MATERIALS CHEMISTRY: PROPERTIES AND APPLICATIONS

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1. Introduction To Material Chemistry

Life in the 21st century relies heavily on various advanced materials. We often take for granted the micro- and nanoscale components that make up everyday items like microwaves, laptops, cell phones, tablets, and modern transportation. Yet, we seldom appreciate the materials behind these technological advances (Heilbron, 2003; Wright & Sommerdijk, 2018). Materials can be broadly defined as any solid-state substance or device used to meet societal needs, from basic building materials like glass, wood, and aluminum to nanoscale components that may not yet be widely utilized. A general classification of various types of materials is illustrated in Fig. 1.1. Classification of materials can be ambiguous; for instance, thin films under 1 μm may be classified as 2-D nanomaterials if thinner than 100 nm. Liquid crystals have properties between amorphous and crystalline phases, and composites often include both inorganic and organic elements (Brush, 1988; Shirota, 2000). Materials chemistry broadly focuses on the relationships between the atomic, ionic, or molecular structures of materials and their physical and chemical properties. This encompasses fields like polymer chemistry, solid-state chemistry, and surface chemistry. The discipline involves analyzing the structure and properties of current materials, creating and characterizing new materials, and employing advanced computational methods to understand both existing and yet-to-be-fabricated materials (Fahlman, 2023). The field has evolved significantly over the past few decades, driven by advances in technology and a deeper understanding of molecular and atomic interactions. Materials chemists utilize principles from chemistry, physics, and engineering to create materials that meet specific functional requirements, leading to innovations in various industries such as electronics, healthcare, energy, and environmental science (Cahn, 2001)(Ozin et al., 2009). The significance of materials chemistry is multifaceted, encompassing its impact on scientific progress, technological advancements, and societal development. One of the core contributions of materials chemistry is its ability to convert raw materials into advanced functional materials with tailored properties. This transformation is critical for the development of high-performance products that enhance efficiency, durability, and functionality across various applications.

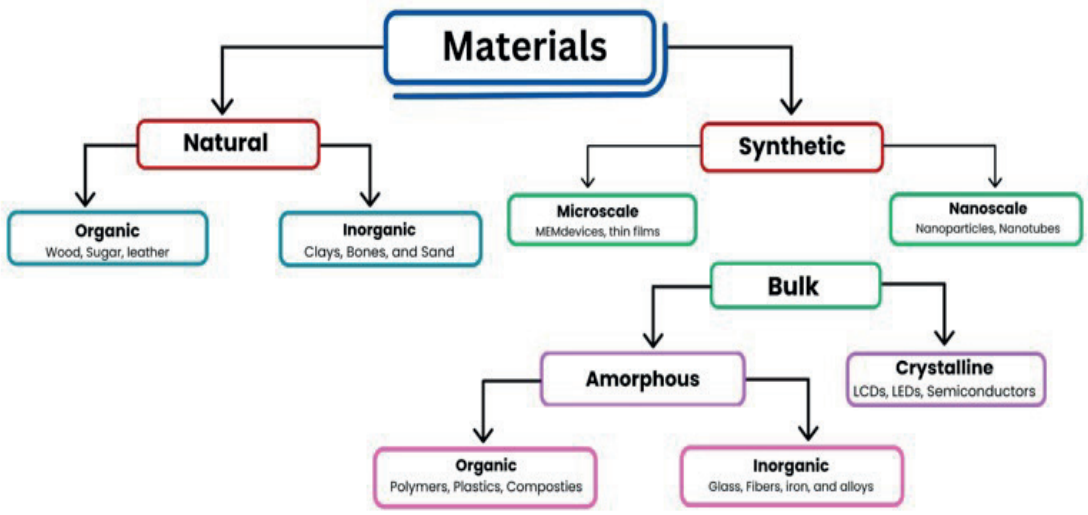


Figure 1. General classification of various types of materials

Materials chemistry is central to the development of new energy solutions. For instance, the quest for sustainable energy sources has led to the creation of high-efficiency photovoltaic cells, which convert sunlight into electricity. These solar cells are often based on novel materials such as perovskites, which have shown remarkable efficiency improvements in recent years (Grätzel, 2001). Additionally, materials chemistry plays a crucial role in the development of energy storage systems, such as batteries and supercapacitors, which are essential for the integration of renewable energy sources into the power grid (Bruce et al., 2008). In the healthcare sector, materials chemistry has led to significant advancements in medical diagnostics and therapeutics. The development of biocompatible materials has revolutionized the design of medical implants and prosthetics, advancing patient wellness and quality of life. Furthermore, materials chemists have developed advanced drug delivery systems that can target specific sites within the body, enhancing the effectiveness of treatment while minimizing side negative consequence (Langer & Peppas, 2003). Environmental protection is another area where materials chemistry has a profound impact. The creation of materials that can remove pollutants from air and water, such as advanced filtration membranes and catalytic converters, is crucial for mitigating environmental contamination. Materials chemistry also contributes to the development of sustainable materials and processes that reduce the environmental footprint of industrial activities (Anastas & Warner, 2000).

Moreover, materials chemistry is integral to the advancement of electronics and information technology. The miniaturization of electronic components and the development of new materials for semiconductors, such as graphene and other two-dimensional materials, have enabled the continued progression of Moore's Law and the creation of faster, more efficient electronic devices (Novoselov et al., 2004). The interdisciplinary nature of materials chemistry fosters collaboration among chemists, physicists, engineers, and biologists, leading to a holistic approach to solving complex scientific and technological challenges. This collaborative effort is essential for the continuous development of innovative materials and technologies that drive economic growth and improve the quality of life globally. This chapter delves into the essential aspects of materials chemistry, encompassing synthesis and fabrication techniques, characterization methods, and the diverse properties of materials. It underscores the importance of understanding the relationships between structure and properties and explores practical applications across various industries. The objective is to provide a comprehensive view of materials chemistry, highlighting both foundational principles and the latest advancements in the field.

The chapter begins with an introduction to materials chemistry, including its significance and scope. It then explores synthesis and fabrication techniques, discussing common methods such as chemical vapor deposition, sol-gel processing, and hydrothermal synthesis, as well as fabrication techniques for different types of materials like thin films, nanoparticles, and composites. This is followed by a section on characterization techniques, covering various methods such as spectroscopy, microscopy, diffraction, and thermal analysis, and their applications in probing material properties at different length scales. The chapter also examines the mechanical, electrical, magnetic, thermal, optical, and chemical properties of materials. An exploration of structure-property relationships follows, illustrating how material structure influences properties, with examples from different classes of materials and discussions on defects, microstructure, and phase transitions. Finally, the chapter highlights practical applications of materials chemistry in industries such as electronics, healthcare, energy, environment, and structural materials.

The primary objectives of this chapter are to provide a foundational understanding of materials chemistry, introduce key synthesis and fabrication techniques, explain various characterization methods and their applications, examine the diverse properties of materials, explore the relationship between material structure and properties, and highlight practical applications of materials chemistry in different industries. Additionally, it aims to inspire further research and innovation in the field. This chapter is intended for a diverse audience, including students at the undergraduate and graduate levels in chemistry, materials science, and related fields, researchers engaged in materials research and development, industry practitioners such as engineers and technologists working in sectors that utilize advanced materials, educators seeking comprehensive resources for teaching materials chemistry, and general readers with an interest in the advancements and applications of materials science.

Materials chemistry is a dynamic and essential field that continues to drive innovation and address critical global challenges. This chapter aims to provide readers with a thorough understanding of the principles, methods, and applications of materials chemistry, equipping them with the knowledge to appreciate its significance and potential. Through detailed discussions and illustrative examples, readers will gain insights into how materials chemistry shapes our world and what future developments might hold.

2. Synthesis and Fabrication Techniques

This chapter dives into the fundamental methods for creating and shaping materials at the heart of material chemistry. We will explore various synthesis techniques, delve into fabrication methods for different material types, and discuss crucial considerations for controlling the final properties of your material.

2.1 Overview of Common Synthesis Methods

2.1.1 Chemical Vapor Deposition (CVD): Precursor chemicals are converted into a solid phase onto a substrate through reactions or decomposition. In chemical vapor deposition (CVD), vapor-phase compounds, typically mixed with an inert carrier gas, undergo a reaction at a heated surface, resulting in the formation of a solid film (POWELL et al., 1966)(Wahl et al., 2014). The significance of CVD lies in its versatility to deposit a wide range of elements and compounds at relatively low temperatures and atmospheric pressure. It allows for the formation of amorphous, polycrystalline, epitaxial, and uniaxially oriented polycrystalline films with high purity. Key aspects of CVD include the chemical reactions, the thermodynamics and kinetics of the reactors, and the transport of material and energy to and from the reaction site. Below is a list of examples of common types of chemical reactions used in CVD (Frey & Khan, 2015).

- **Pyrolysis:** The simplest CVD process, pyrolysis, involves the decomposition of a gaseous compound on a hot surface, resulting in the deposition of a stable residue.

Examples include: Deposition of pyrolytic graphite from methane (CH_4) at a substrate temperature of 2200°C, Deposition of silicon from monosilane (SiH_4) within the temperature range of 800–1350°C, and Deposition of nickel from nickel carbonyl [$Ni(CO)_4$] at approximately 100°C (Tavares et al., 2008).

- **Reduction:** Hydrogen is the most commonly used reducing agent in CVD processes. Examples include deposition of silicon through the hydrogen reduction of silicon tetrachloride ($SiCl_4$) at approximately 1000°C, and deposition of tungsten via the hydrogen reduction of tungsten hexafluoride (WF_6) at around 800°C. Additionally, hydrogen reduction is employed to enhance the pyrolytic process by removing unwanted byproducts as gaseous hydrogen compounds, requiring less energy for their removal.
- **Oxidation:** Silicon dioxide films can be formed through the oxidation of silane (SiH_4) in the presence of oxygen (O_2).
- **Nitridation:** Silicon nitride films can be deposited by reacting silane (SiH_4) with ammonia (NH_3) in a chemical vapor deposition process.
- **Carbidization:** Titanium carbide deposition occur via titanium tetrachloride ($TiCl_4$) and methane (CH_4) reaction at a substrate temperature of 1850°C.
- **Chemical-transport reaction:** In these processes, the targeted material is conveyed from the source to the substrate, where it forms a film, is governed by a difference exists in the equilibrium constants of the reactant source and the carrier phase, and between the substrate and the carrier phase, when each is maintained under varying thermal condition.
- **Spray pyrolysis:** This technique involves dissolving the reagents in a carrier liquid, which is then sprayed on a heated substrate as fine droplets. Upon contact with the hot surface, the solvent dissipates, and the leftover constituents interact to form the intended material. For example, cadmium sulfide films can be produced by spray pyrolysis of a solution containing thiourea and cadmium chloride in water, substrate temperature optimized at 300°C (Chamberlin & Skarman, 1966).

2.1.2 Sol-Gel Processing: Liquid precursors form a colloidal suspension (sol) that transforms into a gel network and then a solid material. The sol-gel method is effective for modifying substrate surfaces, offering the key advantage of achieving high surface area and stability. The properties of sol-gel materials depend on the experimental conditions. The process consists of two main reactions: (1) hydrolysis of the precursor in acidic or basic conditions, and (2) polycondensation of the hydrolyzed products (Pena-Pereira et al., 2012). The key factors contributing to the widespread use of this method are its relative simplicity compared to other coating processes and its ability to significantly improve metallic biomaterial coating layers on the substrate (J. X. Zhang et al., 2011). To prepare the solution (sol), calcium and phosphorus precursors (CaP) are typically combined with distilled water and pure ethanol, which act as solvents (Costa et al., 2012). Ethanol is primarily employed to dissolve phosphorus precursors, such as phosphorus pentoxide or triethyl phosphite. Subsequently, a small amount of water is added to facilitate the hydrolysis of the sol (Kessler et al., 2006). Similarly, to dissolve the calcium precursor, typically calcium nitrate, ethanol is used. The resulting solution is then added drop by drop to the hydrolyzed phosphorus solution (Singh, 2012). Finally, the solution is refluxed at various temperatures to evaporate the solvents. This process is repeated until the solution reaches the desired viscosity, becoming a sol-gel. The chemical composition of the precursors significantly affects the temperature needed for apatite formation and the related chemical activities (Amerinatanzi et al., 2017). Due to its simplicity, the sol-gel process is inexpensive and highly adaptable to various coating compositions and sample

geometries. Additionally, it provides a strong adhesive coating layer, ensuring a robust substrate-coating bond (Qu & Wei, 2008). The dip coating process consists of three steps: dipping, withdrawing, and drying. Samples are immersed in the prepared solution and then withdrawn at a constant speed to achieve a uniform thickness across the substrate's surface.

The sol-gel method is easy, cheap, and provides excellent coatings, leading to its growing applications. Enhancing adhesion and preventing delamination are crucial but under-studied. Research on new precursors and their effects on corrosion resistance and adhesion is needed. Key parameters like pH, solvents, aging, temperature, molar ratios, hydrolysis kinetics, curing, and crack formation during drying and heat treatment should be studied to better control coating properties (D. Wang & Bierwagen, 2009). Current sol-gel methods face limitations due to lengthy preparation, aging, and curing times, and the risk of phase separation during heat treatment, particularly in hybrid coatings. Optimizing both new and existing sol-gel processes is necessary. Sol-gel coatings can be applied via dip coating, spraying, and spinning. A new method, electrochemical deposition, controls pH, colloid concentration, and deposition voltage and time, providing reliable coatings for complex geometries with controllable compositions (Toki et al., 1988). Most sol-gel materials like TEOS (Tetraethyl Orthosilicate) and TMOS (Tetramethyl Orthosilicate) are toxic and expensive. A better solution is to use environmentally friendly materials like silicates and titanates, which have good coating properties. Adding metal particles to the sol can increase coating toughness and thickness. Zinc and magnesium particles, in particular, offer excellent corrosion protection for coated substrates (Philipp & Schmidt, 1984).

2.1.3 Hydrothermal Synthesis: Hydrothermal synthesis utilizes high-temperature and high-pressure water environments to create crystalline materials. Hydrothermal processing yields nanocrystalline inorganic materials through a direct precursor-product correlation, enabling versatile material synthesis without additional structure-directing agents (Whittingham, 1996). In brief, this synthesis method capitalizes on the solubility of most inorganic substances in water under high temperatures and pressures, followed by crystallization from the fluid. Water at elevated temperatures is crucial for the transformation of precursor materials, as implied by the method's name. The synthesis method, commonly referred to as solvothermal, utilizes water as well as other solvents, aligning with the general process principle. Additives may be introduced to modify the properties of pure hydrothermal water. Polar solvents (e.g., NH3, aqueous solutions containing HF or other acids or bases) or even non-polar solvents (e.g., pure, supercritical CO2) can be employed to broaden the method's applicability. However, these solvents may present challenges such as toxicity and corrosion issues for autoclave materials, potentially compromising the simplicity and elegance of the original process (Schäf et al., 2005).

Hydrothermal processing allows for systematic adjustment of both physical and chemical parameters to establish a direct correlation between precursor and product. However, the method is complex due to numerous interacting parameters (Byrappa & Yoshimura, 2001). In-situ observation of the process remains challenging and has not been satisfactorily addressed yet.

Temperature significantly influences the kinetics of product formation and the thermodynamic stability of the product phase. Pressure is crucial for solubility and the supersaturation range, directing the crystallization process and affecting the thermodynamic stability of the product phase (e.g., excessively high synthesis pressure can lead to the crystallization of denser phases). The external pressure mode is preferred to mitigate the influence of temperature-driven autogeneous pressure, making low temperature-high pressure syntheses possible, known as high-pressure hydrothermal synthesis (HPHS). Time is also crucial, with kinetically stable phases favored in short-term processes and

thermodynamically stable phases typically formed in long-term experiments, corresponding to the chosen temperature-pressure regime. This phenomenon arises from re-dissolution and recrystallization of formed phases. Additionally, factors like convection within the reaction vessel and the state of aggregation of precursor materials (e.g., macroscopic crystals, nanocrystalline phases, or glass) must be considered to effectively control the process parameters (Schäf et al., 2005).

2.2. Fabrication Techniques for Different Materials

2.2.1 Thin Films: Thin films are layers of material with thicknesses ranging from several nanometers to micrometers, created by the precise condensation of atoms, molecules, and ions onto substrates. This process is achieved either directly through physical methods or via chemical and electrochemical reactions (Chopra & Kaur, 1983). Due to the numerous benefits of using thin films in batteries, solar cells, and various electronics, a wide range of techniques has been developed for their fabrication. The fabrication techniques for thin films can be divided into two categories: (1) gas phase methods and (2) liquid phase methods as outlined in Table 1.

Table 1. List of some well-established techniques for fabricating thin films.

Gas phase methods	Liquid phase methods
1. Magnetron sputtering	1. Electrospray deposition
2. Pulsed laser deposition	2. Electrochemical deposition
3. Atomic layer deposition	3. Sol-gel method
4. Chemical vapor deposition	4. Molecular precursor method

In this context, gas-phase fabrication techniques deposit materials sourced from small particles of bulk solids or vaporized chemical precursors. In contrast, liquid-phase fabrication techniques entail a reaction between a substrate and a chemical precursor in liquid form (Lu & Nagai, 2019).

2.2. Nanoparticles: Different synthesis methods can produce various types of nanostructures, which are defined by having at least one or two dimensions within the 1–100 nm range. Nanoparticles can be synthesized through several techniques, such as co-precipitation, hydrothermal synthesis, sputtering, sol-gel processing, ultrasound treatment, microwave synthesis, and inert gas condensation. These methods are capable of producing both dry particles and nanoparticles dispersed in liquid. Nanostructures can be formed either by assembling them from individual atoms or by reducing the size of microparticles to the nanoscale (Rane et al., 2018). Methods such as wet chemical synthesis, hydrothermal synthesis, and ultrasonic processing allow for precise control over the size, shape, and surface properties of nanoparticles (Jamkhande et al., 2019).

2.2.3 Composites: A typical composite material comprises two or more distinct materials combined and bonded on a macroscopic scale. Generally, a composite material includes reinforcement elements (such as fibers, particles, flakes, or fillers) embedded within a matrix (which can be polymers, metals, or ceramics). The matrix maintains the structure and shape, while the reinforcement elements enhance the mechanical properties of the composite. When properly designed, the combined material exhibits superior strength compared to the individual components (Nagavally, 2016).

There are various methods for fabricating composite components. Some, like injection molding, are adapted from other fields, while others are specifically developed to address unique design or manufacturing challenges. The choice of method depends on the materials, part design, and intended application. Composite fabrication processes typically involve molding to shape the resin and reinforcement. A mold tool is essential to form the resin/

fiber combination into the desired shape before and during curing.

