Drude model is a classic model used to explain electrical conduction in metals, proposing that electrons behave like a gas of free particles.

The main features of the model :

Principles of the Drude Model:

1. **Free electrons:** The electrons in a metal are considered to be free particles that move around inside the material at random.
2. **Collisions :** Electrons collide with impurities, defects and phonons (crystal lattice vibrations). These collisions modify their trajectory and speed.
3. **Speed and current:** By applying an electric field, the electrons are subjected to a force that gives them an average speed, and an electric current is generated.
4. **Relaxation time:** The model introduces the concept of 'relaxation time' (τ), which is the average time between two collisions. This allows the movement of electrons to be linked to electrical resistance.

Ohm's Law: Drude's model explains Ohm's Law, which states that the current (I) through a conductor is proportional to the voltage (V) applied, with resistance (R) depending on the properties of the material.

Important equations:

- Ohm's global law: U=RI

- Local Ohm's law: $\vec{j} = \delta\vec{E}$

- Current density (J): $\vec{j} = ne\vec{E}$

where n is the electron density (number of electrons per unit volume), e is the elementary charge and v is the speed of the electrons.

Electrical resistance :

R=AρL

where ρ is the resistivity, L is the length of the conductor and . A is the cross-sectional area.

- the definition of the overall (or average in the statistical sense) velocity of the electrons < v > from the current density $j = -ne < v >$ (e denotes the elementary electric charge).

the fundamental principle of dynamics in the reference frame of the laboratory, assumed to be galilean. To do this, we will assume that at t=0, the electron emerges from a collision. Then, at time t, its velocity verifies the relation (E is stationary):

$$\vec{v} = \vec{v_0} - \frac{e\vec{E}}{m}t$$

$$< \vec{v} >=< \vec{v_0} > + < \frac{-e\vec{E}}{m}t >= \vec{0} - \frac{e\vec{E}}{m} < t >= -\frac{e\tau}{m}\vec{E}$$

$$: \sigma = \frac{ne^2\tau}{m} : \quad \vec{j} = -ne < \vec{v} >= \frac{ne^2\tau}{m}\vec{E}$$

The advantage of Drude's model is that it gives a relationship between a measurable macroscopic quantity and a microscopic quantity : by measuring the conductivity (or resistivity) of a material, we can trace the relaxation time, just as we were able to estimate the electron density n.

Limitations of the Drude Model :

- **Inability to explain certain properties:** The model does not take quantum effects into account, which limits its ability to explain certain properties of metals, such as low-temperature conductivity and magnetic effects.

- **Free electron model:** It does not take into account the nature of energy bands and the electronic structure of materials.

2-Sumerfeld theory of metals:

The assumptions of Drude's model are retained, but we take into account the fact that electrons have a quantum nature: they are fermions obeying Pauli's principle. To describe electrons, we no longer use the fundamental principle of dynamics but the stationary Schrödinger equation.

2. This is written on the assumption that the electrons are free (no potential in the Hamiltonian) and independent (an assumption that allows us to decouple the Schrödinger equations from the individual electrons and to consider solving the problem for a single-electron wave function) :

$$-\frac{\hbar^2}{2m}\Delta\psi = E\psi$$

Solving the Schrödinger equation with these boundary conditions then gives :

$$\psi(\vec{r}) = \frac{1}{\sqrt{V}}\exp\left(i\vec{k}\cdot\vec{r}\right) \text{ avec } E = \frac{\hbar^2\vec{k}^2}{2m}$$
$$\vec{k} = \frac{2\pi}{L}\vec{n} \text{ avec } \vec{n} = n_x\vec{e_x} + n_y\vec{e_y} + n_z\vec{e_z} \in \mathbb{Z}^3$$

limitations of the Sommerfeld model :

1. Electron/ion interactions are not taken into account in this model (electrons are free), whereas a quick order of magnitude shows that the typical interaction energy is of the order of the Fermi energy.

2. We still can't explain why some materials are conductors, while others are insulators. For example, boron is an insulator whereas aluminium, just below it in the periodic table, is a conductor. Similarly, graphite carbon is conductive, while diamond carbon is insulating.

3-Band theory:

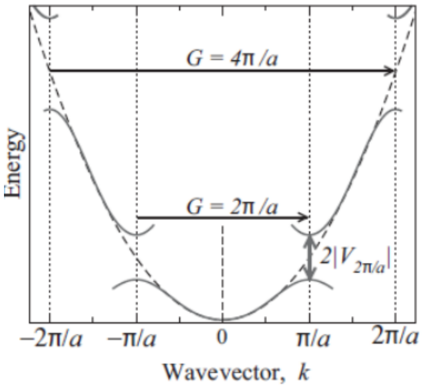
Introduction and classification of solids:

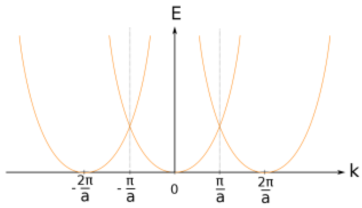
- the valence band: this is the highest energy band that is completely filled.