Various techniques are used for the fabrication of composites tailored to application needs, including hand lay-up, filament winding, resin transfer molding (RTM), and autoclave processing (Nagavally, 2016; Summerscales, 1991). Hand lay-up is cost-effective and versatile, ideal for large structures like boat hulls, though labor-intensive and less consistent. Filament winding, perfect for cylindrical shapes like pipes, offers high precision but is limited to rotationally symmetric components. RTM, a closed-mold process, produces high-quality parts with excellent surface finishes, suitable for aerospace and automotive industries, though it requires expensive tooling and longer cycle times. Autoclave processing, used for critical aerospace components, delivers the highest quality composites with minimal void content, but is costly due to the high expenses of autoclaves and tooling. Each technique balances mechanical properties, production volume, and cost (Nagavally, 2016).

2.3. Considerations for Controlling Material Properties

Controlling material properties is a critical aspect of materials science and engineering, as it directly impacts the performance, reliability, and durability of materials in various applications. Several factors must be considered to effectively control and optimize material properties, including precursor selection, reaction conditions, processing parameters, environmental conditions, and testing methods.

2.3.1 Precursor Selection

The tarting materials play a crucial role in determining the ultimate composition and characteristics of the material. Choosing the appropriate precursors can determine the purity, phase, and elemental constituents of the synthesized material. For instance, in the synthesis of advanced ceramics, the choice of precursors affects the grain size, porosity, and mechanical strength of the final product (Callister, 1997). High-purity precursors are often preferred to minimize impurities that could negatively affect the material's performance (Lark-Horovitz & Johnson, 1959).

2.3.2 Reaction Conditions

Temperature, pressure, and reaction time are critical factors that influence crystallinity, morphology, and defect concentration in materials. For example, variations in annealing temperature can affect the grain size and phase distribution in metals, thereby impacting their mechanical properties (Shaba et al., 2021). Similarly, in polymer synthesis, reaction conditions such as temperature and catalyst concentration can dictate the molecular weight distribution and, consequently, the mechanical and thermal properties of the polymer (Rudin, 1989).

2.3.3 Processing Parameters

Fabrication techniques like deposition rate, solution concentration, and processing temperature play crucial roles in shaping the final material. In thin-film deposition, the deposition rate and substrate temperature can affect the film's thickness, crystallinity, and surface roughness (Acosta, 2021). For composite materials, the concentration of the matrix and reinforcement phases, along with the curing temperature, can significantly influence the composite's mechanical strength and thermal stability (Bouhfid et al., 2019).

2.3.4 Environmental Conditions

Environmental conditions during processing and in-service environments can significantly impact material properties. Factors such as temperature, humidity, and exposure to chemicals or radiation need to be controlled to achieve the desired performance of materials.

For instance, metals exposed to high temperatures during processing can experience grain growth, which might reduce their mechanical strength (Akbarpour & Kim, 2015). In polymers, prolonged exposure to UV radiation can lead to photo-oxidative degradation, affecting their mechanical properties and color (Luyt & Malik, 2019).

2.3.5 Testing and Characterization

Accurate testing and characterization are essential to understand and control material properties. Techniques such as tensile testing, hardness testing, scanning electron microscopy (SEM), and X-ray diffraction (XRD) provide valuable insights into the mechanical, microstructural, and compositional attributes of materials (C. Suryanarayana, 1998). By thoroughly characterizing the material, engineers can identify any deviations from the desired properties and make necessary adjustments in the processing or material selection.

2.3.6 Alloy Design and Composition Control

Alloy design is a sophisticated approach to controlling material properties by precisely manipulating the composition of metallic elements. Progress in computational materials science has facilitated the development of high-performance alloys customized to meet specific application requirements. The addition of elements such as carbon, manganese, and vanadium in specific proportions can significantly enhance the wear resistance, hardness, and toughness of steels (Han et al., 2021). Moreover, modern techniques like additive manufacturing allow for the creation of functionally graded materials, where the composition varies gradually to optimize performance at different sections of the component.

2.3.7 Surface Treatments

Surface treatments are another crucial consideration for controlling material properties, especially in applications where surface interactions play a significant role. Techniques such as surface hardening, coating, and plating can enhance surface properties like wear resistance, corrosion resistance, and friction characteristics. For instance, nitriding or carburizing can significantly increase the surface hardness of steel components, thereby extending their service life in demanding applications (Bell, 1991).

2.3.8 Residual Stresses and Defects

Managing residual stresses and minimizing defects are important for maintaining the integrity and performance of materials. Residual stresses, which can arise from differential cooling rates during processing, can lead to distortion, cracking, and premature failure. Techniques such as stress-relief annealing, and controlled cooling can help mitigate these stresses (Schajer & Ruud, 2013). Additionally, identifying and reducing defects such as porosity, inclusions, and cracks through improved processing techniques and quality control measures is vital for ensuring material reliability.

2.3.9. Thermomechanical Treatments

Thermomechanical treatments combine thermal and mechanical processing to refine grain structures and enhance material properties. Processes such as rolling, forging, and hot isostatic pressing (HIP) can improve the mechanical strength, toughness, and fatigue resistance of materials. For instance, thermomechanical processing of titanium alloys can result in a fine, uniform microstructure that enhances their performance in aerospace applications (Alluaibi & Cojocaru, 2018).

3. Characterization Techniques

3.1 Overview of Characterization Methods

Characterization techniques are essential tools in material science, providing detailed information about the composition, structure, and properties of materials. These methods can be broadly categorized into spectroscopy, microscopy, diffraction, and thermal analysis.

3.1.1 Spectroscopy: Spectroscopy techniques, such as infrared (IR), nuclear magnetic resonance (NMR), and Raman spectroscopy are employed to identify chemical compositions and molecular structures. IR spectroscopy detects and analyzes the absorption of infrared radiation by molecules, thereby identifying the specific functional groups present in a material (B. H. Stuart, 2005). NMR spectroscopy utilizes the magnetic properties of nuclei to determine the structure and dynamics of molecules (Marion, 2013). Raman spectroscopy involves the scattering of light by molecular vibrations, providing a fingerprint of molecular structure (Andre Lyon et al., 1998).

3.1.2 Microscopy: Microscopy techniques, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), optical microscopy, and atomic force microscopy (AFM), allow visualization of materials at various scales. Optical microscopy uses visible light to magnify images of small objects, useful for biological samples and general imaging (Huang & Murphy, 2004). SEM provides high-resolution images of surfaces using a focused electron beam, revealing topographical and compositional information (de Assumpcão Pereira-da-Silva & Ferri, 2017). TEM transmits electrons through a thin sample, providing atomic-scale resolution of internal structures (Williams & Carter, 1996). AFM utilizes a cantilever featuring a sharp tip to scan surfaces at the nanoscale, measuring topography and mechanical properties (Giessibl, 2003).

3.1.3 Diffraction: X-ray diffraction (XRD) and electron diffraction are essential techniques for determining crystallographic structures. XRD involves directing X-rays at a material and analyzing the resulting diffraction pattern to identify phases and measure lattice parameters (Ali et al., 2022). Electron diffraction, often used in conjunction with TEM, provides information on crystal orientation and defects (Bendersky & Gayle, 2001).

3.1.4 Thermal Analysis: Thermal analysis techniques, including techniques such as thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and dynamic mechanical analysis (DMA), investigate how the properties of materials vary with temperature. DSC measures heat flows associated with phase transitions, such as melting and crystallization (Haines et al., 1998). TGA monitors weight changes as a material is heated, indicating thermal stability and composition. DMA assesses mechanical properties like modulus and damping as a function of temperature and frequency (Prime et al., 2009).

3.2. Principles and Applications of Various Techniques

Each characterization technique is based on specific principles and is suited for probing different material properties.

3.2.1 Spectroscopy

3.2.1.1 Infrared (IR) Spectroscopy:

Principle: IR spectroscopy is based on the absorption of infrared light by molecules, causing vibrations in the molecular bonds. When IR radiation passes through a sample, certain wavelengths are absorbed, corresponding to the vibrational frequencies of the bonds in the molecules. The resulting IR spectrum represents the absorbed light as a function of wavelength or frequency (B. Stuart, 2021).

Mechanism: Different functional groups in a molecule absorb characteristic frequencies of IR radiation, allowing for identification of these groups. For instance, a carbonyl group (C=O) typically absorbs strongly near 1700 cm -1. The IR spectrum acts as a molecular fingerprint that can be used to identify and quantify different components in a sample.

Applications: Used for identifying functional groups in organic and inorganic compounds, studying chemical bonding, and analyzing complex mixtures in fields like pharmaceuticals, polymers, and environmental science.

3.2.1.2 Nuclear Magnetic Resonance (NMR) Spectroscopy:

Principle: NMR spectroscopy exploits the magnetic properties of certain atomic nuclei. When placed in a strong magnetic field, nuclei such as ^1H or ^13C absorb and re-emit electromagnetic radiation at characteristic frequencies, dependent on the local chemical environment (Andre Lyon et al., 1998).

Mechanism: The resonance frequency of a nucleus in a magnetic field is influenced by the surrounding electron cloud, which provides information about the molecular structure. The resulting NMR spectrum displays chemical shifts, multiplicity (splitting patterns due to spin-spin coupling), and integration (relative number of nuclei contributing to each signal).

Applications: Widely used in organic chemistry and biochemistry to determine molecular structure, study dynamics, and investigate molecular interactions.

3.2.1.3 Raman Spectroscopy:

Principle: Raman spectroscopy is based on the inelastic scattering of light (Raman scattering). When monochromatic light (usually from a laser) interacts with a sample, most photons are elastically scattered (Rayleigh scattering). A small fraction of photons is inelastically scattered, experiencing a shift in energy corresponding to vibrational modes of the molecules (Ferrari et al., 2004).

Mechanism: The Raman effect results in a spectrum that offers insights into rotational, vibrational, and other low-frequency modes within a system. The shifts in the scattered light frequency are specific to the molecular vibrations, providing a complementary technique to IR spectroscopy.

Applications: Used for characterizing molecular structures, studying chemical compositions, and investigating material properties in fields such as chemistry, materials science, and biology.

3.2.2 Microscopy

3.2.2.1 Optical Microscopy:

Principle: utilizes visible light and lenses to magnify and observe small objects. The resolution is limited by the wavelength of light, typically around 200 nm for visible light (Huang & Murphy, 2004).

Mechanism: Light emitted from a source is concentrated onto the sample using objective lenses, and the transmitted or reflected light is collected to form an image. Advanced techniques like fluorescence microscopy use specific wavelengths to excite fluorescent molecules, providing detailed images of biological specimens.

Applications: Commonly used in biological sciences for examining cell structures, tissues, and microorganisms. Also used in materials science for studying microstructures of metals and polymers.

3.2.2.2 Scanning Electron Microscopy (SEM):

Principle: SEM utilizes a concentrated beam of high-energy electrons to scan the surface

of a sample. The interactions between the electrons and the sample atoms produce signals that are detected to form detailed images (Goldstein et al., 2018).

Mechanism: Upon striking the sample, the electron beam generates secondary electrons, backscattered electrons, and characteristic X-rays. Secondary electrons yield details regarding surface topography, whereas backscattered electrons provide contrast based on composition. X-ray signals can be used for elemental analysis.

Applications: Extensively used for high-resolution imaging of surfaces, studying microstructures, and compositional analysis in materials science, nanotechnology, and biological sciences.

3.2.2.3 Transmission Electron Microscopy (TEM):

Principle: TEM operates by passing a beam of electrons through an ultra-thin sample. The transmitted electrons are focused to form an image with atomic-scale resolution (Howe et al., 2012).

Mechanism: The electron beam interacts with the sample, leading to scattering based on the atomic structure. The scattered electrons are collected to produce an image, which can show detailed crystallographic and morphological information. Techniques like electron diffraction and high-resolution TEM (HRTEM) further enhance structural analysis.

Applications: Used for atomic-scale imaging of materials, studying crystallography, and investigating defects and interfaces in materials science and nanotechnology.

3.2.2.4 Atomic Force Microscopy (AFM):

Principle: AFM employs a cantilever equipped with a sharp tip to scan across the surface of a sample. The forces between the tip and the sample surface cause deflections of the cantilever, which are measured to create a topographical map (BLANCHARD, 1996).

Mechanism: As the tip scans across the surface, interactions such as van der Waals forces, electrostatic forces, and mechanical contact cause the cantilever to bend. A photodiode detects the laser beam reflected off the backside of the cantilever to measure these deflections with high precision.

Applications: Used for nanoscale imaging of surface topography, mechanical property measurement, and manipulation of nanostructures in materials science, biology, and nanotechnology.

3.2.3 Diffraction

3.2.3.1 X-ray Diffraction (XRD):

Principle: XRD is based on the constructive interference of X-rays that are scattered by the periodic atomic planes in a crystalline material. The angles and intensities of the diffracted beams reveal information about the crystal structure. (Ali et al., 2022).

Mechanism: When X-rays hit a crystal, they are diffracted in specific directions defined by Bragg's law ($n\lambda = 2d \sin\theta$), where n is an integer, λ is the wavelength, d is the distance between atomic planes, and θ is the diffraction angle. The resulting diffraction pattern is analyzed to determine lattice parameters, phase identification, and crystallite size.

Applications: Widely used for identifying crystalline phases, determining crystal structures, studying polycrystalline materials, and analyzing thin films and coatings in materials science and chemistry.

3.2.3.2 Electron Diffraction:

Principle: Electron diffraction relies on the wave nature of electrons. When a beam of electrons interacts with a crystalline sample, the electrons are diffracted, producing patterns that

can be analyzed to gain structural information (Ali et al., 2022).

Mechanism: Similar to X-ray diffraction, the electrons are scattered by the periodic atomic structure, creating diffraction patterns that provide information about crystal orientation, interatomic spacing, and defects. Techniques like selected area electron diffraction (SAED) in TEM are commonly used.

Applications: Used for crystallographic analysis of small volumes, nanocrystalline materials, and defects in materials science and solid-state physics.

3.2.4 Thermal Analysis

3.2.4.1 Differential Scanning Calorimetry (DSC):

Principle: DSC measures the heat flow into or out of a sample during heating or cooling, providing information about thermal transitions such as crystallization, melting, and glass transitions (Haines et al., 1998).

Mechanism: The sample and a reference are exposed to a precisely controlled temperature program. The heat flow needed to keep both the sample and reference at the same temperature is recorded. Detecting endothermic (heat-absorbing) and exothermic (heat-releasing) events enables the analysis of phase transitions and thermal characteristics.

Applications: DSC is employed to investigate the thermal characteristics of polymers, pharmaceuticals, and various materials, encompassing melting points, crystallization behavior, and glass transition temperatures.

3.2.4.2. Thermogravimetric Analysis (TGA):

Principle: TGA computes the variation in mass of a sample as it is undergoes thermal energy increment, apprise about thermal strength, composition, and decomposition operations (Prime et al., 2009).

Mechanism: The sample is positioned on a balance with a conditional atmosphere (inert or reactive). As the temperature elevated, evaporation caused mass change, decomposition, or oxidation are monitored. The outcome TGA curve imply weight changes as a repercussions of temperature.

Applications: Utilized to examine the thermal stability and chemical composition of analysis, analyze decomposition kinetics, and study the effects of additives in polymers and composites.

3.2.4.3 Dynamic Mechanical Analysis (DMA):

Principle: DMA characterize the mechanical durability of a material as it is deformed in the course of periodic stress, providing information about viscoelastic behavior, modulus, and damping (Placet & Foltête, 2010).

Mechanism: The sample is subjected to an oscillating force, and the following distortion (strain) is analyzed. The storage modulus (elastic response), loss modulus (viscous response), and damping factor (tan δ) are determined as functions of temperature and frequency.

Applications: Examine the viscoelastic behavior of polymers, composites, additionally biological materials, including glass transition temperatures, relaxation processes, and mechanical performance.

3.3. Importance of Characterization in Understanding Structure-Property Relationships

Characterization techniques are indispensable for understanding the structure-property relationships in materials. By elucidating the detailed structure of materials, these techniques enable the optimization of material properties for specific applications. For example:

Material Design: Tailoring materials with specific properties by understanding how atomic or molecular structures influence macroscopic behaviors. For instance, controlling the degree of crystallinity in polymers can significantly impact their mechanical strength and thermal properties (Chung, 2017).

Quality Control: Ensuring materials meet specified standards and perform reliably in industrial settings. Techniques like XRD and SEM are routinely used to monitor manufacturing processes and assess material quality (Ali et al., 2022).

4. Properties of Materials

Metals have properties like mechanical, thermal, electrical resistivity, and optical properties. As with people, various materials respond differently to different conditions and the reactions determine their application in our daily lives and particular uses. Like suits, scientists and engineers owe it to it to understand these characteristics and design materials that are suitable for our technological requirements (Askeland et al., 2003). The understanding of material characteristics is the fundamental starting point of designing durable yet lightweight structures for constructions and vehicles, as well as sophisticated technological products, and medical equipment. When we explore and even try to manipulate these attributes, what we find is a world teeming with possibilities, which adds to the ever-growing potential in every single aspect of our lives. Materials are solid-state substances or technology that can satisfy current, or future wants in society. The concept of property requires clarification: when materials are used, they undergo certain reactions due to the external forces which come into contact with them. For instance, a substance can become deformed by external forces and a smooth metal surface can reflect light. An attribute is an inherent characteristic of an object that determines its identity and the manner in which it responds to a certain treatment. Usually, the property definitions are set without paying attention to the shape or size of the material under consideration (Mittemeijer, 2010).

Materials can be categorically assigned into six core groups established on their significant qualities: mechanical, electrical, thermal, magnetic, optical, and deteriorative. Strength, toughness, and elastic modulus (stiffness) are mechanical characteristics that help define a relationship between deformation and an externally applied load or force. An electric field serves as the driving force for electrical characteristics including electrical conductivity and dielectric constant. Specific heat capacity and thermal conductivity are two factors that define the thermal properties of a solid body. Magnetic properties can be determined by how a material behaves under an applied magnetic field. When it comes to optical qualities, light or also called electromagnetic radiation serves as the stimulus. Specific optical properties include reflectivity and index of refraction (Callister, 1997). Apart from structure and characteristics, science and engineering of materials also include important factors of performance as well as processing. The processing method of a material with reference to these which composed of four critical parts, defines sample configuration. In addition, the properties of a material define the material.

4.1 Mechanical Properties:

Failure is common with many materials during operation; for instance, the aluminum alloys used in airplane wings and the steel used in automobile axels. It is therefore paramount for one to recognize the various qualities of the material and design their parts in order to avert excessive deformation and fractures. Mechanical design exclusively depends on the characteristics of this material and its capabilities manifested in terms of stiffness, strength, hardness, ductility, and toughness (Pelleg, 2013). These properties also indicate how a material behaves when subjected to loads or pressures that are exerted on it. Comprehensively organized laboratory tests, which mimic service conditions, are performed to accomplish ascertain the mechanical properties of a material. External conditions and the nature and time for which the load is applied should also be taken into account. The load can be either shear, compressive, or tensile, and can either be variable

at any time or fixed at any given time. Its duration can range from several seconds to several years depending on the sort of application being made. The service temperature may be the key factor.

4.1.1 Understanding Strength in Metals

Strength is one of the main mechanical characteristics that define how well metals can handle laid on them forces. It is a major aspect of determining whether a given metal is suitable for a certain structural or technical application. Four mechanical properties of strength commonly utilized include tensile strength, compressive strength, yield strength and ultimate strength. All these categories play a role in explaining how a particular metal will behave under certain loads and conditions.