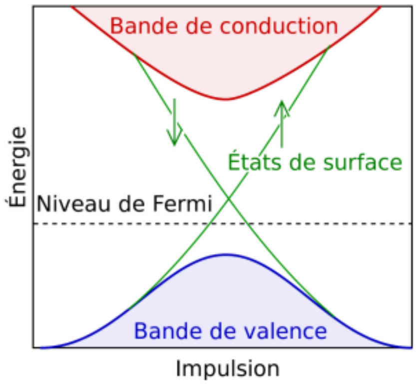
- the conduction band: this is the band just above the valence band. Depending on how full the conduction band is, we can define different types of behaviour

For simplicity's sake, let's consider a 1D solid model. Bloch's theorem states that, as the potential is periodic with step a, so are the wave functions, and therefore the energies are periodic with period n2π/a, n ∈ N. For an energetic condensed matter type approach, Dispersion relation :

$$E = \hbar^2 k^2 / 2m,$$







Semiconductor :

Introduction :

Materials are classified into three categories according to their electrical properties:

I.1.1. Conductors: iron (Fe), copper (Cu), gold (Au), silver (Ag) and aluminium (Al), resistivity ρfaible at room temperature, less than 10^{-5} Ωcm.

I.1.2 Insulators: such as glass, silica (SiO2), carbon (diamond). resistivity ρ est greater than 10^{8} Ωcm,

I.1.3. Semiconductors

This is a class of materials between metals and insulators, whose resistivity varies between 10^{-5} Ωcm and 10^{4} Ωcm. Electricity is carried by charge carriers, electrons and holes. A semiconductor can be either intrinsic (pure) or extrinsic (doped with impurity atoms).

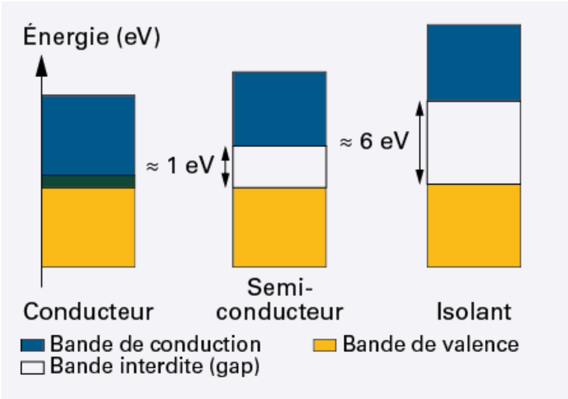
The transition from one energy band to another:

When energy is applied to a material, either by heating or illumination, some electrons can switch from the valence band to the conduction band.

For a conductor, the valence and conduction bands overlap. Electrons can therefore move freely from one band to the other. Current can flow. This is the case, for example, with copper, silver or gold.

For an insulator, the bands are very far apart, about 6 eV (electron volts). Electrons cannot move from one band to the other.

For a semiconductor, the gap exists but it is smaller than for an insulator. It is 1.12 eV for silicon, for example. It can therefore become conductive, if it is illuminated for example, which excites the valence electrons. The elementary semiconductors are silicon (Si) and germanium (Ge).


Énergie (eV)
≈ 1 eV
≈ 6 eV
Conducteur
Semi-
conducteur
Isolant
Bande de conduction
Bande de valence
Bande interdite (gap)

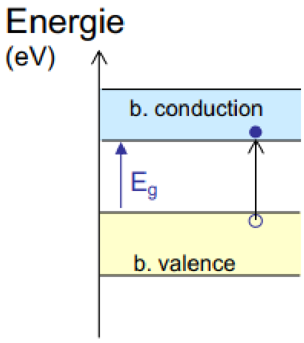
II. Semiconductor spectra :

1) The absorption spectrum of semiconductors

The difference between the valence band and the conduction band of a semiconductor is about 1 eV. 1 eV corresponds to the energy of radiation with a wavelength of around 1,200 nm.

The absorption spectra in Figure 2 show that most semiconductors absorb wavelengths of less than 1,200 nm, which is sufficient to pass through the gap and allow electrons to circulate.

300°K	Si	Ge
Eg [eV]	1,12	0,66



The bandgap Eg represents the minimum energy required to break the bond.

In a semiconductor there are 2 types of charge carriers :

- **negative carriers:** electrons in the conduction band,
- **positive carriers:** the holes in the valence band.

3 Classification Semiconductors according to composition :

I.2.1. Simple semiconductor

This is a semiconductor composed of a single atomic element, such as the semiconductors in column IV of the periodic table, like silicon (Si) and germanium (Ge).

I.2.2. Compound semiconductor

This is a semiconductor composed of at least two different types of atoms. They can be binary semiconductors which belong to the different classes II-VI, III-V, IV-IV, IV-VI.....etc. There are also ternary semiconductors composed of three types of atoms and quaternary semiconductors composed of four types of atoms.

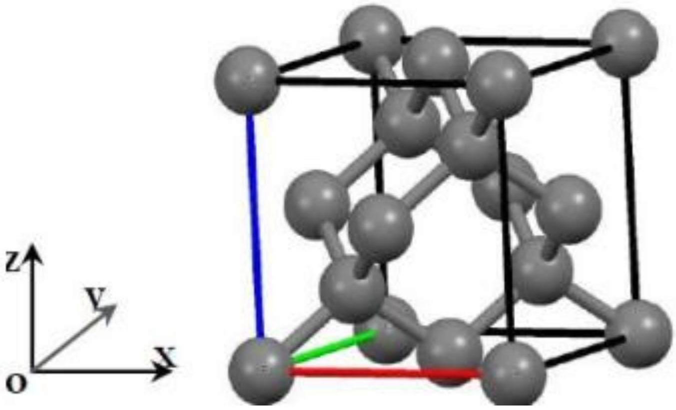
4- Semiconductor crystal structure :

In general, semiconductors crystallise in one of the following structures:

Diamond structure: (Si and Ge)