There are various measures of strength; however, the most common one is tensile strength. Tensile strength on the other hand means the amount of stress that can be applied on a material particularly a metal in cases of tension force before it breaks. Tensile test is one in which a material is deliberately placed under fixed tensile stress to its failure in order to obtain its tensile strength. This property is very vital in materials that are likely to come under tension or in such applications as cables, bridges, and beams which are normally under pulling forces. Some of the frequently used units of pressure measurement include Megapascal (MPa) and Pounds Force per square inch (psi). Tensile strength is reportedly the most commonly used value for expressing strength. Tensile strength refers to the maximum stress that is usually placed on any such metal before it fractures. Tensile test refers to the stretching of a sample to the point of failure under a specific load in order to establish tensile strength. This feature is rather significant for the materials used in various structures such as cables, bridges, and beams as they are exposed to tensile stresses. Typically, pressure is expressed in term of pound force per square inch (psi) or in megapascal (MPa).

Compressive Strength: It is the ability of a metal to withstand loads that tends to reduce its cross-sectional area by compressing it. This is especially necessary in structures where weight or layers of the metal are likely to buckle when pressed with pressure such as in columns, support systems, and foundations. While some ductile materials have similar tensile and compressive strength values, brittle materials may drastically differ in these values where the latter is usually higher as compared to the former. When stress is applied it can be seen that many metals display certain elastic and flexible behavior. Metals must have the characteristic of the ability to deform at the elastic area and then regain their initial form after the stress has been released. The slope of the curve in the specific region is recognized as the modulus of elasticity or Young's modulus, which characterizes the stiffness of a material. In this region the metals get its permanent set and deformed irreversibly since the imposed load is beyond the yield limit. Ductility is the capacity of a metal to deform in the flexible state without breaking and is part of mechanical properties.

The Ultimate Tensile Strength (UTS) on the other hand is the maximum tensile stress that a material can withstand in tension associated with other materials such as metals when exposed to tension forces. Beyond this point another process referred to as necking occurs whereby the metal flow reduces in cross sectional area until it reaches the point where it fractures. The ultimate strength of a metal is necessary to understand the limits of using the particular metal if it is exposed to the maximum load application. Forces such as composition, microstructure, and production methods are the main determinants of metals strength. The process of adding alloying elements also helps to enhance the overall strength of the primary metals. For instances when carbon is added into iron it gets combine to form steel which has a much higher strength than that of iron heat treatments like quenching and tempering have the ability to modify the microstructure of metals, resulting in improved strength and hardness.

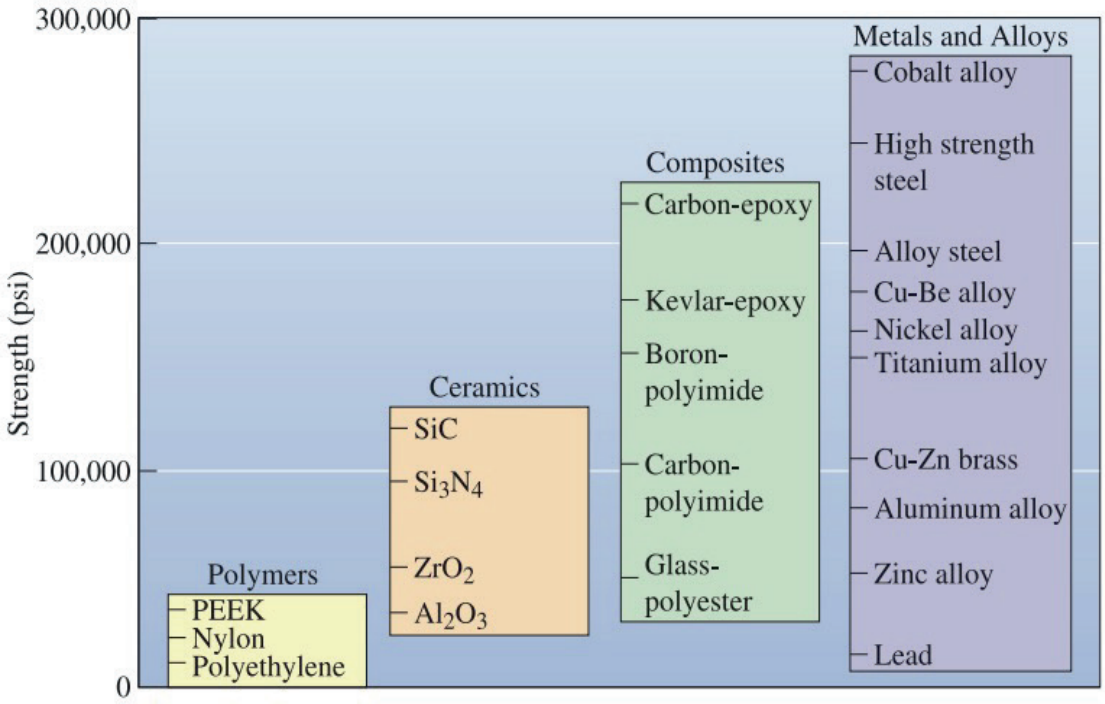


Figure 2. Strengths of materials

The practical use of metals is based on their inherent strength, which allows structures to endure and sustain both load-bearing and operational loads without experiencing any catastrophic failure. The strength of metals is a fundamental aspect of modern engineering and design, whether it be in the construction of skyscrapers, the manufacturing of machinery, or the fabrication of common consumer products. Gaining knowledge and enhancing the effectiveness of metals enables the creation of products and buildings that are safer, more efficient, and have a longer lifespan.

4.1.2 Hardness

Hardness is one of the essential mechanical properties that reflect the ability of the material to bear deformation, indentation, or scratching. It is an important property which is very important in the determination of the ability of a material to perform under conditions of friction and erosion. By defining hardness, engineers and designers can then choose the right materials for specific applications, thereby guaranteeing the longevity of products and structures. Hardness can be scientifically described as the material characteristic to withstand the formation in relation to permanent indentations at a very localized scale and can therefore be viewed as a gauge of the extent of ease regarding the materials surface is capable of being altered permanently. This attribute is most important especially where the material may be used in applications that might involve physical contact such as cutting tools, bearings, gears and surface coatings.

There are many approaches to the determination of the hardness of material with each method being applicable to specific classes of materials and purposes. Some of the common techniques used in hardness testing are Brinell, Rockwell, Vickers, Knoop, and Mohs hardness. A Brinell test is a technique that involves pressing a hard steel or carbide ball against a material's surface with a certain force. They assert that this test is particularly ideal when it comes to assessing the hardness of material that has a rough or an irregular surface. The Rockwell test is employed to determine the depth of the indentation made by a considerable load, then a smaller load, and is applicable for various materials (Pintaude, 2023). The Vickers test uses a diamond pyramid indenter to obtain accurate results for delicate materials and tiny parts. The Knoop hardness test, which is similar to the Vickers test, employs a pyramidal diamond indenter that is more extended and ideal for measuring the hardness of ceramic materials and thin layers. Mohs test is a qualitative procedure

to rank materials by the way they scratch which helps in identification of minerals.

The material hardness of a substance depends on its composition, microstructure, heat treatments and work hardening. From the viewpoint of material chemistry, the hardness of a material depends significantly on its composition which defines the kinds as well as the proportions of the components used in making the material. The process of strengthening steel is achieved by adding carbon to iron since carbides limit the flow of dislocations and thus increases the toughness of the metal. Grain size and the organization aspect influences the hardness of materials and thus the microstructure. Normally, a material with fine grains is harder than the material with coarse grains, mainly because of grain refining mechanism at grain boundaries. Quenching and tempering are some of the heat treatments that affect the hardness of a metal through the alteration of its microstructure. Tempered steel is stronger than annealed steel because it forms martensite. Similarly, the formation of plastic deformation during the operations like machining and forming improves the hardness of a material through the process of work hardening, particularly in metals like copper and aluminum.

Various industrial processes rely on the understanding and control of hardness. For instance, when using steel to produce cutting tools, it is desirable that hardness is high in order to reduce wear rate by cutting through materials. Ceramic-matrix composite parts used in automotive industries and aerospace applications have a high degree of wear resistance and maintain their strength under pressure. Besides the wear, hardness is often connected with other mechanical properties such as tensile strength and fatigue strength. Hard material has a higher ability to withstand cracks and bending moment when force is applied on it hence it is ideal for use in high performance (Dhanasekar et al., 2022).

Hardness determines how much a material can stand to deform and to be abraded. Various hardness testing techniques provide crucial information that enables determination of materials suitable for certain applications, reliability, endurance, and dependability. Engineering experts can enhance the quality and endurance of the products they create through understanding the facets of hardness and the material chemistry behind it and calculating it accurately.

4.1.3 Elasticity

Elasticity refers to a material capacity that allows the component to return to its pre-deformation state after being deformed in a force-dominated regime. Knowing how materials behave under load and containing the force that will put it under stress is critical in engineering structures and components that will not deform permanently under load. E modulus is obtained by stress (σ) and strain (ε) relationship within the elastic limit of material. This relationship is in most cases described by Hooke's law which postulates that

$$\sigma = E\varepsilon$$

where E represents the Young's modulus of the material.

Young's modulus (E) measures the stiffness of a material in terms of stress and strain on the stress-strain graph and is relevant to the linear portion of the curve. High Young's modulus materials like steel as well as diamond are quite rigid and can resist deformation thereby being suitable for uses where firmness and strength of structure is desirable. On the other hand, those that have low Young's modulus like elastomers and polymers among others are more flexible and can even deform significantly when stressed. This characteristic is useful in situations where flexibility and the ability to accommodate energy are desirable.

However, it is important to note that there are several elastic moduli that can be used to describe how a material reacts to different forms of stress. Shear modulus (G) describes the behavior of a material subjected to shear stress that defines the ability of the material to resist changes in shape without changing volume. The bulk modulus (K) indicates a material's response to equal pressure,

proving its effectiveness in maintaining or changing compression. These moduli are related and dependent on the Poisson's ratio (v) of the material: this is the ratio of lateral strain to axial strain when a rod of the material is subjected to uniaxial stress (Kim & Chen, 2004).

The nature and organization of the atoms and molecules in the material determine its elastic properties. Metals have metallic structure that allows the atomic planes in the metal lattice to slide past one another, which makes metals possess highly desirable elastic properties. This is because polymers elongated chains of molecules are capable of stretching to regain their original forms. Ceramics and glasses composed of ionic or covalent bonds hold less elasticity and higher levels of brittleness due to the restricted freedom of atoms (Basu & Balani, 2011). The yield point is also referred to as the elastic limit is the maximum limit up to which stress can be applied before experiencing some amount of elastic deformation. Beyond this limit, the material moves to the plastic deformation regime where the stress strain relationship becomes nonlinear, and the deformation is not fully recoverable. The elastic limit is one of the most significant design factors which ensure that materials perform at their elastic limit under service loads and conditions in order to prevent failure (Reiner, 1948). In various engineering applications, elasticity is a significant consideration. Any steel and concrete that is used in civil engineering applications must be able to have some level of elasticity so as to be capable of absorbing and releasing energy from loads and vibrations thereby increasing the structural durability and safety. In automotive engineering, elasticity of tires and suspension is essential in improving automobile comfort and maneuverability. This is done by smooth and efficient isolation of road vibrations and maintaining constant contact with the road surface. Biomedical engineering applies elastic materials such as in prosthetics and implants to mimic the biomechanical movement of tissues so as to provide not only utility but also quality comfort to the user (Egbo, 2021).

The aim of emergence in material science is to increase the flexibility of structure by incorporating molecular design modifications and seeking composites. Scientists can also manipulate the elastic properties of the materials through altering the size, shape, and even the nature of the structure. This enables them to meet the exact performance standards wherever they are and in whatever circumstances. By understanding and managing flexibility at the molecular level, it is possible to create elaborate materials with high mechanical performance and reliability.

Elasticity is one of the critical properties with regard to the ability of the material to bear force which influences their functionality and durability in various applications. Elasticity is a measure of shape memory of a material and is described by factors such as Young 's modulus, Shear modulus, and Bulk modulus. Engineers and scientists are then able to use our understanding of elasticity to design materials or structures to achieve the optimal level of performance and reliability in a variety of harsh or challenging environments.

4.1.4 Toughness

Toughness is crucial material property that refers to the capacity of a material to deform plastically in an elastic manner without cracking. This represents the capacity of a materials resistance to crack initiation as well as propagation, especially in cases of shock and impact loadings. Toughness is a synergy of strength and ductility, which is the total amount of energy that a material can withstand before fracture (Kobayashi, 2004) . It is defined as the area under the stress-strain curve derived from a tensile test where the properties of both elastic and plastic deformation are incorporated.

In this regard, materials with high toughness are those which can bear high amount of stress and strain before getting damaged. Some of the metals that possess high toughness include steel commonly used for construction and car manufacturing since they have both high strength and ductility. This is why steel is preferred for use in areas that require hardness and elasticity like the construction of bridges, buildings, and vehicles bodies (Callister, 1997). On the other hand,

materials such as ceramics and glass are normally very rigid and have low amounts of toughness as they have high stress levels but low plastics deformation capacity causing them to break. In general, the strength of materials depends on microstructure, chemical content, and temperature. In metals, features that can improve this property are fine grained structure and/or presence of alloying elements that create high toughness, such as nickel and chromium in steel. Other heat treatment procedures like tempering can also improve the toughness by altering the microstructure and placing internal stresses in order. Toughness in the case of polymers and composites depends highly on the molecular structure and the reinforcing phases. Said deformation in polymers like increasing the toughness by using cross-linking to avoid the extension of cracks.

Temperature has a significant influence in terms of toughness. Most materials have improved toughness at increased temperatures due to higher atomic diffusion that enables more deformation before failure. At low temperatures however, many materials become loss their toughness and a material that is very important in cold environments becomes brittle. This shift from ductile to brittle behavior with decreasing temperature is an important factor that needs to be taken into account when selecting material and designing parts (Feng et al., 2017).

Toughness is usually conducted by impact tests like Charpy or Izod test that estimate the amount of energy required to fracture the material (Handbook, 2000). These tests involve use of a hammer to strike a notched sample and determining the energy needed to fracture the material. The results give the relative ranking in terms of hardness and are effective in the assessment of materials used in impact applications. For safety and reliability of structures and components in engineering practice it is crucial to achieve sufficient level of toughness. For instance, the aerospace industry requires high toughness of materials as they experience dynamic loads in the process of flight. Likewise, in construction, the measure of strength indicates a material's capability to dissipate energy from an earthquake or impact without failure.

Overall, the toughness is an all-encompassing parameter that describes a material's ability to accommodate energy and plastically deform before failure or cracking due to crack propagation. It is dependent on microstructure, composition, temperature, as well as loading conditions. High-toughness materials are useful in areas where there is a need for durable and robust structures that can resist impacts and shock loads for safe and reliable functioning of various engineering systems (Billinton & Allan, 1992). Toughness and its control through material choices and processing methods are basic to improving the performance and durability of numerous applied technologies today.

4.1.5 Plasticity

Plasticity is a physical property that describes the ability of a given material to undergo permanent deformation without breaking. This particular characteristic varies significantly depending on the type of materials under consideration; these include metals, ceramics, polymers and semiconductors (Askeland et al., 2003). This variation can be attributed to the fact that atomic characteristics of the materials and how they bond are provoked by natural material chemistry.

Due to the nature of metallic bonding and forming of crystals, flexibility of metals is evident. Since metallic connections are inherently delocalized, atoms can only glide over one another in a smooth fashion when stressed, and this reduces the possibilities of breakages. It is possible to deform a crystal plastically through the movement of dislocations as line defect within the crystal. Metallic materials are highly sensitive to their microstructure in terms of the characteristics of the grain size distribution and the type of alloying constituents (Becker, 2004). Mechanical properties like increasing the density of dislocations and promoting grain formation by means of an annealing process can promote plasticity. Copper and aluminum are relatively ductile metals that require less effort in terms of creating various forms and shapes in various assignments (Chakrabarty, 2012).

This is attributed to the fact that ceramics are ionic and covalent bonded materials, which limits atomic mobility. Such connections are known to have high directional strength and cannot

easily allow the movement of dislocations. Therefore, they are susceptible to brittle fracture during deformation as opposed to plastic deformation. The flexibility of ceramics is further restricted by their features of the crystal structure, which consists of rigid and tightly packed atoms (Basu & Balani, 2011). The advancement in material chemistry, the abilities to dope and make composite ceramics tries to enhance the mechanical properties associated with ceramics. However, the fragility of these materials remains a considerable challenge to date because of their intrinsic nature. Ceramics have relatively low plasticity and are valuable due to their high hardness, high melting temperatures and chemical inertness which make them suitable for applications where they would be subjected to high heat or friction.

The elasticity of polymers depends on the molecular structure of the polymer and types of linkages that are available in it. Thermoplastics do entail elongated polymer chains that are wound together and hence linked by van der Waals forces, and this gives them considerable flexibility (Howe, 1993). With the application of heat, these polymers become ductile, and the movement of individual chains becomes random and undergoes irreparable deformation. Thermosetting polymers go through a process of curing where their molecules solidify and then form a rigid series of bonds. This network reduces their versatility and capability to modify their shape and form and thus makes them more fragile. One can be able to change the degree of flexibility of polymers through using copolymers including the use of plasticizers and also the extent or level of crystalline formations. Certain thermoplastics including polyethylene and polyvinyl chloride (PVC) are commonly used where flexibility and molding capability is required like packaging and pipe sections (Oberoi & Malik, 2022).

Materials like silicon and germanium for instance, have restricted mobility because of their covalent frameworks and crystal structures. Under namely, low temperatures, semiconductors are known to be very brittle and easily crack under pressure (Pirouz et al., 1999). However, when these substances are subjected to high temperatures, then a certain amount of the deformation is possible due to the movement of dislocations, which bear a passing similarity to what may be observed with metals; though these materials are not as prone to this sort of deformation as metals are. New approach in material chemistry and nanotechnology in recent years is looking at how to make semiconductors more flexible (Sun & Rogers, 2007). This includes using dopants as well as developing structured materials to increase mechanical properties specifically to electrical and opto-electron applications.

In a way, the ability of a material to change shape is determined largely by how atoms are connected together and the characteristics of the microstructure of a material which is in turn dictated by the chemistry of the given material. Metals are of a higher rank when it comes to metals, because they have specific metallic bonds that cause great free movement of electrons, and thus a great ability to take plastic deformation. whereas ceramics, restricted by strong ionic and covalent interactions, have a minimal ability to undergo plastic deformation. Polymers exhibit a wide range of flexibility depending on their molecular structure and bonding, while semiconductors typically have limited plasticity, which can be improved through chemical and structural alterations (Q. Zhang et al., 2022). Comprehending and controlling these characteristics is essential for enhancing materials for certain purposes, ranging from structural elements to electrical gadgets.

4.2 Electrical Properties

Now we will examine the electrical behavior of materials focusing on their trait under an extrinsic electric field, or how they interact to an imposed electric field. We embark on an exploration of the electrical conduction phenomenon, including its expression characteristics, the material's conductivity is dictated by its electron energy level daigram, and the mechanism of electron conduction (Solymar et al., 2014). These ideas also apply to semiconductors, insulators, and metals. First, the properties of semiconductors are discussed in detail, followed by semiconductor devices. Additionally, included are the dielectric properties of insulating materials.

Table 1-Electrical conductivities of some common metals

Metals	Electrical Conductivity $[(\Omega.m)^{-1}]$
Silver	$6.8x10^7$
Copper	$6x10^7$
Gold	$4.3x10^7$
Aluminum	3.8x10
Iron	$1x10^7$
Bras (70 cu-30 zn)	$1.6x10^7$
Platinum	$0.94x10^7$
Plain carbon steel	$0.6x10^7$
Stainless steel	$0.2x10^7$

Ferroelectricity and piezoelectricity are the subjects of the latter sections.

4.2.1 Electrical conduction:

Ohm's Law

A solid substance's capacity to efficiently conduct electric current is a vital electrical property. According to Ohm's law, the applied voltage (V) and current (I) are related by the fundamental relation:

$$V=IR$$

where R denotes the material's resistance to electric charge flow. Electric potential difference(V), electric current (I), and electrical resistance(R) are quantified using unit i volts (J/C), amperes (C/s), and ohms (V/A). The electrical resistance is impacted by its geometric organization and is current-independence across diverse materials. The electrical resistivity r is unaffected by its physical dimension but correlated to R in accordance with the relation.

$$\rho=RA/l$$

The voltage is measured at two distinct point, separated by a defined distance e, and A represent the orthogonal cross-sectional area with respect to the current alignment. The units for Rare ohmmeters (Ω-m). derived from Ohm's law.

4.2.2 Electrical Conductivity

Electrical conductivity and resistivity are inversely connected, and it specifies the electrical behavior of materials. Mathematically,

$$\sigma=1/\rho$$

It indicates the degree to which a substance can conduct an electric current easily. Reciprocal ohmmeters (Ω.m)-1 are the units used for σ. The descriptions of electrical qualities that follow make use of both conductivity and resistivity.

Moreover, Equation 18.1, Ohm's law may be exemplified by

$$J=\sigma E$$

The current density J, is defined as—the current per unit of specimen area I/A—an E symbolizes the electric field strength, or the voltage gradient between two points, divided by the distance between them.

No other physical attribute varies as much as the electrical conductivities of solid materials, which can vary by more than 27 orders of magnitude. There are three categories in this categorization scheme for solid materials: conductors, semiconductors, and insulators. This classification scheme is based on how easily a material conducts an electric current. Metals have conductivities of 107 (Ω.m)-1, making them good conductors. Electrical insulators are materials that exhibit remarkably low level of conductivities, which fall amongst 10-10 and 10-20 (Ω.m)-1 (Callister, 1997). These materials are at the other extremity of the spectrum. Semiconductors are materials having intermediate conductivities, usually between 10-6 and 104 (Ω.m)-1.

4.2.3 Energy band structures in solids

Electronic conduction is the only type of conduction allowed in all materials, including conductors, semiconductors, and insulators. The quantity of mobile electrons that are participate in the conduction process solely determines the degree of electronic conduction. However, it is important to note that a selected group of electrons within an atom experience acceleration under influence of an electric field. Each material determines the concentration of electrons accessible for conducting electricity based on the configuration of electron energy levels and the electrons' filling of these states. Conducting a comprehensive examination of these topics is challenging and necessitates a deep understanding of quantum mechanical principles (Bassani & Celli, 1961). As a result, the subsequent advancements may exclude certain concepts and streamline others. The lecture explored the concepts of electron energy levels, their occupancies, and the resulting electron configurations for atoms in isolation. Electrons can occupy unique energy levels in each atom, which we group into shells and subshells. We use integers like 1, 2, 3, etc. to represent shells, and alphabetical notation s, p, d, and f to represent subshells. Each subshell, namely s, p, d, and f, has one, three, five, and seven states, respectively. The Pauli exclusion principle dictates that electrons in the majority of atoms occupy the state alone with the minimal energies. Specifically, each state can accommodate two electrons with opposite spins. An isolated atom's electron configuration depicts the organization of electrons within the permitted energy level. This enables us to apply some of these concepts to tangible substances. A solid is a collection of atoms, denoted as N, first isolated, then assembled and connected to create the organized atomic structure observed in a crystal lattice material. At significant distances, individual atom operates independently from the others. Furthermore, they possess identical energy state of an atom and electron configurations, as if they were separate entities. However, the nuclei of adjacent atoms influence or disrupt the electrons as they approach each other. This phenomenon results in the fragmentation of a solid material into a sequence of electron energy states with a high degree of proximity and derived from distinct atomic states, thus forming an electron energy band (Callister, 1997). The atoms primarily affect the electron shells on the outermost layer as they come together, defining the initial level of splitting. The energy levels within each band are discrete, but the differences between adjacent states are minimal. Band creation is unlikely to occur for the electron subshells located closest to the nucleus when the band gap separation is at equilibrium. Furthermore, as depicted in the illustration, there might be spaces between neighboring bands. Generally, energies within these gaps are unavailable for electron occupation.

Each band contains an equal number of states, representing the combined contribution of all N atom states. For example, a p band encompasses 3N states, whereas a s band spans N states. Each energy level can accommodate a maximum of two electrons, each with opposite spins. Bands in solids consist of electrons that formerly held similar energy levels in individual atoms. For instance, electrons from the 4s orbitals of isolated atoms make up the 4s energy band in a solid. It is worth mentioning that bands may only be partially occupied in some situations, while in other cases they may not be occupied at all. The layout of an object's outermost electron bands and

their electron filling, known as its electron band structure, determine its electrical characteristics. We observe four different and unique forms of band topologies at a temperature of absolute zero (0 K) (Siu, 2022). In the initial situation, the outermost layer contains electrons only to a certain extent; the Fermi energy Ef represents the energy level associated with the highest occupied state. Certain metals, specifically monovalent metals like copper, exhibit the described band structure. A single 4s electron is denoted by each copper atom. Despite this, in a solid with N atoms and the 4s energy band can only accommodate a maximum of 2N electrons. Consequently, solid occupies only half of its electron sites. In metallic solid, a second band structure is observed, featuring an overlap between an unoccupied band and an occupied band. In terms of magnesium's energy band diagram, each atom's 3s subshell contains two electrons. On the other hand, solidification causes the 3s, 3p energy level to coincide or intersect. The Fermi energy, at absolute zero temperature (0 K), represents the energy level where two electrons occupy N atoms in each of their N states. The last two band structures are indistinguishable in that they both exhibit an energy band gap that divides the valence band, which is completely filled with electrons, from the conduction band, which is empty. Within this gap, electrons in highly pure materials may lack energy. Electrons in highly purified materials may lack energy within this specific range. The magnitude of the energy gap determines the disparity between the two band structures. In semiconductors, the band gap is narrow (Figure 18.4d), while in insulators, it is significantly wider (Figure 18.4c). Both of these band topologies possess Fermi energy, that exist in the band gap, close to its midpoint.

4.2.3.1 Metals

In order for an electron to be liberated, it must be stimulated or elevated to one of the unoccupied and accessible energy levels beyond the Fermi energy Ef. In metals, which exhibit either of the band structures, there exist unoccupied energy levels next to the maximum occupied state at Ef. Consequently, a relatively low energy is sufficient to elevate electrons to the vacant states that are situated at a lower energy level, as depicted in Figure 3 Usually, the electric field provides enough energy to stimulate a significant electron occupancy excited to conducting states.

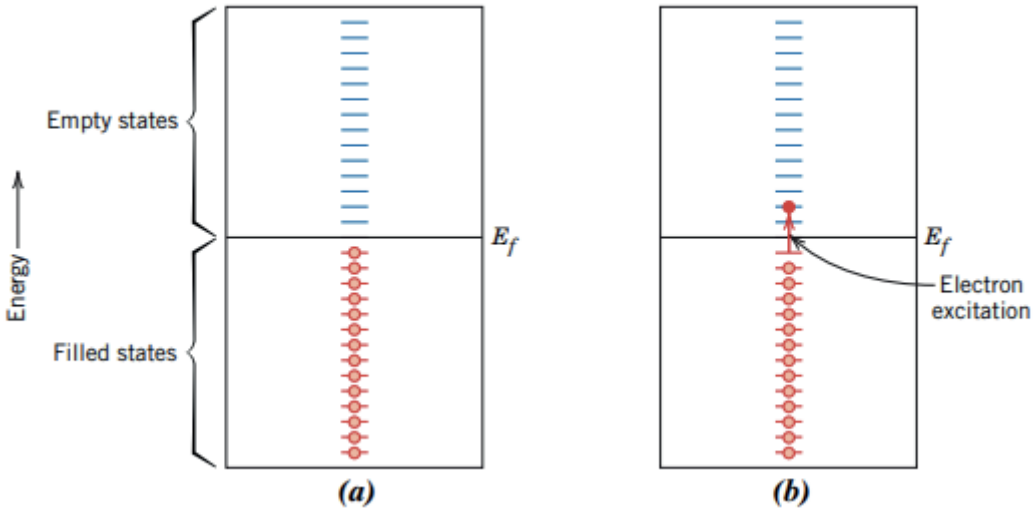


Figure.3. For a metal, occupancy of electron states (a) before and (b) after an electron excitation.

The metallic bonding model assumes that all valence electrons are free to move and create a homogeneous electron gas/cloud throughout the ion core lattice. Although these electrons are not specifically attached to any individual atom, they still need to be stimulated in order to become fully unrestricted conducting electrons (Papaconstantopoulos, 1986). Thus, despite only a small proportion of electrons being stimulated, this nevertheless yields a considerable quantity of unbound electrons, resulting in elevated electrical conductivity.

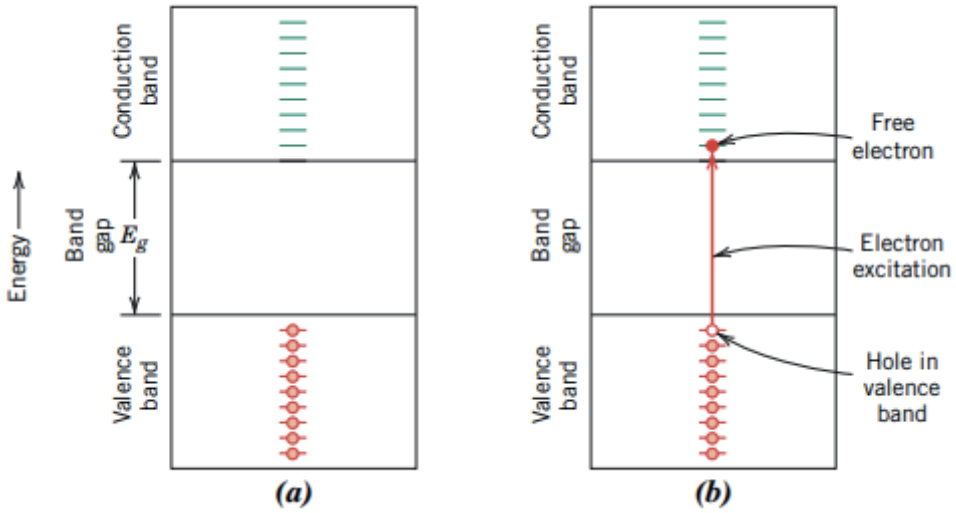


Figure 4. electron state occupation in non-conducting and semiconductor (a) before and (b) after an electron transition from the valence to the conduction band, creating a pair of free electron and hole

4.2.3.2 Insulators and semiconductors

These are two types of materials that have different electrical conductivity properties. In insulators and semiconductors, there is a lack of accessible unoccupied states around the upper limit of the occupied valence band. Hence, in order for electrons to attain freedom, is compelled to be elevated above the energy band gap and occupy vacant positions at the lowermost level of the conduction band. To do this, it is necessary to provide an electron with the precise amount of energy that corresponds to the difference across these two energy level, is roughly/ equivalent to the energy of the band gap Ef.

For numerous materials, the band gap has a width of several electron volts. Usually, the excitation energy is derived from a non-electrical source, such as heat or light, with heat being the more common source. The quantity of electrons that are thermally stimulated to go into the conduction band is contingent upon the width of the energy band gap and the temperature. At a specific temperature, a higher value of Ef leads to a decreased likelihood of a valence electron being elevated to an energy level in the conduction band, resulting in a reduced number of conduction electrons. Put simply, a greater band gap results in less electrical conductivity at a specific temperature. Hence, the differentiation between semiconductors and insulators is in the magnitude of the band gap: it is narrow for semiconductors and comparatively broad for insulators. As temperature elevate in a semiconductor or an insulator augments the thermal energy accessible for electron excitation, which stimulates a greater number of electrons to move into the conduction band, consequently, conductivity is improved

Atomic bonding models play a key role in understanding the electrical properties of insulator and semiconductors. Electrically insulating materials exhibit either ionic or highly covalent interatomic bonding, where peripheral electrons are firmly attached to or jointly held by specific atoms. The electrons in the crystal are strongly confined to specific regions and are not able to move freely. In the context of semiconductors, the bonding is primarily covalent and possesses a relatively low strength, resulting in valence electrons being less tightly linked to the atoms. As a result, these electrons can be more readily expelled through thermal excitation compared to insulators.

4.2.4 Electron mobility

Free electron experiences a force when subjected to an electric field, causing them to accelerate

in the opposite direction of the field due to their negative charge. Quantum mechanics states that within a flawless crystal structure, electron in motion do not interact with atomic nuclei. Under these circumstances, the existence of an incident field will cause the free electron to accelerate, resulting in a continuously growing electric current. Nevertheless, it is understood that when a field is applied, a current reaches a steady value immediately, indicating the presence of frictional forces that oppose the acceleration caused by the external field. The scattering of electrons by crystal imperfection's, resulting a force that oppose their motion. such as foreign atoms, missing atom(vacant sites), extra atom, dislocations, and even the atoms thermal motion (Askeland et al., 2003). Every instance of scattering results in the electron losing its kinetic energy and altering its travel direction. Nevertheless, there is a certain amount of electron movement in the opposite direction of the field, and this movement of electric charge is what constitutes the electric current.

The scattering phenomenon is observed as an impediment to the flow of an electric current. The extent of this scattering is described by several parameters, such as the mean electron velocity and the electron transport efficiency. The drift velocity, denoted as υ_d, is the mean velocity of electrons aligned with the applied field of direction .

The relationship between it and the electric field is one of direct proportionality, expressed as follow,

$$\upsilon_d = \mu_e E$$

The electron mobility, denoted as me, is a constant that represents the frequency of scattering events. It is measured in square meters per volt-second (m^2/V. s).

The conductivity of most materials can be represented by the equation.

$$\sigma = n \mid e \mid \mu_e$$

where n is the density of electron available for conduction per unit volume (e.g., per cubic meter) and |e| is the absolute charge of an electron ($1.6 * 10^{-19}$ C). Therefore, the conductance of material is directly related to either the quantity of unbound electrons and the ability of electrons to move.

4.2.5 Electrical Resistivity

The electrical resistivity of materials is an inherent property that shows significant variance among different types of materials, including metals, ceramics, polymers, and semiconductors, due to their distinct atomic and electronic structures. Free electrons in metals, not bound to any specific atom, form a "sea" of delocalized electrons, leading to their low electrical resistivity.

The metallic bonding model allows for the unimpeded passage of electrons throughout the lattice, thereby facilitating efficient electrical conduction. However, lattice defects like dislocations, impurities, and thermal vibrations (phonons) cause electron scattering, which significantly increases the resistivity of metals. With an increase in temperature, the phononic interactions become more prominent, resulting in a rise in resistance (J. Chen et al., 2022). Copper and silver possess remarkably low resistivities, making them extremely effective conductors (Cho et al., 2010). On the other hand, ceramics typically exhibit high electrical resistivity due to their ionic or covalent bonding, which restricts the movement of electrons and impedes their free flow. These strong connections create a rigid and orderly structure, firmly binding electrons to their respective atoms or ions, significantly hindering electrical conduction. While some ceramics, like zinc oxide, can display conductivity at high temperatures under particular conditions (Moezzi et al., 2012), they generally act as insulators. Their high resistance is advantageous in situations that require electrical insulation and stability at high temperatures.

Polymers generally display a significant degree of electrical resistance (Hummel & Hummel,

2001). Covalent bonding in the carbon-hydrogen backbone of most polymers creates a structure that limits the mobility of electrons, inhibiting their free movement. Consequently, polymers generally demonstrate insulating characteristics. Conjugated double bonds, when incorporated into the polymer structure, create conductive polymers that significantly reduce resistance (Bidan, 1992). To increase the number of charge carriers in electrical and optoelectronic applications, substances that donate or take electrons impregnate conductive polymers.

Semiconductors have an electrical resistance that falls between metal resistance and insulator resistance (Rahman, 2014). They show a high level of sensitivity to temperature changes and are highly susceptible to pollutants. A slight disparity in energy levels between the valence band and the conduction band dictates their electrical properties. At low temperatures, semiconductors have a high resistivity because there is a lack of electrons that have enough thermal energy to cross the band gap. With an increase in temperature, more electrons get sufficient energy to move from the valence band to the conduction band, leading to a reduction in resistivity. Specific impurities (n-type or p-type doping) inject additional charge carriers into semiconductors, significantly altering their electrical properties and enabling precise resistivity changes. It is crucial to have the capability to alter or adapt the properties of semiconductor devices, such as diodes, transistors, and integrated circuits, in order for them to function correctly.

4.2.6 Electrical Characteristics of Commercial Alloy

Copper is the most common metal conductor because it is so good at moving electricity. Oxygen-free high-conductivity (OFHC) copper is copper that possessing a limited concentration of oxygen and other impurities. Well-suited for various electrical purpose. Electrical conduction is also achieved with aluminium, even though it is only about half as good at conducting electricity as copper. Even though silver is a better conductor than both copper and aluminum, it is too expensive to be widely used (Pino et al., 2014).

Increasing the mechanical strength of a metal combination without making it much less conductive to electricity is sometimes needed. When doing this, conductivity and hardness are often traded off. This is especially true when solid-solution alloying or cold working is used. g a second phase that does not affect conductivity as much is a familiar way to boost strength with a small degree of influence on conductive behavior. For instance, Precipitation hardening treatment enhances the strength of copper-beryllium alloys, but they are only about five times as good at conducting electricity as pure copper (Lomakin et al., 2019).

When used in places like furnace heating parts, high electrical resistance is a good thing. The spreading of electrons makes it easier for energy to be lost as heat. For these kinds of uses, the materials need to have high melting points, high resistivities, and the ability to stay solid at high temperatures. Because of these qualities, nichrome, which is a combination of nickel and chromium, is often used for heating elements.

4.2.7 Dielectric Behavior

A dielectric material is an insulating substance that cannot conduct electricity and has the ability to form an electric dipole structure. This means that it may create a separation of positive and negative charges at the molecular or atomic level. Dielectric materials are utilized in capacitors due to their interaction with electric fields, which is a result of dipole interactions.