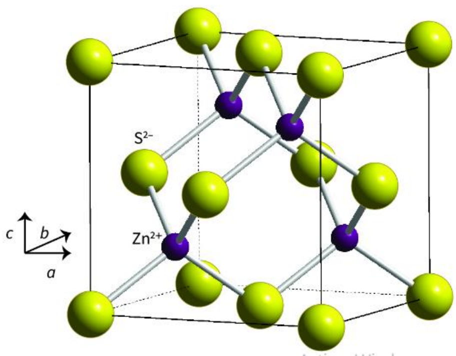
This structure consists of two face-centred cubic (F.C.C.) lattices nested in such a way that four atoms are placed at the nodes of the F.C.C. lattice and four other atoms are placed in (1/4,1/4,1/4), (3/4,1/4,3/4), (1/4,3/4,3/4) and (3/4,3/4,1/4).

each atom is tetrahedrally linked to four other atoms



Zinc blend structure: ZnS

In this structure, the two C.F.C. lattices contain two different types of atoms. Four atoms occupy the nodes of the first C.F.C. and four other atoms are placed inside the cube and occupy the positions (1/4,1/4,1/4), (3/4,1/4,3/4), (1/4,3/4,3/4) and (3/4,3/4,1/4).

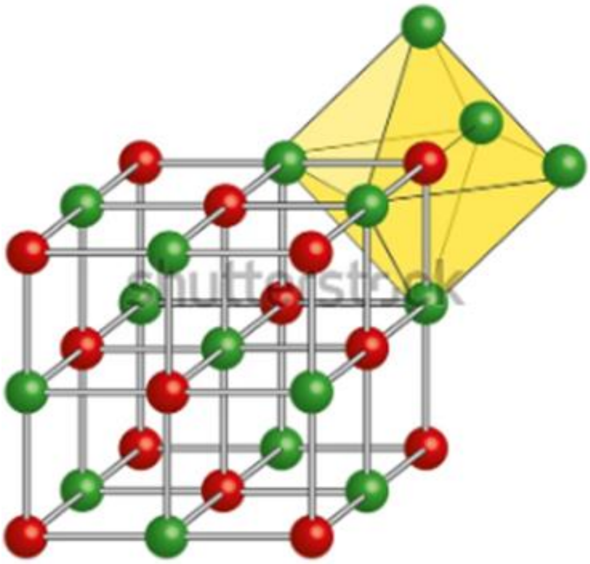


NaCl structure: lead sulphide (PbS)

The pattern consists of the Pb+2 ion (0, 0.0) and the S-2 ion (1/2, 0.0).

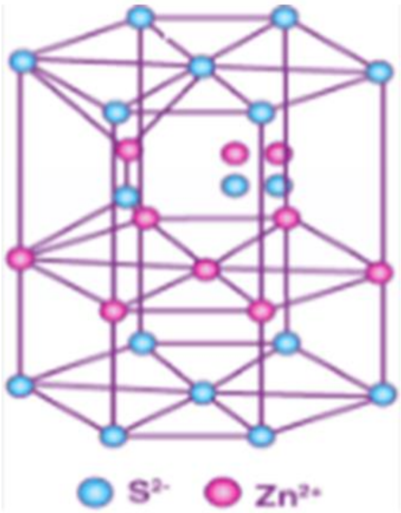
Each ion is in a regular octahedral medium and is therefore surrounded by 6 ions of opposite signs

Periodic pattern	NaCl
Atomic positions	Na^+ (0 , 0 , 0), Cl^- (½ , 0 , 0)

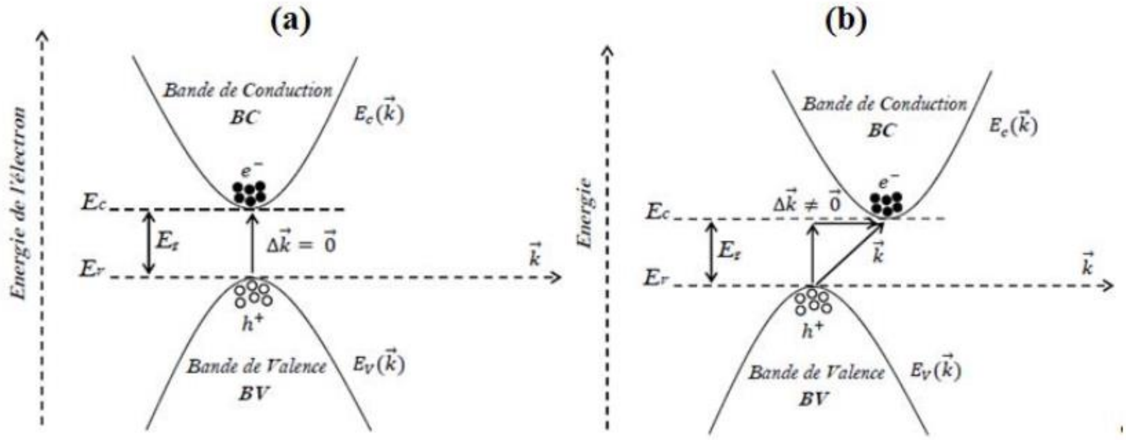


Wurtzite structure: (hexagonal)

In this structure, the pattern consists of two different atoms occupying the positions (0,0,0) and (1/3,2/3,1/2). As in the zinc blende structure, each atom is surrounded by four atoms of the other element, forming tetrahedrons.



Direct or indirect gap :



(a): A gap is said to be direct: if the maximum of BV and the minimum of BC are located at the same point.