When a capacitor is subjected to a voltage, one plate acquires a positive charge while the other plate acquires a negative charge. This results in an electric field that is directed from the positive plate to the negative plate. The capacitance C is directly proportional to the quantity of charge stored on each plate Q and is inversely proportional to the voltage V applied across the capacitor.

$$C=Q/V$$

The units of capacitance are expressed as the ratio of coulombs to volts, or in farads (F).

Analyze a parallel-plate capacitor with a vacuum-filled space between its plates (as shown in Figure 5).

$$C=\varepsilon_o A/L$$

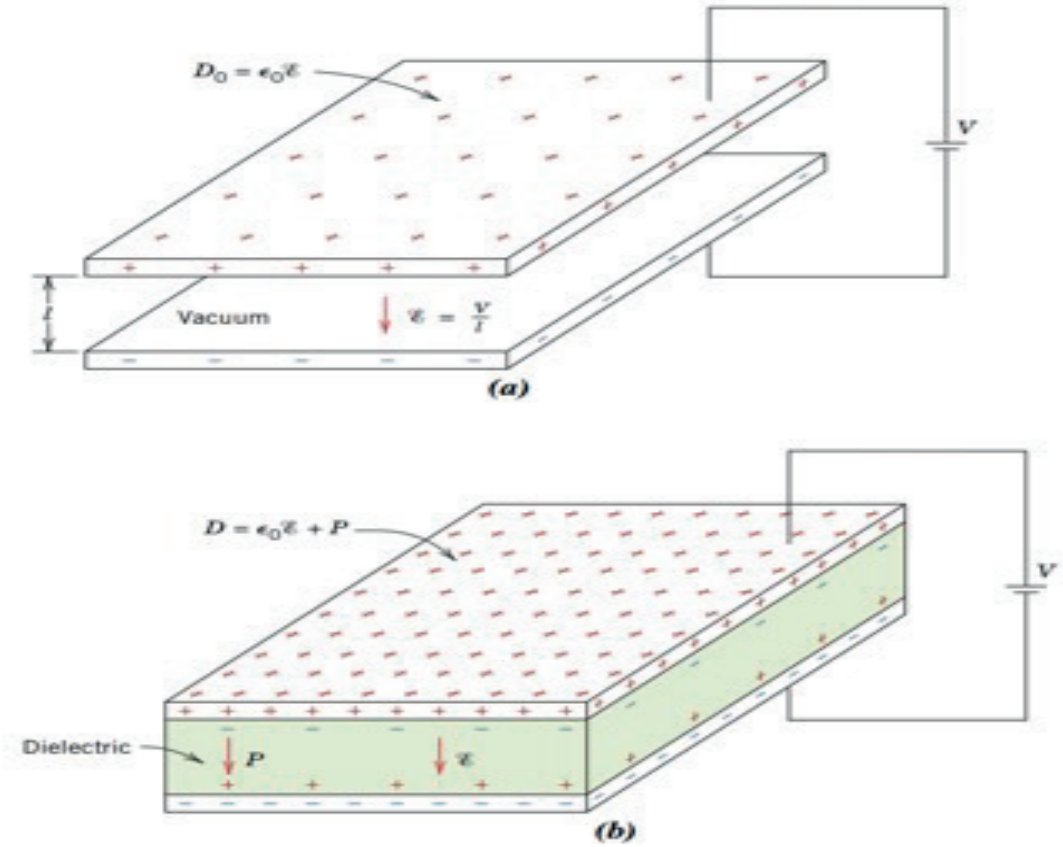


Figure 5. A parallel-plate capacitor (a) under vacuum conditions and (b) with a dielectric substrate. (From K. M. Ralls, T. H. Courtney, and J. Wulff, Introduction to Materials Science and Engineering.)

The capacitance can be calculated using the equation where A is a parameter representing the surface area of the plates and l is the gap width between the plate. The constant ε_o, known as the vacuum permittivity, equal to 8.85 x 1012 F/m, applicable everywhere.

When a dielectric material is placed between the plates in Figure 5,

$$C=\varepsilon A/L$$

The permittivity of this dielectric media, denoted as ε, has a higher value than εo. The relative permittivity (εr), also known as the dielectric constant, is defined as the ratio.

$$\varepsilon_r=\varepsilon/\varepsilon_o$$

The dielectric constant is a value greater than one that quantifies the increase in charge storage capacity when a dielectric medium is inserted within the plates spacing. When designing capacitors, the dielectric constant is a key material property to consider. The table provides the ε_r values for several dielectric materials.

Table 2 Typical Room-Temperature Electrical Conductivities

Material	Dielectric Constant		Dielectric Strength (V/mil)
	60 Hz	1 MHz	
	Ceramics		
Titanate ceramics		15-10,000	50-300
Mica		5.4-8.7	1000-2000
Steatite (MgO-Si02)		5.5-7.5	200-350
Soda—lime glass	6.9	6.9	250
Porcelain	6	6	40—400
Fused silica	4	3.8	250
	Polymers		
Phenol-formaldehyde	5.3	4.8	300-400
Nylon 6,6	4	3.6	400
Polystyrene	2.6	2.6	500-700
Polyethylene	2.3	2.3	450-500
Polytetrafluoroethylene	2.1	2.1	400-500

4.2.8 Other Electrical Characteristics of Materials

Two additional groundbreaking and innovative electrical attributes can be observed in subset of material, are worth mentioning briefly—ferroelectricity and piezoelectricity.

4.2.8.1 Ferroelectricity

An example of a dielectric material is ferroelectric materials, which can become polarized even when there isn't an electric field acting on them. They are like ferromagnetic materials, which can have magnetic qualities that last a long time. The structure of barium titanate, a typical ferroelectric material, shows that ferroelectric materials have permanent electric dipoles. Barium titanate spontaneously polarizes because of the way the Ti+4, O-2 Ba+2 ions are arranged in a repeating unit cell (Chakrabarti, 2011), As demonstrated in Figure 6. The unit cell has tetragonal symmetry, which means that the Ba ions are anchored at the corner points. This results in a cell shape that is a slightly longer cube.

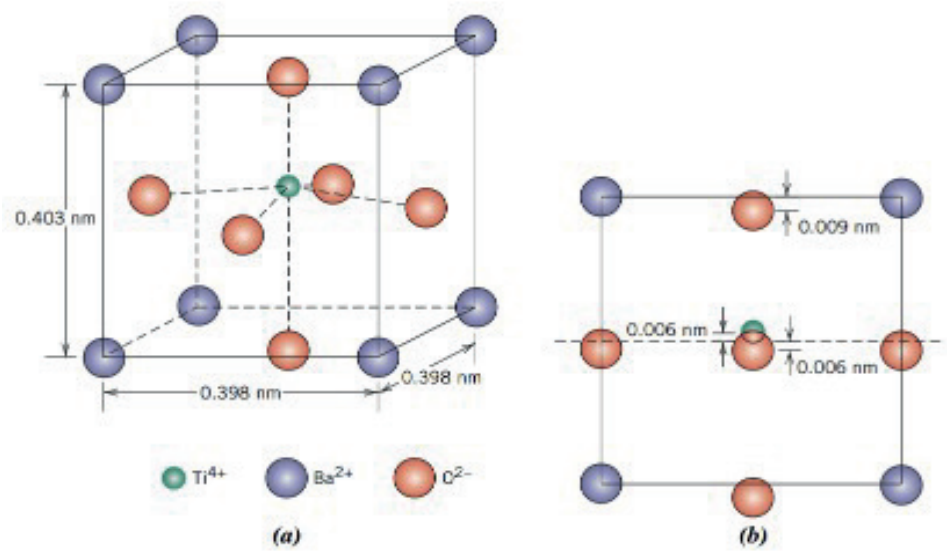


Figure 6. A Barium titanate (BaTiO3) unit cell (a) in an isometric projection, and (b) looking at one face, which shows the displacements of Ti_4 and O_2 ions from the center of the face

The dipole moment in barium titanate is caused by the O^{-2} and Ti^{+4} ions moving out of their balanced places, as depicted in the unit cell's side view. The O^{-2} ions are close to the middles of all six faces, but a little below them. The Ti+4 ions, on the other hand, are farther away from the unit cell's center and higher up. Because of this, each unit cell has a constant ionic dipole moment, which can be seen in Figure 6b. If you heat barium titanate beyond its ferroelectric Curie temperature of 120°C (250°F), the repeating unit cell shapes up into a cube and the ions line up evenly. This change creates a perovskite crystal structure, which takes away the ferroelectric qualities of the material.

In ferroelectric materials, spontaneous polarization happens when permanent dipoles that are close to each other interact and line up in the same way (Krohns & Lunkenheimer, 2019). In barium titanate, the oxide ion O^{-2} and tetravalent titanium ion, Ti^{+4} ions having the same orientation throughout all unit cells that are in a certain volume of the material. Rochelle salt ($NaKCl_4H_4O_6$) is another mineral that shows ferroelectricity (Kandpal et al., 2023). Potassium niobate $KnbO^{-3}$, potassium dihydrogen phosphate (KH_2PO_4), and lead zirconate–titanate (Pb [ZrO_3]) are some of the chemicals that are used (F. Li, 2013). When applied electric fields with relatively low frequencies, ferroelectric materials have very high dielectric constants. At room temperature, the dielectric constant of barium titanate can reach up to 5000. This means that capacitors fabricated from this material can have a significantly reduced size compared to those made from traditional dielectric materials.

4.2.8.2 Piezo magneticity

Piezoelectricity, which is a term that translates to "pressure electricity," is a peculiar phenomenon that is demonstrated by specific ceramic materials and certain polymers. Electric polarization (an electric field or voltage) in the piezoelectric crystal is induced by mechanical strain (dimensional change) from an applied external force (F. Li et al., 2020) (Figure 8). Reversal of the force lead to reversal of the electrical field direction, such as from tension to compression. These materials also exhibit the piezoelectric converse effect, marked via the generation of a mechanical strain in response to an electrical field.

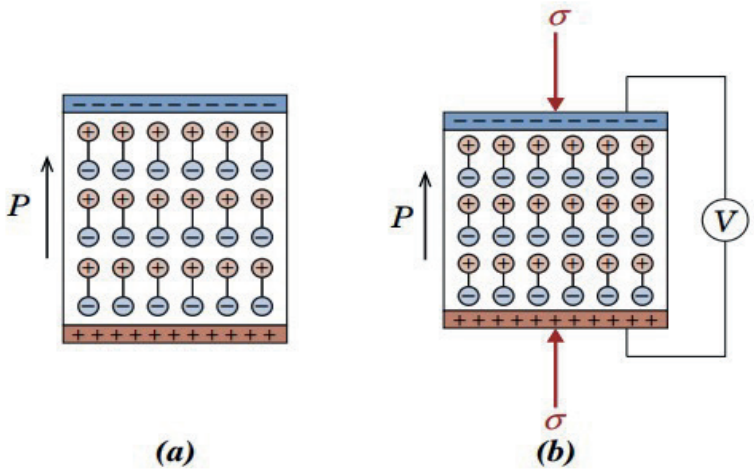


Figure 7-(a) Dipoles within a piezoelectric material. **(b)** A voltage is generated when the material is subjected to a compressive stress.

Additionally, piezoelectric materials can function as transducers, facilitating the conversion of mechanical and electrical energies. In sonar systems, an underwater detection system that utilizes ultrasonic emission and reception to identify and localize submerged objects, including submarine's, piezoelectric ceramics were one of the early applications (Manbachi & Cobbold, 2011). The oscillation of a piezoelectric crystal in response to a high-frequency electrical signal

excites a transducer, generates mechanical vibrations that propagate as a pressure waves through the water. These signals are reflected back when they encounter an object. The reflected vibrational energy is then received by another piezoelectric material, which further converts it into an electrical impulse. The range to the reflecting object is calculated based on the time delay between signal transmission and reception.

A recent increase in the utilization of piezoelectric devices has been attributed to the growing interest of consumers in sophisticated devices and the advancements in automation. These components are employed in a variety of contemporary applications, include automotive (wheel electronic balances, seat-belt buzzers, tire tread depth sensor, keyless entry, and crash detection for airbag sensors), computer accessories (microphones, micro actuators for hard disks, speaker and notebook transformers), commercial/consumer (smoke detection system, strain gauges, ultrasonic welding equipment, and precise ink-jet printer heads), and medical (compact insulin pumps, ultrasonic therapy for pain, and ultrasonic phacoemulsification cataract-removal devices) (Yan et al., 2020). Ceramic materials that are piezoelectric entail potassium niobate (KNbO3), lead zirconate (PbZrO3), lead zirconate-titanate (PZT) [Pb(Zr,Ti)O3], and barium titanate (BaTiO3). This characteristic is found in materials with low symmetry and complex crystal structures (Sahu, 2011). Heating above Curie temperature augmented piezoelectric features of polycrystalline specimen's and subsequently reducing it to ambient temperature in a electric field with high field strength.

4.3. Thermal Properties

Thermal property pertains to how a material reacts when exposed to heat. When a solid absorbs heat energy, its temperature increases, and its size expands. If there are temperature differences inside the specimen, the energy can be transferred to colder areas, perhaps causing the experimental material become molten (Ventura & Perfetti, 2014). Specific heat capacity, thermal expansion, and thermal conductivity/heat transfer coefficient are essential qualities that play a crucial role in the practical use of solid material.

4.3.1 Heat Capacity

Heating a solid material, its temperature goes up, signifying that it has absorbed thermal energy. Heat capacity is a measure of how well a material can gain heat from its nearby medium. It quantifies the amount of energy needed to increase the temperature of the substance by one unit. The heat capacity C is mathematically defined by the following expression:

$$C=dQ/dT$$

where a dT temperature change requires energy dQ to create. Heat capacity is normally stated in units of J/mol. K or cal/mol. K per mole of substance. Sometimes used, specific heat (typically indicated by a lowercase c) is the heat capacity per unit mass expressed in a variety of units (J/kg. K, cal/g. K, Btu/lb_m. F).

Depending on the surroundings that accompany heat transmission (Rohsenow et al., 1998), this attribute can be quantified in two ways; one aspect is the capacity for heat at the fixed specimen volume, Cυ; the other scenario involved uniformed external pressure, C_p. for the majority of solid materials at moderate temperature and lower, the difference is extremely little, C_p is consistently higher than or equal to Cυ in magnitude.

4.3.2 Vibrational Heat Capacity

The principle means for thermal energy uptake in most solids is through the amplification of atomic oscillation energy in the atoms. Atoms in rigid materials exhibit continuous, rapid oscillations at exceptionally high frequencies and with comparatively small magnitudes. The vibrations of nearby atoms are connected due to atomic bonding, instead of being independent of each other. The synchronized vibration generates traveling waves in the lattice, as depicted in

Figure 7. These can be considered as elastic waves or sound waves, characterized by extremely high frequencies and small wavelength, that travel through the crystal at sonic velocities. The thermal vibrational energy of a material is comprised of a sequence of elastic waves that exhibit a variety of frequencies and spatial distribution. The energy is quantized, meaning that only specific energy values are permitted. A phonon represents a discrete packet of vibrational energy. A phonon is similar to a photon, which is a quantum of electromagnetic energy. Phonons are sometimes used to refer to vibrational waves. The thermal randomization of delocalized electrons during electrical conduction is caused by the interaction with vibrational waves. Additionally, these elastic waves facilitate energy transfer during heat conduction.

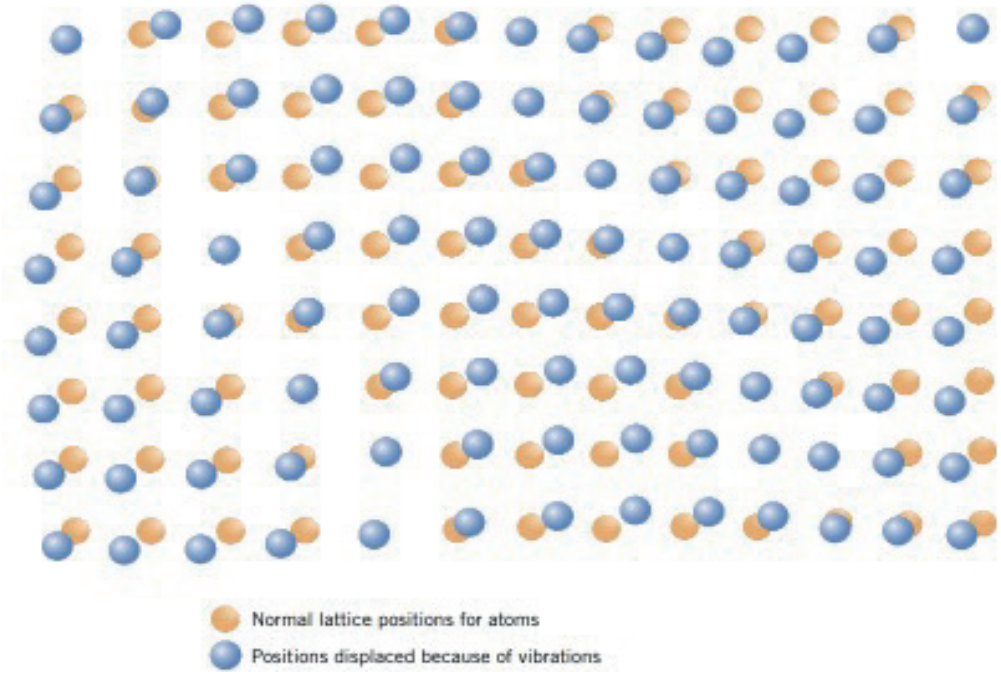


Figure 8 Schematic illustrating the creation of lattice waves within a crystal through atomic vibrations. (Hummel, 1998)

Thermal expansion

Most solid substances undergo expansion when they are heated and contraction when they are cooled. The thermal expansion coefficient of a solid substance represents the length variation with temperature.

$$(l_f - l_o)/l_o = \alpha_l(T_f - T_o)$$

where l_o and l_f represent, respectively, initial and final lengths with the temperature

change from T_o to T_f. The parameter al is called the linear coefficient of thermal expansion.

Thermal expansion occurs because of the uneven curvature of the potential energy through, not because of the higher amplitudes of atomic vibrations as temperature increases (Mittal et al., 2018). If the potential energy curve exhibited symmetry, as shown in Figure8, there would be an absence of any overall alteration in interatomic separation, resulting in the absence of thermal expansion.