(b): A gap is said to be indirect: the minimum of B_C is located at a distance $\Delta \vec{k} \neq 0$ from the maximum of B_V in the Brillouin zone.

5- Intrinsic semiconductors at equilibrium :

An intrinsic semiconductor is a pure undoped material.

Concentration of free charge carriers

In an N-type extrinsic semiconductor, the concentration of electrons is given by

the concentration of electrons is given by the following relationship :

$$n = N_c \exp -\left(\frac{E_c - E_{Fn}}{k_B T}\right)$$

the concentration of holes in a P-type semiconductor is :

$$p = N_v \exp\left(\frac{E_v - E_{Fp}}{k_B T}\right)$$

Fermi-Dirac level :

A semiconductor is considered to be a system made up of N electrons seeking to occupy the lowest energy state. At 0K, the electrons occupy all the low-energy levels in B_V. As the absolute temperature T increases, the distribution of electrons is governed by the Fermi-Dirac statistics

$$f_n(E) = \frac{1}{1 + exp\left(\frac{E - E_F}{k_B T}\right)}$$

k_B is Boltzmann's constant ($k_B = 1.38 \times 10^{-23}$ J.K^{-1})

E_F is the Fermi energy level, which represents the highest level occupied at 0K.

a.Density of states :

The density of allowed states is defined as the number of places available per unit volume, occupied or not by electrons, in B_C and holes in B_V, it is expressed by the relation :

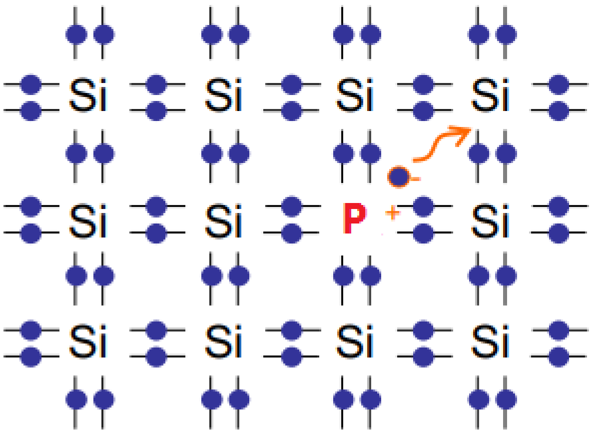
$$D_C(E) = 4\pi\left(\frac{2m_e}{h^2}\right)^{\frac{3}{2}}(E - E_C)^{1/2} \text{ pour les electrons}$$

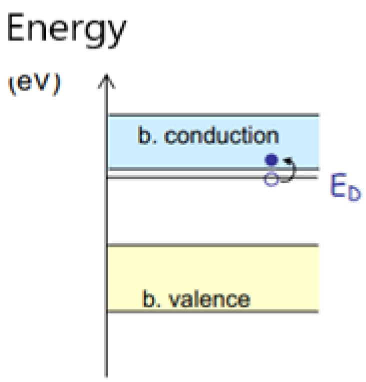
$$D_V(E) = 4\pi\left(\frac{2m_t}{h^2}\right)^{\frac{3}{2}}(E_V - E)^{1/2} \text{ pour les trous}$$

b. N-type extrinsic semiconductor: (negative = sign of majority charge carriers)

Si doped with P. The P atom has 5 valence electrons, four of which bond with the four electrons of the neighbouring Si atoms to free the fifth electron, which does not fit into the bond formed, and which finds itself immersed in the positive field of the P+ ion.

- release of one free electron, the other 4 bonding to the neighbouring Si atoms (donor atom)



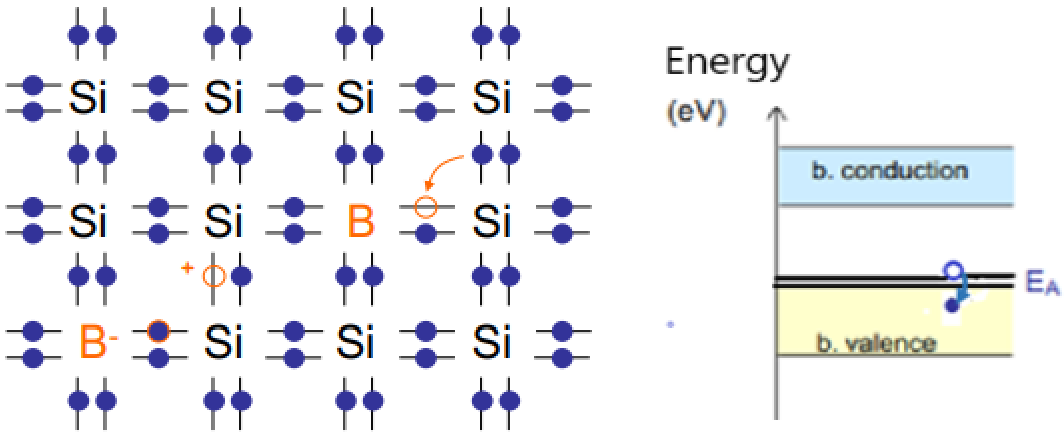


The introduction of impurities (doping) leads to the creation of an Ed energy level of the donor atom in the band gap.

C. P-type extrinsic semiconductor (positive = sign of majority carriers) :

Obtained by doping = introduction of group III atoms (see periodic classification, 3 on the valence layer) in place of Si atoms, generally boron B or gallium Ga.

The association with its four neighbours gives the B atom seven electrons on the outer layer, which is not enough to make it stable and it is then tempted to steal one from a close neighbour. B therefore becomes negatively ionised (B^-) and a free hole moves from atom to atom.



the introduction of the impurity (doping) creates an energy level Ea in the forbidden band, close to E_v

Superconductors:

Superconductors are materials that can conduct electricity without resistance at very low temperatures close to absolute zero. These materials can carry current at very high intensities and store electricity without any loss. This remarkable property enables very efficient electricity transmission and has potential applications in areas like magnetoencephalography, magnetic levitation trains, and energy storage.

Superconductors have several unique properties that distinguish them from ordinary materials.

Characteristics:

1. **Zero Electrical Resistance:** Superconductors conduct electricity without any resistance, which allows electrical currents to flow without energy loss.

2. **Meissner Effect:** Superconductors expel magnetic fields from their interior when cooled below their critical temperature, which makes them capable of floating above a magnet (the levitation effect).
3. **Critical Temperature (Tc):** Each superconductor has a temperature below which it becomes superconductive. This temperature varies depending on the material.
4. **Diamagnetic Properties:** Due to the Meissner effect, superconductors are perfect diamagnets, meaning they can repel magnetic fields.
5. **Anisotropy:** Some superconductors exhibit properties that depend on the direction, which can affect their electrical and magnetic behavior.
6. **Vortex Phenomenon:** In some type II superconductors, magnetic flux lines can penetrate the material in the form of vortices, allowing a mixture of superconducting and normal conductivity.

These properties pave the way for numerous applications, especially in advanced magnetic systems, magnetic levitation trains, and fundamental physics research.

Applications of Superconductors:

Superconductors have a wide range of applications due to their unique properties, including zero electrical resistance and the ability to create strong magnetic fields. Below are some key applications:

1. **Magnetic Resonance Imaging (MRI)**
   - **Functioning**: MRI machines use superconducting coils to generate powerful and uniform magnetic fields. These fields are crucial for aligning the nuclear spins in the body,

- Superconductors enable MRI devices to produce high-resolution images, which are essential for medical diagnoses, particularly in neurology and oncology.

2. **Magnetic Levitation Trains (Maglev)**

- **Functioning**: Maglev trains utilize superconductors to create magnetic fields that allow the train to levitate above the tracks. This eliminates friction, enabling high-speed travel.

Maglev trains can reach speeds over 500 km/h, providing fast, efficient transportation and reducing maintenance costs for rail infrastructure.

3. **Electrical Power Systems**

- **Functioning**: Superconducting cables can transmit electricity without energy losses due to resistance. This is especially useful in power generation centers and for interconnecting electrical grids.

The use of superconducting cables improves the efficiency of electrical systems, reduces losses, and allows energy to be transmitted over long distances without degradation.

4. **Magnetometers (SQUIDs)**

- **Functioning**: Superconducting Quantum Interference Devices (SQUIDs) take advantage of the ability of superconductors to detect very small magnetic flux variations. They operate using a superconducting loop with two junctions, enabling detection of minute changes in magnetic fields.

SQUIDs are crucial in scientific and industrial applications, such as geological research, biomedical studies, and infrastructure monitoring.

5. **Electronic Devices**

- **Functioning**: Superconductors enable the creation of circuits that consume very little energy. Superconducting filters, for example, can select specific frequencies with much greater efficiency than conventional devices.

In telecommunications, these devices improve signal quality and reduce noise, which is critical for high-speed data transmission.

6. **Particle Physics**

   - **Functioning**: In particle accelerators like the Large Hadron Collider (LHC), superconductors are used to generate powerful magnetic fields that steer and accelerate particles to nearly the speed of light.

   This enables scientists to explore the fundamental nature of matter and test physical theories, contributing to advancements in modern physics.

7. **Energy Storage**

   - **Functioning**: Superconductor-based storage devices, such as superconducting magnetic energy storage (SMES) systems, store energy in the form of electromagnetic fields.

   These systems offer very low-loss energy storage, which is crucial for balancing supply and demand in electrical grids, especially with the integration of renewable energy sources.

8. **Quantum Research and Computing**

   - **Functioning**: In quantum computing systems, qubits can be made from superconducting circuits, utilizing the quantum properties of superconductors to perform calculations.

Superconductors play a pivotal role in advancing quantum computing, which has the potential to revolutionize fields like cryptography, optimization, and artificial intelligence.

Superconductors are at the core of many cutting-edge technologies and continue to contribute to innovations across diverse fields.

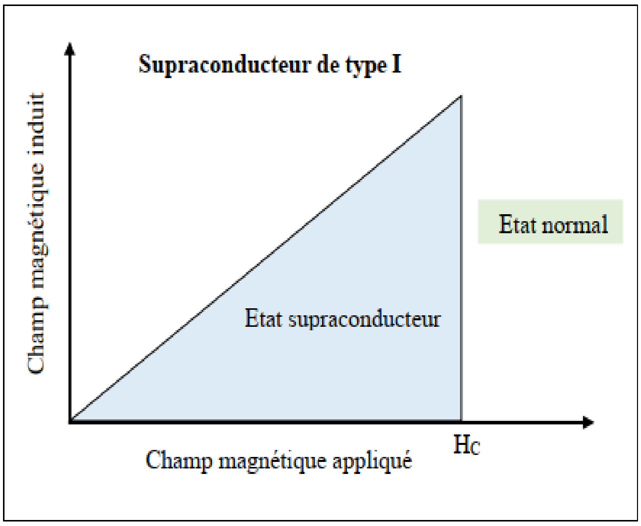
These technologies promise revolutionary advancements in data processing, with the potential to solve complex problems much faster than current computers.