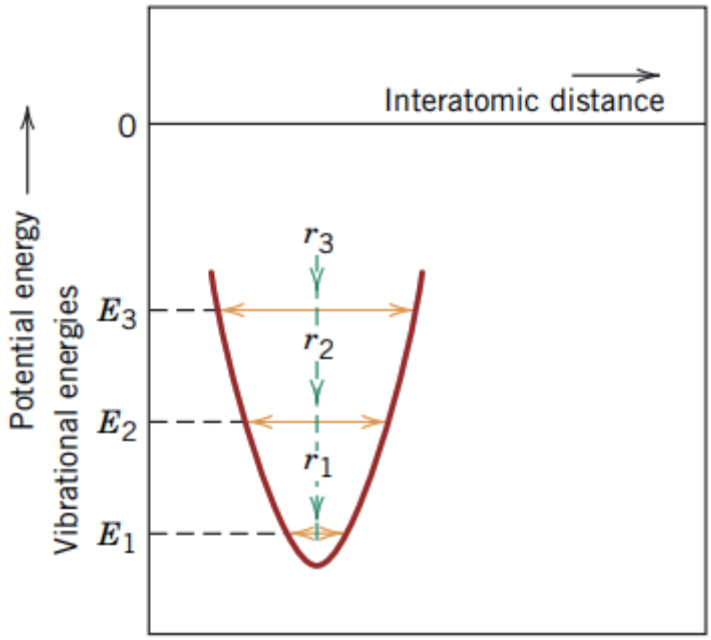


Figure 9 For a symmetric potential energy–versus–interatomic distance curve, there is no increase in interatomic separation with rising temperature (i.e., r1 = r2 = r3). (Adapted from R. M. Rose, L. A. Shepard, and J. Wulff, The Structure and Properties of Materials, Vol. 4, Electronic Properties

The depth and narrowness of the potential energy trough increases as the atomic bonding energy increases for each type of material, including metals, ceramics, and polymers. Consequently, the rise in temperature leads to a smaller increase in interatomic separation, resulting in a reduced value of l. Regarding temperature dependency, the coefficient of expansion becomes more as the temperature increases. For a more extensive compilation of coefficients of thermal expansion.

The linear coefficients of thermal expansion for typical metals vary from approximately 5 x 10^{-6} to 25 x 10^{-6} °C^{-1} (Grimvall, 1999). These values fall within a range of magnitudes of the coefficients for material such as ceramic and polymer. Outlined in the essential information box, various metal alloys with reduced-expansion and managed-expansion properties were created. These alloys are utilized in situations where dimensional stability is necessary despite changes in temperature.

Ceramic materials exhibit high interatomic bonding forces, resulting a reduced thermal expansion coefficient. The reading for thermal expansion habitually vary from approximately 0.5 x 10^{-6} to 15 x 10^{-6} °C^{-1} (Kompan et al., 2008). Non-crystalline ceramics and ceramics with cubic crystal formations exhibit isotropy. Alternatively, when heated, certain ceramic materials exhibit anisotropic behavior, meaning they contract along certain crystallographic orientations while expanding along others. The coefficient of expansion in inorganic glasses is composition dependent. Fused silica, which is a type of high-purity SiO2 glass, exhibits a low coefficient of thermal expansion (Moore & Smith, 2022), measuring 0.4x10^{-6} °C^{-1}. This phenomenon can be attributed to a low atomic packing density, which results in only minor changes in macroscopic dimensions when there is interatomic expansion.

Ceramic materials intended for exposure to temperature fluctuations must possess relatively low and isotropic coefficients of thermal expansion. Alternatively, these fragile materials may undergo fracture due to uneven dimensional alterations caused by thermal shock.

Polymers are large molecules composed of repeating subunits called monomers. Certain polymeric materials exhibit significant thermal expansions when heated, with coefficients ranging

from around 50 x 10^{-6} to 400 x 10^{-6} $°C^{-1}$. Linear and branched polymers have the greatest values due to the weak secondary intermolecular connections and minimal crosslinking (Takata & Aoki, 2018). As crosslinking increases, the expansion coefficient drops. Phenol-formaldehyde and similar thermosetting network polymers, have the lowest values due to the predominantly covalent bonding.

4.4 Optical properties

Optical qualities pertain to the manner in which a substance reacts when subjected to electromagnetic radiation, namely visible light. This chapter commences by examining fundamental principles and concepts pertaining to the characteristics of electromagnetic radiation and its potential interactions with solid materials. Subsequently, it analyzes the optical properties of metallic and nonmetallic substances, with specific attention to their absorption, reflection, and transmission traits (Tilley, 2020). The concluding sections address luminescence, photoconductivity, and light amplification by stimulated emission of radiation (laser), along with their practical applications and the utilization of optical fibers in communications.

The behavior of light as it interacts with a substance is strongly influenced by the material's structure and electrical characteristics. Below is an analysis of how several material categories interact with light:

Metals possess a delocalized electron cloud, which results in their high reflectivity across a wide range of wavelengths. The "sea of electrons" easily engages with incoming light waves, resulting in their reflection. Nevertheless, certain metals have the ability to absorb particular wavelengths, resulting in the manifestation of their distinctive colors. Gold exhibits the property of selectively absorbing blue light, which leads to its characteristic warm yellow color (Guo et al., 2023). The optical characteristics of ceramics differ based on their unique composition and crystal lattice. Certain ceramics, such as alumina (aluminum oxide), seem white and non-transparent because of the phenomenon of light scattering occurring within its microstructure (Sharma, 2013). Furthermore, certain ceramics have the ability to be transparent within specified ranges of wavelengths. Yttrium aluminum garnet (YAG) is transparent to infrared radiation, which makes it valuable for laser applications (X. Li, 2009). The addition of particular elements to ceramics can further alter their light absorption and emission characteristics.

Semiconductors occupy an attractive position between conductors and insulators in terms of their interaction with light. Their electrical conductivity and interaction with light are significantly affected by their band gap, which is the energy difference between the valence and conduction bands. Semiconductors with narrower band gaps have the ability to capture photons with lower energy levels, such as visible light (Klein, 1968). On the other hand, semiconductors with wider band gaps allow visible light to pass through them but can absorb photons with higher energy levels, such as ultraviolet (UV) radiation. The flexibility to adjust their properties makes them suitable for many purposes such as solar cells (which absorb sunlight) or light-emitting diodes (LEDs) that produce distinct hues of light when stimulated by electricity.

Polymers are substances that consist of large molecules made up of repeating subunits called monomers. The optical characteristics of polymers are greatly influenced by their chemical composition and the existence of functional groups. Polymers with transparency, such as polystyrene (often found in throwaway cups), have a molecular structure that is relatively simple and weak intermolecular connections, which enables most light to flow through (Carraher Jr, 2017). In contrast, polymers containing conjugated double bonds, such as those found in certain types of plastics, have the ability to absorb particular wavelengths of light, which causes them to exhibit a colorful look. By incorporating light-absorbing or light-emitting molecules into polymers, their optical capabilities are enhanced, rendering them highly useful in various applications such as optical fibers or organic light-emitting diodes (OLEDs) (Carlos et al., 2007).

Comprehending these connections between the structure and properties enables us to create

materials tailored for particular optical uses. By manipulating the structures of materials, such as metallic mirrors and LEDs, a wide range of opportunities in the field of optics can be explored.

4.5 Chemical properties and reactivity

The atomic and molecular structures of materials such as metals, ceramics, polymers, and semiconductors dictate their chemical characteristics and reactivity, ultimately shaping their behavior in different chemical surroundings. These features are essential for their utilization in various sectors and technologies.

Metals have the property of electron loss, which enables them to readily create positive ions. The reason for this characteristic is the low ionization energy and the existence of delocalized electrons in a metallic link. Metals readily engage in oxidation-reduction reactions, as demonstrated by their corrosion behavior (F. Li et al., 2022). Iron undergoes a chemical reaction with oxygen and water to create rust, which is iron oxide. In contrast, highly reactive metals such as sodium react vigorously with water, resulting in the production of hydrogen gas and a hydroxide compound. Metals like platinum and gold have reduced reactivity, which makes them well-suited for applications in jewelry and electronic contacts because of their resistance to oxidation and corrosion. Alloying can alter the reactivity of metals, leading to increased resistance against chemical assault and improved mechanical qualities (Davis, 2001).

Ceramics typically demonstrate exceptional chemical stability as a result of their robust ionic and covalent interactions. Due to their inherent stability, these materials exhibit resistance to the majority of chemical reactions occurring at normal room temperature, hence making them highly appropriate for use in hostile chemical environments. For example, alumina (Al_2O_3) and zirconia (ZrO2) exhibit exceptional resistance to both acids and alkalis (Sequeira et al., 2017). Nevertheless, ceramics exhibit a reaction when exposed to high temperatures. For instance, silicon carbide (SiC) undergoes oxidation at extreme temperatures, leading to the creation of a protective film of silicon dioxide (SiO2) that effectively halts further oxidation (Gupta & Akhtar, 2011). Ceramics are highly valuable in applications such as chemical processing equipment, refractory materials, and biomedical implants due to their inertness, which is essential for withstanding chemical attack.

Polymers exhibit a diverse array of chemical characteristics and reactivities that are contingent upon their molecular structure (Sperling, 2005). Polymers primarily consist of carbon atoms, which can create different functional groups that impact their reactivity. For instance, polyethylene exhibits chemical inertness and resistance to numerous chemicals owing to its uncomplicated hydrocarbon structure, but polyvinyl chloride (PVC) has chlorine atoms, rendering it more chemically reactive (Khanam & AlMaadeed, 2015). Polymers can undergo deterioration through mechanisms such as hydrolysis, oxidation, and photodegradation. For example, polyesters can undergo hydrolytic breakdown when exposed to water (Hosseini et al., 2007). Polymers can have their resistance to chemicals improved by either cross-linking or by adding stabilizers and antioxidants. These additives provide protection against breakdown caused by heat and oxidation (Sperling, 2005).

Semiconductors have distinctive chemical properties as a result of their moderate electrical conductivity and band gap structure (Landsberg, 2016). Silicon, the predominant semiconductor, is unreactive at ambient temperature but can undergo oxidation at elevated temperatures to create a safeguarding layer of silicon dioxide (SiO_2), which is crucial in the manufacturing of semiconductor devices. Doping is a method used to modify the electrical properties of semiconductors without affecting their chemical stability. It involves introducing small amounts of impurities to alter their reactivity. Semiconductors such as gallium arsenide (GaAs) display distinct reactivity in comparison to silicon (Fang et al., 1990). GaAs has the ability to undergo oxidation, resulting in the formation of gallium oxide (Ga_2O_3) and arsenic oxides. These oxides have the potential to impact the performance of electronic devices. The chemical characteristics of semiconductors play a critical role in their functionality within electronic devices, where the chemistry of their surfaces

and the stability of their interfaces are essential for ensuring device dependability and performance.

The atomic and molecular structures of metals, ceramics, polymers, and semiconductors have a significant impact on their chemical characteristics and reactivity. Metals often have a tendency to react and corrode, while ceramics are chemically stable and can withstand high temperatures. Polymers have varying levels of reactivity depending on their composition, and semiconductors have controlled reactivity that is crucial for electronic applications. Comprehending these characteristics is crucial for choosing and designing materials for particular chemical surroundings and uses.

5 Structure-Property Relationship

5.1 Influence of material structure on its properties

The interesting dance between structure and characteristics governs the universe of materials. A material's macroscopic behavior is determined by the arrangement of its constituent atoms, including its crystal structure, bonding types, and defect existence. For example, metals are excellent at electrical conduction because of their easily movable electron cloud, which is delocalized (Newnham, 2012). On the other hand, despite their remarkable strength and thermal durability, ceramics—which are frequently bound together by strong ionic or covalent bonds—have poor electrical conductivity. Similar to this, the structure of polymers allows for customization of their strength, flexibility, or certain capabilities due to their chain architecture and intermolecular interactions. Through the understanding of these structure-property correlations, material scientists can create novel materials with characteristics that are ideal for our constantly changing technological requirements.

Structure-property interactions in materials science concern to understanding how the intrinsic structure of a material at different scales (atomic, molecular, micro, and macro) impacts its qualities and behavior under diverse circumstances. The relationship described is essential in various categories of materials, such as metals, ceramics, polymers, and composites (Y. Q. Cheng & Ma, 2011). It plays a critical role in customizing materials for specific purposes. In this analysis, we will explore the connections between the structure and qualities of different material classes, emphasizing the complex relationship between their structural characteristics and their specific attributes.

5.2 Structure-property relationships in different classes of materials:

5.2.1 Metals

Metals are distinguished by their crystalline structures, which are commonly organized in a face-centered cubic (FCC), body-centered cubic (BCC), or hexagonal close-packed (HCP) lattice (Askeland et al., 2003). The mechanical, thermal, and electrical properties of these structures are greatly influenced by the atomic arrangement within them.

The crystal structure and existence of flaws primarily determine the mechanical properties of metals, including strength, ductility, and hardness. Metals such as aluminum and copper, which have a face-centered cubic (FCC) structure, typically demonstrate a notable capacity for plastic deformation and high ductility, allowing them to endure large deformation before breakdown. The reason for this is the abundance of slip systems (planes that allow for dislocation movement) in FCC metals, which makes deformation easier (Wood, 1940).

Unlike FCC metals, BCC metals such as iron and chromium possess a smaller number of slip systems, resulting in greater strength and hardness but reduced ductility (Weinberger et al., 2013). Dislocations, grain boundaries, and other imperfections significantly influence the mechanical characteristics. Work hardening, also known as the increase in strength, caused by plastic deformation, occurs as a consequence of the multiplication and interaction of dislocations within the structure of the metal (Pant et al., 2003).

Metals possess exceptional conductivity for both heat and electricity, which is a result of the presence of their unbound electrons. The density and mobility of these electrons are influenced by the crystal structure. Within pure metals, the crystal lattice possesses a high degree of symmetry, which facilitates the unrestricted movement of electrons. This, in turn, leads to elevated levels of electrical and thermal conductivity. Nevertheless, the presence of impurities and alloying elements can disperse these unbound electrons, resulting in a decrease in conductivity. For instance, the addition of carbon to iron in order to create steel greatly diminishes its electrical conductivity in comparison to pure iron.

Ceramics are commonly made up of ionic or covalent bonding, leading to a structure that is either crystalline or partly crystalline. Ceramics possess distinctive mechanical, thermal, and electrical capabilities due to their robust bonding and intricate crystal structures. They are renowned for their exceptional hardness and inherent brittleness. The presence of ionic or covalent connections results in the formation of a rigid and stable lattice structure, which contributes to their exceptional compressive strength. Nevertheless, the inherent bonding characteristics impede the mobility of dislocations, leading to reduced ductility and increased brittleness. Flaws and microcracks in ceramics can greatly affect their mechanical strength, often resulting in complete failure when subjected to tensile stress (Munz & Fett, 2013).

Ceramics typically have exceptional thermal stability and great temperature tolerance. This phenomenon can be attributed to the robust intermolecular connections within their crystalline arrangement, necessitating a substantial amount of energy for disintegration. In addition, ceramics exhibit lower heat conductivity in comparison to metals, making them advantageous for applications that necessitate thermal insulation. For instance, the application of ceramic tiles on space shuttles serves to shield them from the severe temperatures encountered during re-entry into the Earth's atmosphere.

The electrical characteristics of ceramics exhibit significant variability based on their structure and composition. Certain ceramics, like alumina, possess exceptional electrical insulating properties because they lack free electrons and have bonding that is confined in nature (Sequeira et al., 2017). On the other hand, ceramics such as zinc oxide and barium titanate display semiconducting and dielectric characteristics, respectively. The electrical behavior of these materials is influenced by their crystal structure, which governs the mobility and interaction of charges inside the lattice.

5.2.2 Polymers

Polymers consist of elongated sequences of recurring molecular units known as monomers, and their characteristics are greatly influenced by the organization and interplay of these sequences.

Factors such as chain length, cross-linking, and crystallinity have an impact on the mechanical properties of polymers, including elasticity, tensile strength, and toughness. Amorphous polymers, characterized by their disordered and intertwined chains, typically demonstrate a high degree of elasticity and are capable of experiencing substantial deformation. Cross-linked polymers, characterized by interconnecting chains, exhibit increased rigidity and enhanced tensile strength. Crystalline polymers, which contain organized sections within the material, demonstrate greater strength and resistance to deformation in comparison to their amorphous counterparts.

The structure of polymers also determines their thermal characteristics. Crystalline polymers generally exhibit higher melting points and glass transition temperatures in comparison to amorphous polymers (Takata & Aoki, 2018). Cross-links can increase thermal stability by necessitating a greater amount of energy to disrupt the interconnected chain network. Thermosetting polymers, characterized by their extensive cross-linking, do not undergo melting when heated. Instead, they undergo decomposition, rendering them ideal for use in high-temperature scenarios.

Polymers typically exhibit electrical insulating properties as a result of their limited availability

of free electrons. Conjugated double bonds introduced into the polymer chain facilitate electron mobility, leading to the formation of conductive polymers (Ates et al., 2012). The electrical conductivity of the polymer is substantially influenced by its structural characteristics, such as the level of conjugation and the presence of dopants. Conductive polymers, such as polyaniline and polythiophene, find application in a range of electrical devices, including flexible screens and organic solar cells.

Composites are substances created through the amalgamation of two or more distinct elements in order to get qualities that surpass those of the individual constituents. The links between the structure and properties of composites are influenced by the characteristics of the matrix and reinforcement materials, as well as the interface between them.

The distribution, orientation, and interaction of the reinforcing material inside the matrix make a substantial impact on the mechanical response of composites, including strength, stiffness, and toughness. Carbon fiber-reinforced polymers (CFRPs) demonstrate exceptional strength and rigidity as a result of the arrangement of robust carbon fibers within a polymer matrix (Hegde et al., 2019). The interface between the fibers and the matrix is crucial for the transfer of loads and the overall mechanical performance. Inadequate adhesion at the interface can result in detachment and structural failure when subjected to stress.

The thermal characteristics of composites are determined by the thermal conductivities of both the matrix and the reinforcement, as well as the proportions in which they are present. For instance, the incorporation of ceramic particles into a polymer matrix can augment the thermal stability and heat resistance of the composite. The composition of the structure, including the arrangement of various materials, can also generate thermal barriers or channels that are specifically designed for thermal management purposes.

By integrating conductive fillers into an insulating matrix, the electrical characteristics of composites can be deliberately manipulated. For example, the incorporation of carbon nanotubes or metallic particles into a polymer matrix can result in a composite material that exhibits improved electrical conductivity. The percolation threshold, also known as the critical concentration of conductive fillers, required to establish a continuous conducting network, plays a crucial role in determining the electrical characteristics of the composite material. Composites can be produced for specific applications, such as electromagnetic interference shielding and flexible electronics (M. Chen et al., 2014), by precisely regulating the filler content and distribution to achieve desired electrical characteristics.

Gaining insight into the connections between the structure and qualities of materials is essential for the purpose of designing and creating materials that possess the needed characteristics for certain uses. The mechanical and thermal properties of metals are greatly influenced by the arrangement of atoms in the crystal lattice and the occurrence of defects (Pelleg, 2013). Ceramics possess distinctive characteristics as a result of their robust bonding and intricate crystal structures, rendering them well-suited for applications requiring high temperatures and insulation. The molecular structure, chain length, and degree of crystal order of polymers hold a critical impact on their charcteristics properties, allowing for a diverse spectrum of mechanical, thermal, and electrical characteristics. Composites leverage the benefits of many materials to attain exceptional qualities, with the interplay between the matrix and reinforcement being a crucial determinant.