Types of Superconductors: There are two main categories of superconductors:

1. **Type I Superconductors:**

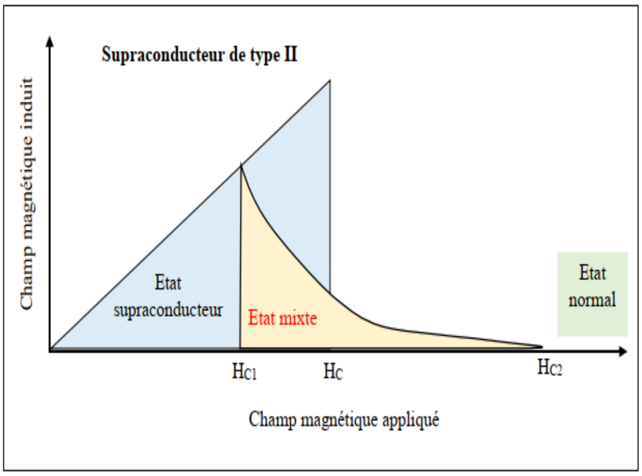
These are generally pure metals that exhibit a transition to the superconducting state at very low temperatures. They display a simple behavior when exposed to magnetic fields, but they cannot withstand high magnetic fields.

Type I superconductors are characterized by a single critical magnetic field, denoted as **Hc**. This is the maximum magnetic field strength that a Type I superconductor can tolerate before it loses its superconducting properties.



2. **Type II Superconductors**:

These are often alloys or ceramic compounds that can withstand higher magnetic fields and are commonly used in practical applications. Examples of these materials include NbTi (niobium-titanium) and cuprates (e.g., $YBa_2Cu_3O_7$). Type II superconductors are capable of maintaining their superconducting properties even in the presence of much stronger magnetic fields compared to Type I superconductors.



The study of superconductors is an active field of research, with efforts to discover or develop new materials that can become superconductors at higher temperatures. This could revolutionize the energy industry and electrical technologies.

Chapter IV : Magnetic and optical properties of solids

Types of Magnetic Properties

Optical properties of solids

Kramers-Kronig relations

Electrical excitation vector

Absorption phenomenon

Types of Absorption Phenomena

1.Energetic Absorption

2. Absorption of Matter

Applications of Absorption

Optical reflection

The magnetic properties of solids :

The magnetic properties of solids concern the behaviour of materials when exposed to a magnetic field.

I. Introduction to Magnetic Properties

The magnetic properties of solids are mainly due to the presence of atomic magnetic moments, resulting from the spin and orbital motion of electrons. These properties can be classified into several categories, each presenting distinct behaviours when subjected to a magnetic field.

II. Types of Magnetic Properties

1. Ferromagnetism

- Characteristics :

o Ferromagnetic materials have magnetic domains that can align under the effect of an external magnetic field.

They retain this magnetisation even after the field is removed.

- Mechanism :

Unpaired electrons in atoms generate a magnetic moment. Interactions between these moments (ferromagnetic coupling) promote parallel alignment in the domains.

- Examples:

Iron, cobalt, nickel.

- Applications :

Used in permanent magnets, electric motors, transformers, and data storage devices.

2. Paramagnetism

- Characteristics :

Paramagnetic materials acquire a weak magnetisation in the presence of a magnetic field, but this magnetisation disappears when the field is removed.

Mechanism :

Magnetisation arises from the magnetic moments of unpaired electrons temporarily aligning in the direction of the applied field.

- Examples:

Aluminium, platinum, oxides such as TiO_2 .

- Applications:

Used in magnetic resonance imaging (MRI) machines and for magnetic susceptibility studies.

3. Diamagnetism :

- Characteristics:

Diamagnetic materials have a very low negative susceptibility to magnetic fields, making them slightly repulsive.

- Mechanism:

When subjected to a magnetic field, the electronic orbitals move in such a way as to induce an opposite magnetic moment, thus generating a repulsive force.

- Examples:

Copper, silver, bismuth, graphite.

- Applications:

Used in magnetic levitation devices (such as levitating trains), as well as in scientific experiments to minimise magnetic influences.

4. Antiferromagnetism

- Characteristics :

In antiferromagnetic materials, the opposing magnetic moments cancel out, resulting in zero magnetisation on a macroscopic scale.

- Mechanism :

The magnetic moments of atoms align in opposite directions in regular structures, often due to antiferromagnetic coupling interactions.

- Examples

Include,Iron oxide (FeO), MnO.

- Applications :

Used in low-energy magnetic devices and in studies of quantum phenomena.

5. Ferrimagnetism :

- Characteristics :

Ferrimagnetic materials have magnetic moments of different sizes that align in opposite directions, resulting in a positive net magnetisation.

- Mechanism :

Combining ions with opposite spins where one spin is stronger than the other.

- Examples :

Ferrites such as magnetite ($Fe_3 O_4$).

- Applications:

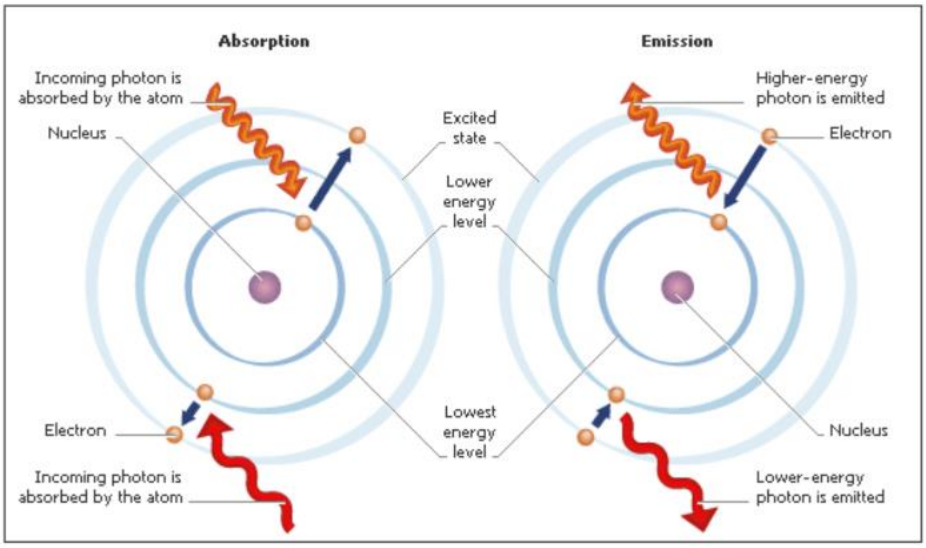
Used in hard disk read/write heads, in radio frequency, and in telecommunications.

The magnetic properties of solids are crucial to many modern technologies. Understanding them has led to the development of new materials and applications, from data storage devices to innovations in electronics and transport.

Optical properties of solids

The optical properties of solids are essential for understanding how materials interact with light and other forms of electromagnetic radiation. These properties determine behaviours such as the transmission, reflection, absorption and scattering of light.

The optical properties of solids refer to the way in which these materials interact with light.



- The optical properties of solids are essential for understanding how materials interact with light and other forms of electromagnetic radiation. These properties determine behaviours such as the transmission, reflection, absorption and scattering of light.
- The study of the optical properties of solids (absorption, reflection, transmission, etc.) has been shown to be a powerful tool for understanding the electronic and atomic structure of these materials.

Kramers-Kronig relations :

Kramers-Kronig relations are based on the principle of causality, which states that the response of a physical system to a disturbance cannot precede that disturbance. This principle is essential to ensure consistency between the real and imaginary parts of the dielectric function:

- The real part $\epsilon'(\omega)$ and the imaginary part $\epsilon''(\omega)$ of a dielectric material are linked by these relationships, ensuring that if one is known (measured), the other can be determined.

In solids, optical properties can be described by the complex dielectric function :

$$\varepsilon(\omega) = \varepsilon_1(\omega) + i\varepsilon_2(w)$$

Electrical excitation vector :

The electron response of a solid can be described macroscopically, by the complex dielectric constant ε(*k*,ω), which relates the electric field vector $\vec{E}$□à the electric induction in the solid D

$$\vec{D}\omega) = \varepsilon(\omega)\vec{E}(\omega)$$

$\varepsilon_2(\omega)$: The imaginary part reflects the absorption of the material

$\varepsilon_1(\omega)$: the real part is related to the polarisation of the medium.

In the case of an isotropic medium :

ε is reduced to a scalar (electromagnetic plane wave)

The two quantities are linked by the relationship:

$$\varepsilon = N^2$$

$$\varepsilon_1(\omega) = n^2 - k^2(\mathrm{w})$$

$$\varepsilon_1(\omega) = 2nk$$

Where:

***n(*ω*)*: Indice de réfraction**

***k(*ω *)* : Coefficient d"extinction**

n(ω): Refractive index

k(ω) : Extinction coefficient

Absorption phenomenon :

Absorption is a physical phenomenon whereby a substance (called an absorber) takes on another form of energy or material, resulting in a transformation of that energy or changes in the structure of the absorbing substance. This phenomenon is essential in various fields of science and technology, such as chemistry, physics, materials and even biology.

Types of Absorption Phenomena :

1.Energetic Absorption

- Light Absorption: When materials absorb photons (light) in certain wavelengths, they can undergo electronic excitation. This phenomenon is often observed in pigments and coloured materials. For example, the green leaves of plants absorb mainly red and blue light for photosynthesis.
- Thermal Absorption: A material absorbs heat, which results in an increase in its temperature. For example, dark surfaces absorb more heat than light surfaces.

2. Absorption of Matter :

Physical Absorption (or Physisorption): This involves a weak interaction (Van der Waals forces) between the absorbing material and the absorbed molecules, as in gas separation.

Chemical Absorption (or Chimisorption): This is a stronger interaction, involving chemical bonds between the absorbed molecules and the material. This phenomenon is crucial in applications such as catalysts.

Applications of Absorption :

Chemical Analysis: Absorption is used in techniques such as UV-Vis spectroscopy to determine the concentration of substances in a solution.

Photovoltaics: Absorbing materials in solar cells play a key role in converting sunlight into electricity.

Radiation protection: Absorbent materials are used to attenuate radiation, as in protective clothing against ionising radiation.

Water treatment: Use of materials that absorb pollutants in water, such as ion exchange resins to remove heavy metals.

Optical reflection :

Optical reflection is a physical phenomenon whereby a light wave (or any other wave) changes direction when it encounters a surface. This phenomenon is fundamental to optics and forms the basis of many applications, such as mirrors, lenses and optical instruments.

The interaction of light with an isotropic medium can also be described by the index of refraction n and absorption K, which respectively characterise the phase and attenuation of the plane wave in the material medium.