By utilizing the understanding of structure-property correlations, materials scientists and engineers have the ability to customize materials to fulfill the specific requirements of many industries, including aerospace, automotive, electronics, and healthcare. A profound comprehension of this subject matter is crucial for the ongoing progress of material technologies and the creation of inventive resolutions to intricate engineering problems.

The behavior of materials is closely connected to their internal structures, which encompass

flaws, microstructure, and phase transitions. These characteristics have significant impacts in different categories of materials, including metals, ceramics, polymers, and semiconductors. Realizing the impact of these factors on the properties of materials is essential in the realm of materials chemistry and engineering.

5.3 Role of defects, microstructure and phase transitions in determining material behavior

5.3.1 Material Imperfections

Defects refer to the presence of flaws or irregularities in the atomic or molecular arrangement of materials. The defects can be categorized as point defects, line defects, and planar defects.

5.3.1.1 Defects at the atomic level

Point defects include vacancies (absence of atoms), interstitials (additional atoms located between regular lattice sites), and substitutional atoms (foreign atoms substituting host atoms). Point flaws in metals have a substantial influence on qualities such as electrical conductivity and strength. For example, the existence of empty spaces can increase the spread of substances, which is crucial for processes such as combining metals and compacting. Point defects in ceramics can impact the ionic conductivity observed in materials utilized for solid oxide fuel cells. Specifically, the presence of oxygen vacancies enables the facilitation of ionic transport (Yasui, 2023).

5.3.1.2 Line Imperfections

Line defects, also known as dislocations, refer to disturbances in the orderly pattern of atoms along a certain line within the crystal lattice. Dislocations play a critical role in influencing the mechanical characteristics of metals (Vitek & Paidar, 2008). They facilitate plastic deformation by facilitating slip, which is the movement of atomic planes past one another. Dislocations' density and mobility have a direct impact on a metal's yield strength and ductility. Methods such as work hardening, which involves raising the density of dislocations, and annealing, which involves reducing the density of dislocations, are used to alter these characteristics.

5.3.1.3 Planar Defects

Planar flaws encompass grain boundaries, twinning boundaries/interfaces, and stacking sequence faults. Grain boundaries, acting as interfaces amidst distinct crystal orientations in polycrystalline materials, have a substantial impact on mechanical behavior (Salvadori & Giacomini, 2013). Metallic materials that have a high concentration of grain boundaries, known as fine-grained metals, generally demonstrate increased strength as a result of the grain boundary strengthening process. In this mechanism, the borders serve as obstacles to the passage of dislocations. Nevertheless, grain boundaries can also serve as locations for corrosion and various types of deterioration (Gertsman & Bruemmer, 2001).

5.3.2 Microstructure

Microstructure refers to the arrangement and characteristics of the small-scale components or features within a material or substance. Microstructure pertains to the arrangement and characteristics of a material at the micrometer to millimeter scale, including properties such as grain size, phase distribution, and the organization of distinct phases (Phillips, 2001).

5.3.2.1 Metals

Thermal and mechanical treatments are used to regulate the microstructure of metals. Steels undergo processes such as quenching and tempering, which result in the formation of distinct microstructures (martensite, bainite, pearlite) that exhibit varying levels of hardness and toughness. By customizing the microstructure, it becomes possible to enhance the qualities of materials to suit certain uses, such as developing high-strength low-alloy steels for building or durable, wear-

resistant tool steels (Alavi Zaree, 2009).

5.3.2.2 Ceramics

In ceramics, the microstructure is commonly defined by the dimensions and arrangement of grains, as well as the existence of porosity. Sintering methods are employed to manipulate the microstructure, minimizing porosity and augmenting density, hence improving mechanical strength and thermal conductivity. Engineered microstructures in advanced ceramics are utilized in applications that demand exceptional thermal stability and resistance to wear, such as turbine blades and cutting tools (Basu & Balani, 2011).

5.3.2.3 Polymers

The microstructure in polymers pertains to the organization and interplay of polymer chains. Crystallinity, cross-linking, and the use of chemicals are significant factors. Polymers with a high degree of crystallinity, such as polyethylene, exhibit enhanced tensile strength and resistance to chemicals. On the other hand, amorphous polymers like polystyrene provide better transparency and resistance to impact. Cross-linking, as observed in vulcanized rubber, improves the material's elasticity and thermal stability, rendering it appropriate for demanding applications such as tires.

5.3.3 Phase transitions

Phase transitions are changes in the physical state of matter, such as from solid to liquid or from liquid to gas. It refers to alterations in the state or structure of a substance, which frequently result in notable modifications in its properties. Phase transitions play a vital role in alloying and heat treatment processes in metals. For instance, the conversion of austenite to martensite in steel leads to the production of a rigid and fragile state that can be tempered to enhance its resilience. Metallurgists can create materials with precise qualities by studying phase diagrams and the impacts of various alloying elements.

5.3.3.1 Phase transitions in ceramics

Ceramics can undergo phase transitions that result in alterations to their crystal structure and mechanical properties. At high temperatures, zirconia experiences a phase shift from tetragonal to monoclinic, resulting in an increase in volume. This characteristic is employed in hardened zirconia ceramics, where the transition caused by stress can improve the resistance to breaking (Patil & Subbarao, 1970).

5.3.3.2 Phase transitions in polymers

Polymers experience phase changes, such as the shift from a glassy state to a more fluid state and the transition from a solid to a liquid state (S. Z. D. Cheng, 2008). The glass transition point (Tg) signifies the shift from fragile, solid state to more flexible, elastic one. This transition is essential for applications that necessitate adaptability and durability under varying temperatures. The melting temperature (Tm) is crucial for processing methods like extrusion and injection molding, as it ensures that the polymer can flow smoothly without undergoing degradation.

Phase transitions in semiconductors

Phase transitions in semiconductors can impact electrical characteristics. For example, the change from a disordered state to an ordered state of silicon greatly enhances its ability to conduct electricity, making crystalline silicon the preferred material for solar cells and electronic devices. Researchers are investigating phase transitions in materials such as VO2, which have the ability to transition from being an insulator to a metal (Whittaker et al., 2011). These transitions are being studied for potential use in smart windows and electrical switches.

Defects, microstructure, and phase transitions tremendous alter the behavior of materials.

These parameters play a crucial role in influencing the mechanical, thermal, electrical, and optical characteristics of metals, ceramics, polymers, and semiconductors. Materials scientists and engineers can create materials with specific qualities for different uses by modifying their internal structures using different processing processes. Having this knowledge is crucial for the progress of technology and the enhancement of the efficiency and resilience of materials in real-world uses.

6 Applications

Materials science plays a crucial role in various fields by providing essential innovations that enhance functionality and performance. Applications of materials span across numerous industries, driving advancements in technology, healthcare, energy, and environmental solutions as shown in Fig 10. These materials are tailored to meet specific requirements, offering unique properties and benefits.

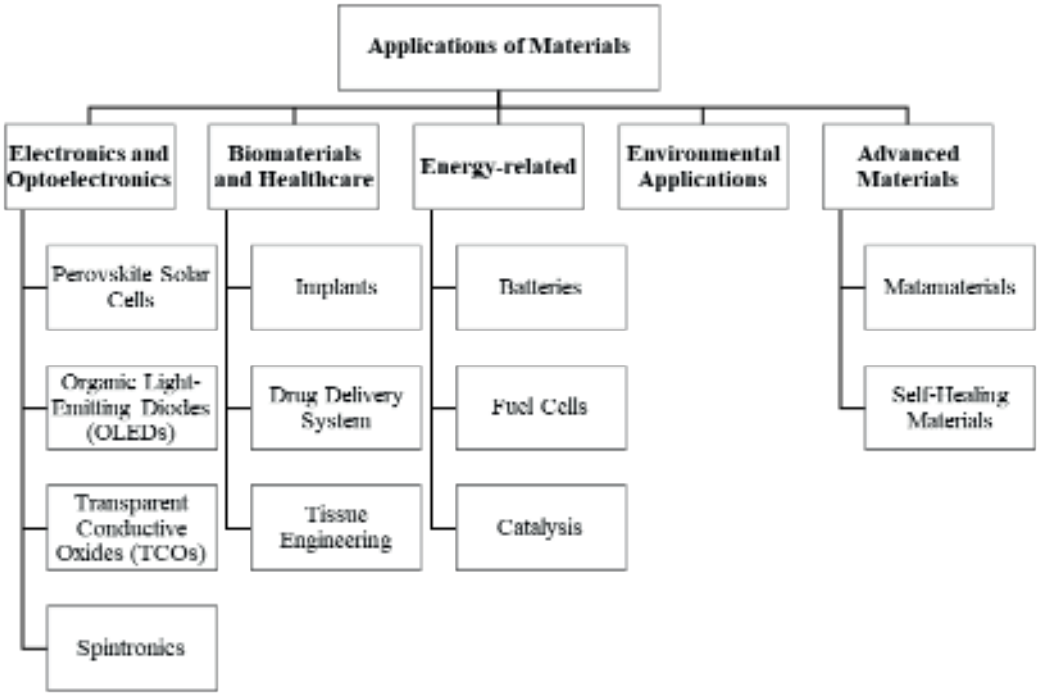


Figure 10 Schematic depicting applications of materials in different fields.

6.1. Electronics and Optoelectronics Applications:

6.1.1 Perovskite solar cells:

The photovoltaic performance of perovskite solar cells, driven by materials chemistry, is largely attributed to their intrinsic properties such as a high absorption coefficient, tunable band gap, large carrier diffusion length, ambipolar carrier-transport ability, and carrier mobility. Organic-inorganic hybrid perovskite (OHIP) materials, with the chemical formula ABX_3 as shown in figure 11, where A is an organic cation, B is an inorganic cation, and X is a halide ion, stand out as efficient and cost-effective candidates for solar cell applications. These materials display exceptional optical and electrical features, including a substantial Bohr radius, feeble binding energy, enhanced dielectric constant, and superior light-absorbing capacity. Typically, a perovskite solar cell consists of an absorber layer, such as $CH_3NH_3PbX_3$, positioned between electron-transport and hole-transport layers. Upon light exposure, the absorber layer generates free charge carriers that traverse through the carrier-transport materials to produce current, with the efficiency of this process depending on the material's thickness. These advanced properties, stemming from meticulous materials chemistry, make OHIP materials pivotal for the development of highly efficient and affordable solar cells

(Suresh Kumar & Chandra Babu Naidu, 2021).

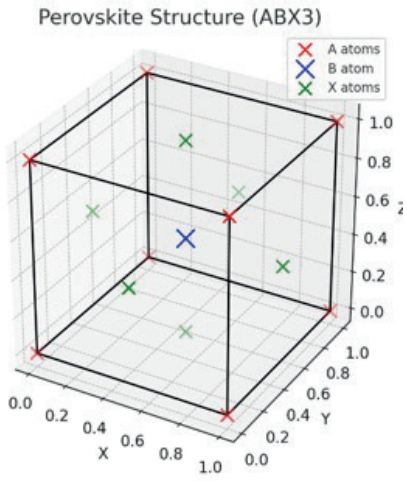


Figure 11 Perovskite Structure.

Miyasaka et al. first showed the application of perovskite materials in solar cells in 2009, using $CH_3NH_3PbX_3$ as a sensitizer in dye-sensitized solar cells (DSSCs), achieving a power conversion efficiency (PCE) of 3.81% (Miyasaka, 2011). Further research has highlighted the potential of organic-inorganic hybrid perovskite (OHIP) materials for solar cell development on account of their favorable inherent properties and the simplicity of their preparation techniques, such as vacuum deposition and atmospheric solution processing. Over a short period, significant advancements have been made, with PCEs improving to as high as 23.3%. The electron-transport layer (ETL) is crucial in perovskite solar cells, traditionally utilizing colloidal thin films of SnO_2, TiO_2, ZnO, or their mesoporous systems. However, these materials often suffer from natural defects and recombination at interfaces. To address these issues, researchers have explored single-atomic layer transition metal dichalcogenides, like MoS_2 and WS_2, as ETL materials due to their virtually defect-free nature and rapid charge carrier transportation capabilities.

The hole-transport layer (HTL) are essential for boosting the efficiency of photovoltaic devices. Extensive research has been conducted on to improving the conductance of HTLs and reducing charge carrier loss at the HTL-perovskite boundary through doping modifications. Among various HTMs, spiro-OMeTAD has been prominent, though its raw form exhibits poor PCE due to insufficient oxidation states. To enhance its performance, dopants such as cobalt complexes and FeCl3, as well as acid additives, have been employed to accelerate the oxidation process and increase hole concentration. Recent innovations include the development of low-cost, dopant-free HTLs, such as fluorinated spiro-OMeTAD-2,7-diamine, which have demonstrated impressive stability and efficiency in CsPbI2Br perovskite solar cells. Additionally, the introduction of CuSeCN films for HTL applications in p-i-n perovskite solar cells has shown promising results, with negligible hysteresis and excellent long-term stability, marking significant progress in the field of high-performance photovoltaic materials (Shi et al., 2020).

To date, most flexible perovskite solar cells have been produced with small surface areas. It is well-documented that as the size of these devices increases, their power conversion efficiency (PCE) tends to decrease due to inevitable film inhomogeneity. Thus, the method used to deposit thin films on a larger scale significantly impacts the performance of these large-area flexible perovskite solar cells. Therefore, it is crucial to develop large-scale deposition techniques for fabricating all layers of flexible perovskite solar cells. Additionally, adopting alternative technologies could further reduce fabrication costs and advance the practical application of these solar cells (F. Chen, 2019).

6.1.2 Organic Light-Emitting Diodes (OLEDs):

The basic structure of an OLED includes a thin organic material layer between two electrodes. The transparent anode is usually indium tin oxide (ITO), while the reflective cathode is metal. When voltage is applied, holes and electrons are injected from the anode and cathode, respectively, into the organic layer (100-150 nm thick). These charges move and recombine to form excitons, emitting photons. The colour of the light depends on the energy gap between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of the organic material. Efficient hole injection requires a low barrier relative to the HOMO level, and effective electron injection requires a low barrier relative to the LUMO level. To enhance performance, low work function metals or stable combinations such as Mg/Ag alloys or LiF with aluminium are used for the cathode (Geffroy et al., 2006). Organic light-emitting diodes (OLEDs) have garnered significant interest due to their potential to revolutionize flat-panel displays by replacing traditional cathode ray tubes (CRTs) and liquid crystal displays (LCDs). The primary advantages of OLEDs in display applications include their self-emissive nature, high luminous efficiency, vibrant full-color capability, wide viewing angles, and high contrast. Additionally, OLEDs offer low power consumption, lightweight designs, large-area display capabilities, and flexibility, making them ideal for diverse mounting options. OLEDs do not require backlighting, polarizers, or diffusers, unlike LCDs, which further enhances their versatility. They are well-suited for various applications such as heads-up instrumentation in aircraft and automobiles, small displays for handheld devices like mobile phones and PDAs, in-car electronics, high-resolution personal communicators, and potentially large flat-panel screens and wall-hanging television display (Wei et al., 2018).

Looking to the future, OLED technology is poised for significant advancements driven by the development of new luminescent materials and innovative fabrication techniques. Researchers are continuously discovering more efficient materials with tunable optical and electronic properties, which promise to surpass the performance of existing options. From a technological perspective, new device configurations and manufacturing methods, such as roll-to-roll processing, are expected to play a crucial role in creating stretchable and biocompatible optoelectronic devices. The efficiency of cutting-edge OLED devices already exceeds that of traditional fluorescent lamps, suggesting that OLEDs will soon replace conventional lighting systems with more efficient alternatives. As research and development progress, we can anticipate even greater advancements in OLED technology, leading to more efficient and versatile lighting and display solutions (Park et al., 2011).

6.1.3 Transparent Conductive Oxides (TCOs):

Transparent conducting oxides (TCOs), a distinctive category of wide bandgap semiconductors, are renowned for their exceptional combination of high conductivity and transparency within the visible spectrum, making them indispensable in photoelectronic. TCOs, such as SnO_2, In_2O_3, ZnO, and CdO, are typically doped with elements like F, In, Ga, Al, Ti, and Cu to enhance their electrical properties. Common n-type TCOs include AZO (Al: ZnO), ITO (Sn: In2O3), and GZO (Ga: ZnO), which are extensively utilized due to their high carrier densities. In contrast, p-type TCOs, such as $CuAlO_2$, $SrCu_2O_3$, and NiOx, have yet to achieve widespread application primarily because of their comparatively lower carrier densities (Z. Wang et al., 2019b). The material chemistry of TCOs also reveals their intriguing permittivity behavior, particularly in the near-infrared (NIR) region where epsilon-near-zero (ENZ) phenomena can induce unique physical effects such as superluminal speeds and large nonlinearities. Moreover, TCOs can excite surface plasmon (SP) modes at interfaces with matched permittivities, enabling the design and fabrication of ultra-compact NIR devices that could potentially replace noble metals in these applications. This versatility underscores the significant role of TCOs in advancing modern optoelectronic and photonic technologies.

Indium tin oxide (ITO), fluorine-doped tin oxide (FTO), aluminum-doped zinc oxide (AZO), and gallium-doped zinc oxide (GZO) are among the widely utilized transparent conducting oxides (TCOs) due to their exceptional combination of high transparency (>95% in the visible range)

and low resistivity (as low as 10^{-4} Ωcm). These TCOs find extensive application in various fields, ranging from optoelectronics to metamaterials and ultrafast switches. For instance, ITO, known for its outstanding performance as a TCO, is employed in metamaterials and hyperbolic metamaterials owing to its ultrafast response and low infrared losses. However, to meet specific application requirements, researchers have developed alternative materials based on indium oxide and cerium oxide, such as ICO:H (indium cerium oxide with 1.3% hydrogen doping). Additionally, Al-doped ZnO (AZO) exhibits relatively low infrared losses compared to other TCOs, making it suitable for plasmonic applications in the communication band. Furthermore, beyond cationic doping, oxygen can also be substituted by other anions, as seen in the case of fluorine-doped tin oxide (FTO), which has been widely used in low-emissivity windows since the 1970s (Visaveliya et al., 2022). Recent advancements have explored the surface plasmon properties of FTO, particularly in the mid-infrared region, showcasing its potential for various applications such as optical resonators and electro-optic modulators.

Moreover, emerging materials like graphene and spinel-type oxides are gaining attention for their unique properties in transparent conductivity. Graphene, a two-dimensional material with ultra-fast carrier mobility, is utilized in transparent electrodes due to its metal-like behavior and ability to support surface plasmons. Its applications extend to optical switches, resonators, and metamaterials in the mid-infrared and terahertz ranges. Similarly, spinel-type oxides exhibit high carrier densities and tunability, making them crucial in photonics applications where few p-type semiconductors can excite surface plasmons in the near-infrared region. For instance, Ga2FeO4 (GFO) nanocrystals demonstrate localized surface plasmon resonance (LSPR) around 1000 nm, with carrier densities that can be tuned to support both p-type and n-type behavior, further highlighting the versatility of spinel-type oxides in photonics and related fields. These advancements in material chemistry pave the way for the development of innovative TCOs with enhanced properties and diverse applications in optoelectronic devices and beyond (Z. Wang et al., 2019a).