The reflection coefficient R(ω) :

Where:

$\boldsymbol{R(\omega)}$: is the amplitude of the reflection coefficient

$$R(\omega) = \frac{E(réfl)}{E(inc)} = \rho(\omega)\exp i\theta(\omega)$$

Where:

ρ(ω) : is the amplitude of the reflection coefficient

θ(ω) : is the phase of the reflection coefficient

The reflection coefficient is related to the refractive index n(ω) and absorption index K(ω) of a crystal by the following relationship:

$$R(\omega) = \frac{(n-1) - K^2}{(n+1)^2 + K^2}$$

Questions

and

answers

Questions :

- What types of piezoelectricity are there?
- What materials possess the piezoelectricity effect?
- What are the applications of piezoelectricity?
- What are the properties of polar crystals?
- What is the difference between dielectric ceramics and insulating ceramics (examples)?
- List the types of magnetic properties

Choose the Correct Answer

1. **What phenomenon are semiconductors sensitive to in order to modulate their conductivity?**
   - □ Temperature
   - □ Pressure
   - □ Humidity
2. **What element is commonly used in semiconductor devices?**
   - □ Iron
   - □ Silicon
   - □ Lead
3. **What is the main characteristic of semiconductors?**
   - □ They always conduct electricity
   - □ They are not affected by temperature
   - □ Their conductivity depends on external conditions
4. **Silicon is:**
   - □ An insulator
   - □ A conductor
   - □ A semiconductor
5. **An insulator has a resistivity of:**
   - □ Very high
   - □ Very low
   - □ Variable depending on temperature

6. **The addition of impurities to a semiconductor to modify its conductivity is called:**
   - □ Thermal conductivity
   - □ Polarization
   - □ Doping
7. **Silicon is used in semiconductors because:**
   - □ It is inexpensive and abundant
   - □ It has an appropriate bandgap
   - □It can be easily doped
8. **In semiconductors, the energy bandgap is:**
   - □ Very large
   - □ No energy gap
   - □ Of intermediate size
9. **In an n-type semiconductor:**
   - □ The majority carriers are holes
   - □ The majority carriers are electrons
   - □ The conductivity is zero
10. **Among the applications of semiconductors, we find:**
    - □ Electric wires
    - □ Building materials
    - □Diodes and transistors
11. **The dielectric constant of a material is:**
    - □ A measure of its conductivity
    - □ A measure of its ability to be polarized
    - □ A measure of its critical temperature
12. **Which of the following materials is a good dielectric?**
    - □ Copper
    - □ Plastic
    - □ Silver
13. **When an electric field is applied to a dielectric, it:**
    - □ Becomes a conductor

• □Becomes polarized

• □ Emits free electrons

14. **Dielectrics are primarily used for:**

• □ Increasing electric flux

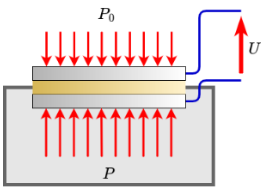
• □ Storing energy in capacitors

• □ Reducing electrical resistance

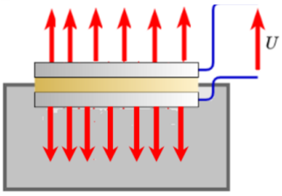
Answer:

- Types of piezoelectricity :

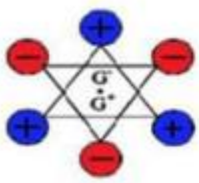
✓ **Direct effect :**

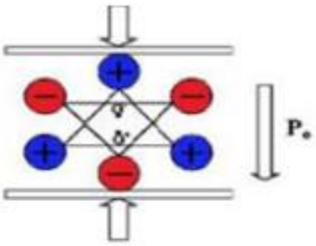


✓ **Reverse effect :**



- What materials possess the piezoelectricity effect?
  - ✓ Piezoelectric materials are crystals that do not have a center of symmetry.





Of the 32 crystalline classes, 21 are non-centrosymmetrical (lacking a center of inversion) and exhibit the piezoelectric effect.

Example: There are some 200 piezoelectric materials used in energy-harvesting applications: quartz crystals, ceramics (barium titanate ($BaTiO3$)), polymers (polylactic acid (PLA)).

- What are the applications of piezoelectricity?

✓ Piezoelectricity applications: Piezoelectric motors, Actuators in the industrial sector, Sensors in the medical sector....

- What are the properties of polar crystals?
- ✓ polar crystal properties: Piezoelectricity, Electrostrictivity, Optical properties ....
- What is the difference between dielectric ceramics and insulating ceramics (examples)?
- ✓ The distinction between insulating and dielectric ceramics is based primarily on their electrical properties and applications.
- ✓ Examples:

 Dielectric ceramics: barium titanate ($BaTiO_3$), titanium zirconate (PZT), lithium silicate (Li_2SiO_3).

 Ceramic insulators : Alumina (Al_2O_3), zirconia (ZrO_2), and alumina silicate.

- List the types of magnetic properties
- ✓ Types of magnetic properties: Ferromagnetism, Paramagnetism, Diamagnetism, Antiferromagnetism, Ferrimagnetism.

Choose the Correct Answer

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Reference :

[1] **K. Talbi** polycopie electromagnétism 2023-2024 Relizane University

[2] : **B.DJELLALI** mémoire ELABORATION ET ARACTERISATON D'UNE CERAMIQUE DIELECTRIQUE A BASE DE PALYGORSKITE 2015/2016

[3] **A. Belayachi** THEORIE DE DRUDE POUR LES METAUX ,Université Mohammed V – Agdal

[4] **B. Marchetti** écanismes de la conduction électrique dans les solides

[5] **H.Salmi** Mémoire de MAGISTER, L'effet de la pression sur les propriétés électroniques et optiques des composés LiMgX (X=N, P, As).