6.1.4 Spintronics:

Spintronics stands as a burgeoning domain poised to shape the landscape of future nanoelectronics devices, aiming to curtail power consumption while amplifying memory and processing capabilities. These innovative devices harness the spin degree of freedom inherent in electrons and/or holes, which may also engage with their orbital moments. Through the deployment of magnetic layers acting as spin-polarizers or analysers, or through spin-orbit coupling mechanisms, control over spin polarization is achieved in these systems. Additionally, spin waves emerge as viable conduits for transporting spin current within these devices (Ohno et al., 2016). Spintronics holds promise for diverse applications, extending into energy harvesting, bioinspired computing, and quantum technologies. From nanoscale spintronics sensors that enhance hard disk drive density to magneto resistive random-access memories (MRAMs) poised to replace flash memories, static random-access memories (SRAM), and dynamic random-access memories (DRAM), spintronics offers multifaceted solutions for memory and processing enhancements (Ohno et al., 2016). Moreover, spin current utilization and torque enable the development of oscillators and information transmission sans current, further expanding the scope of spintronic applications.

The advent of non-local spin-valves has enabled the detection of spin Hall and inverse spin Hall effects, demonstrating lateral device configuration advantages. Additionally, materials exhibiting a large anomalous Hall effect, such as non-collinear antiferromagnetic (AF) materials like Mn5Si3 and Mn3Sn, open avenues for innovative spintronic devices. The continuous exploration of novel materials, efficient charge-to-spin and spin-to-charge current conversion mechanisms and controlled magnetic property manipulation through voltage application hold significant promise for future spintronic advancements, offering potential breakthroughs in fields like IoT, ultralow-power electronics, and high-performance computing (HPC).

In the next decade, the success of magneto resistive random-access memories (MRAM)

is expected to influence the widespread adoption of spintronics across various technologies. Ongoing research on innovative materials, efficient current conversion mechanisms, and precise spin manipulation in semiconductors is crucial for furthering spintronic applications. Moreover, the exploration of oxide materials, characterized by their crystallinity akin to semiconductors, may offer new avenues for future spintronic devices, potentially capitalizing on the advantages conferred by crystalline structures. As such, material research remains pivotal in shaping the trajectory of spintronics over the next 13 years (Hirohata et al., 2020).

6.2 Biomaterials and Healthcare Application:

6.2.1 Implants:

Advances in medical sciences and engineering have led to the development and widespread use of implants in the human body, with research dating back to the 1890s resulting in innovations such as pacemakers and defibrillators. Bioimplants are specialized devices designed to replace, support, or enhance natural organs. Their development has focused on biocompatibility and the ability to replicate the functions of natural body parts. Today, bioimplants are utilized in a wide array of applications, including brain and neural implants, sensory implants, spinal implants, organ stimulation implants, subcutaneous implants, dental implants, cosmetic implants, and other structural implants such as stents, braces, rods, heart valves, bones, pins, hip prostheses, and knee replacements (Prakasam et al., 2017).

Bioimplants can be categorized based on their material type, which includes bioceramics, polymers, and metallic biomaterials. Bioceramics, particularly those based on calcium phosphates, are well-regarded for their similarity to natural bone and are used extensively in tissue engineering applications. These materials are available in various forms such as dense, porous, bimodal, and amorphous states. Recent advancements have focused on bioresorbable bioceramics, which degrade over time and are replaced by natural tissue. Ideal bioactive ceramics are biocompatible, osteoconductive, osteoinductive, enable angiogenesis, and are biodegradable. Common applications of bioceramics include dental, periodontal, cochlear, maxillofacial, and spinal disc implants (Prakasam et al., 2017).

Polymers are also widely used as bioresorbable materials for clinical applications such as bone implants, sutures, and drug delivery devices. Polymers like PGA, PLA, and PLGA are preferred for their non-corrosive properties and ability to be molded into various shapes. However, they may experience a loss of mechanical strength over time due to degradation. Magnesium-based implants are another emerging area, offering potential benefits in orthopedic and cardiovascular applications. Titanium alloys are known for their excellent integration with bone tissue and are used in pacemaker cases, implantable drug pumps, screws, and dental implants (Meffert et al., 1992). The development of metallic-polymer composites continues to evolve, with materials like Mg/PCL showing promise due to their compressive strength and biocompatibility. Despite these advances, there remains a need for further research to optimize the performance and safety of biodegradable and bioresorbable implants in medical applications.

6.2.2 Drug Delivery Systems:

Biodegradable polymeric biomaterials have significantly advanced drug delivery applications and continue to refine pharmaceutical and biomedical fields. Polymers, derived from the Greek words "poly" (many) and "mers" (parts or units), play a crucial role in colloidal drug carrier systems due to their compatibility with body tissues and controlled release kinetics. These systems, which include small particles, optimize drug loading and release properties. Non-toxic, biodegradable, and biocompatible polymers are highly advantageous, especially those capable of crossing the blood-brain barrier and providing protection against chemical degradation. Smart polymers, which respond to environmental stimuli like temperature, pressure, and pH changes, are particularly beneficial for targeted drug delivery, enhancing the precision and efficacy of treatments (Bae, 2002).

Polysaccharides, composed of monosaccharide units joined by O-glycosidic linkages, are stable, hydrophilic, non-toxic, and biocompatible, making them ideal for drug delivery and targeting. Commonly used polysaccharides include hyaluronic acid, chitosan, glycol chitosan, pullulan, dextrin, and alginate. Chitosan and its derivatives, like glycol chitosan, self-assemble into nanoparticles under certain conditions, facilitating multifunctional drug delivery systems. Additionally, polymers such as poly (lactic-co-glycolic acid) (PLGA) have gained popularity due to their biocompatibility, biodegradability, and tunable mechanical properties. These polymers are used in various drug delivery systems, including hydrogels, liposomes, and nanoparticle-based carriers, offering controlled and sustained release of therapeutic agents (Prajapati et al., 2019).

Synthetic biodegradable polymers, such as polyurethanes, polycarbonates, and polyanhydrides, have garnered attention for their biocompatibility and mechanical properties, making them suitable for medical devices and drug delivery systems. Polyurethane-based materials, known for their flexibility and biodegradability, are used in tissue repair and drug delivery applications. Polycarbonates, like poly (trimethyl carbonates) (PTC), exhibit slow degradation and high flexibility, ideal for controlled drug release. Biodegradable polymeric nanocarriers are particularly promising for improving the efficacy of drug, protein, peptide, DNA, or RNA delivery. These nanocarriers offer potential for various drug delivery routes, including oral, parenteral, nasal, and transdermal, as well as for gene delivery and cancer therapy. The development of biodegradable polymers continues to evolve, aiming to enhance their degradation patterns and minimize toxicity, thereby advancing biomedical applications and improving therapeutic outcomes (Zahin et al., 2020).

6.2.3 Tissue Engineering:

Tissue engineering and regenerative medicine is a dynamic field that merges expertise of materials sciences, life sciences, and engineering to create tissue-engineered grafts that can restore and replaced missing or severely damaged tissues and organs. These grafts, composed of scaffolds and biochemical cues from support cells and growth factors, are promising substitutes for donor organs. A biomaterial-based scaffold is crucial in tissue engineering, providing mechanical support, a conducive environment that encourages cell survival, expansion, and maturation, and facilitating tissue repair and regeneration. Ideal scaffolds possess specific architectural, mechanical, physicochemical, and biological properties. They must be porous architecture to support cell attachment and migration, have shape stability and mechanical properties similar to the defect tissues, be biocompatible and biodegradable, and exhibit low immunogenicity (Yi et al., 2017).

The development of tissue-engineered scaffolds that can produce viable artificial tissues and organs is a critical goal of tissue engineering and regenerative medicine. These scaffolds provide mechanical stability for regenerating tissue, integrates biochemical signals, guidance and cellular direction and tissue remodeling, and create an optimal microenvironment for tissue repair and regeneration. Ideal scaffolds must execute various stipulations, including biomechanical properties, surface topology, biodegradability, biocompatibility, and diffusion capacity. At this juncture, tissue-engineered scaffolds molded from synthetic biopolymers and naturally derived biomaterials are frequently employed, as these materials can be tuned to optimize physicochemical performances (Y. Zhang et al., 2020). One of the key benefit of extracellular matrix (ECM) scaffolds is their reduced immunogenicity, reducing the risk of adverse immune responses and chronic inflammation, which can limit the clinical application of allotransplantation and xenotransplantation.

Numerous ECM analogues have been developed to support cellular function, including synthetic scaffolds derived from polymeric substrates, hydrogels synthesized from crosslinked hydrophilic polymers, ceramic-based scaffolds, and natural biopolymers. These analogues mimic physiological 3D microenvironments but often lack the complex biochemical properties and 3D ultrastructure of native mammalian ECM. Advances in proteomic and bioinformatics techniques have improved the understanding of ECM components, facilitating the design and fabrication of biomaterials that meet the anatomical and physiological needs of native tissues. Decellularization

of native tissues and organs has enhanced the application of ECM biomaterials, promoting in situ tissue remodelling and serving as templates for whole-organ engineering. Ongoing improvements in decellularization techniques and recellularization strategies will further advance the biocompatibility, endothelialisation, and functional integration of ECM scaffolds, highlighting the promising future of ECM biomaterials in tissue engineering and regenerative medicine (Jammalamadaka & Tappa, 2018).

6.3 Energy-related Applications:

6.3.1 Batteries:

Materials chemistry plays a crucial role in the production and optimization of electrode materials for energy storage devices, such as lithium-ion batteries and supercapacitors. These devices rely on the conversion of chemical energy into electrical energy, with the energy stored in the chemical bonds of electrode materials. Key performance indicators for these devices include energy density, power density, and safety, all of which are heavily influenced by the electroactivity, electron/ion conductivity, and structural stability of the electrode materials. Critical issues that need to be addressed in electrode materials include energy density, the kinetics of ion and electron transport, storage and reaction, and structural stability during electrochemical reactions (K. Chen & Xue, 2016).

Electrode materials are the fundamental components that determine the performance of batteries and supercapacitors. High-energy electrode materials, capable of multiple-electron transfers per metal cation, have driven the evolution from lead-acid, nickel-cadmium, and nickel metal hydride batteries to modern lithium-ion batteries. The high energy density of lithium-ion batteries has revolutionized portable electronics and the electrification of transport. Among emerging technologies, lithium-sulfur (Li-S) batteries are gaining attention due to their high theoretical energy density and the abundance and low cost of sulfur. However, challenges such as the insulating nature of sulfur and lithium sulfide, the dissolution of intermediate lithium polysulfides, volume changes during cycling, and the formation of a non-uniform solid electrolyte interface must be addressed.

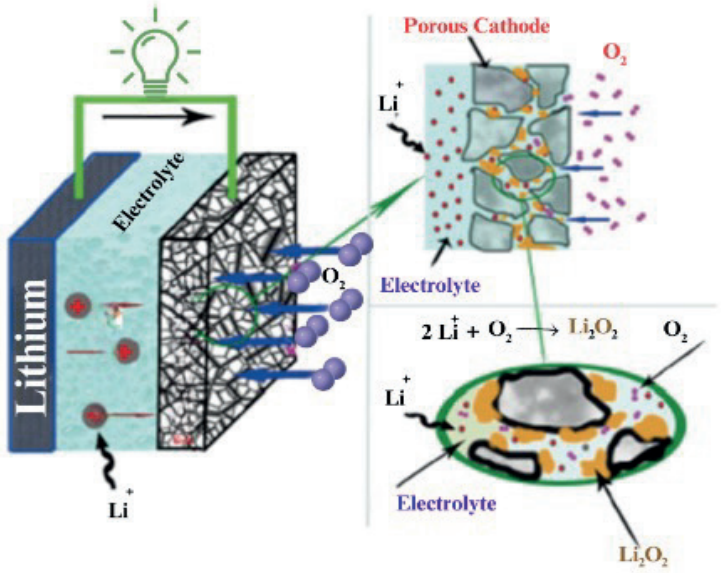


Figure 12 Schematics of aprotic lithium-oxygen battery and the cathode electron structure

Electrolytes in Li-S and Li-O2 batteries play a critical role in ion transport and overall battery performance. In Li-S batteries, the dissolution of polysulfides and the shuttle effect significantly impact performance, necessitating the development of advanced electrolyte systems. Additionally, carbon-based electrode materials, such as graphite and graphene, are extensively used in lithium-ion

batteries as shown in figure. 12 and supercapacitors due to their favorable properties and environmental benefits. Advances in materials chemistry have facilitated the design of electrode materials with enhanced electroactivity and stability, combining experimental and computational approaches to optimize their structure and function. The emergence of hybrid devices like supercapatteries, which combine the properties of batteries and supercapacitors, highlights the ongoing innovation in the field driven by materials chemistry (L. Li et al., 2017).

6.3.2 Fuel Cells:

The escalating interest in efficient yet reasonably priced renewable energy has driven widespread attention in the commercial advancement of fuel cell technology, particularly as a mock-up for combustion-based energy origins. Among the various fuel cell technologies, direct methanol fuel cells (DMFCs) have gained prominence due to their ability to utilize methanol, an abundant and easily stored liquid fuel. Methanol can be readily produced predominantly from natural gas and, to a lesser degree, sustainable energy sources such as biomass, and it boasts a high power density of 6000 Wh/kg. Additionally, DMFCs operate at relatively low temperatures (40-80°C), making them suitable for implementation in the automotive, consumer electronics, and portable power generation (Koenigsmann & Wong, 2011).

DMFCs are uniquely advantageous compared to hydrogen-based fuel cells because of their use of liquid methanol, which simplifies storage and transportation. However, despite these advantages, the commercialization of DMFCs has been hindered by their suboptimal efficiency rating and the sky-high cost of precious metal catalysts, such as platinum. Efforts to reduce platinum loading and improve utilization without compromising electrochemical activity have led to the exploration of alloying platinum with transition metals and using non-noble metal-based electrocatalysts like tungsten trioxide and tungsten carbide. These materials have shown promise due to their high electrical conductivity and stability in acidic media, but further development is necessary to enhance their catalytic performance for widespread use (Koenigsmann & Wong, 2011).

Recent advancements have focused on the potential of one-dimensional (1D) nanostructured electrocatalysts to address the inherent limitations of traditional nanostructured catalysts. The unique structural and electronic properties of 1D nanomaterials, such as preferential disclousure of smooth, impeccable, reduced-energy crystal facets, can enhance both the methanol oxidation reaction (MOR) and oxygen reduction reaction (ORR). Additionally, these nanostructures exhibit improved stability against annulment and ripening, modifying to suit for long-term use. However, there remains a need for scalable, environmentally friendly synthesis techniques and further investigation into the structure-property correlations of these materials to fully realize their potential in upgrading the cost-efficiency and execution of DMFC technology (Maslova et al., 2023).

6.3.3 Catalysis:

Nano-catalysts and catalytic enzyme hold significant aptitude in bioenergy output, an area that bridges biotechnology and renewable energy. These process catalysts are crucial for synthesizing bioenergy by enhancing selectivity, caliber, and yield potential. Nanoparticles, both inorganic and organic, employed to boost biofuel production, proving to be consistent and cost-effective for enzyme immobilization. This immobilization amplify biofuel harvesting in microorganisms. Integrating enzymes with nanotechnology enhances the resilience, functionality, efficiency, and agility of enzymes in bioprocessing. In biodiesel fabrication, nano-catalysts serve as process reactants and catalysts, improving turnover rate, mass transfer, and thermal and physical traits (Cui et al., 2018). The synergistic response of nano- and enzymatic catalysts offers innovative solutions for bioenergy production, addressing environmental issues such as greenhouse gas emissions and climate change. Nano-catalysts, with their high surface area-to-volume ratios, significantly enhance catalyzed transformation, optimizing biodiesel production and improving product quality. Enzymatic catalysts, empowered by nature's efficiency and targetedness, enable the efficient conversion of biomass

feedstocks into bioethanol and biodiesel. This combination of catalysts reduces waste and energy consumption in biofuel production, driving sustainable energy innovation for homes, automobiles, and industries. The ongoing development of extremely dynamic, meticulous, and tailored nano-catalysts is crucial to address the need of industrial-scale biofuel manufacturing, thereby facilitating a shift toward sustainable energy landscape (K. Chen & Xue, 2016) (Wong, 1989).

6.4 Environmental Applications:

Water is a fundamental necessity for all living organisms. However, historical cultivation, globalization, and industrialization have led to significant water contamination, negatively impacting environmental health, particularly aquatic ecosystems. Various pollutants, such as dyes, heavy metals, and microplastics, contribute to water pollution. Dyes, widely used in textiles, food, cosmetics, and medicine, are a major concern as approximately 50% of these dyes are lost in the effluent stream, which is often used for activities like washing and bathing or discarded into rivers, lakes, and canals. Even a small concentration of dye, as low as 1 mg/L, can cause undesirable coloration, making the water unfit for consumption. Heavy metals from industrial processes and microplastics from discarded plastic products also pose significant threats. Microplastics enter the ocean through rain and river movements, leading to seawater pollution and causing digestive blockages, metabolic disorders, and reproductive issues in aquatic organisms. The complex nature of these pollutants disrupts ecological systems, emphasizing the need for effective remediation and treatment methods (Maheshwari et al., 2021).

Biomaterials have emerged as environmentally friendly alternatives for water purification due to their cost-effectiveness, availability, non-toxicity, and excellent performance. Nowadays, the use of biomaterials like chitosan, Luffa, sisal, and hydroxyapatite is highly effective in water and wastewater technology for removing dyes, heavy metals, and pharmaceuticals. Hydroxyapatite, a phosphate material found in bones and teeth, has proven useful in bone tissue engineering, biological delivery systems, and bioactive coatings. Its excellent properties have also made it valuable in environmental pollution control. Hydroxyapatite can be sourced from materials like seashells, sea corals, and various bones, offering versatile applications in removing pollutants (Mamba et al., 2021). Chitosan, a biopolymer known for its biodegradability, non-toxicity, and outstanding chelation behavior, has been extensively studied for dye and heavy metal ion removal. Its ability to be shaped into various forms, such as flakes, powders, beads, gels, films, and porous particles, enhances its practical applicability. The chemical structure of chitosan makes it highly relevant for dye removal applications. Hydrogels, with their porous three-dimensional network structure, offer a high specific surface area and contain many polar functional groups, providing active sites for heavy metal adsorption. Hydrogels can swell significantly in aqueous solutions, increasing their contact area with contaminants and improving adsorption efficiency (Yang et al., 2021). Microplastics, a byproduct of discarded plastic products, pose a significant threat to the water environment. These small plastic fragments enter the ocean through rain and river movements, leading to seawater pollution. Microplastics are ingested by aquatic organisms, causing digestive blockages, metabolic disorders, and reproductive issues. The trend of plastic emissions suggests that, if unmitigated, the amount of plastic in the ocean could surpass that of fish. Technologies to treat microplastics in rivers are urgently needed to prevent further marine ecosystem pollution. Additionally, microplastics can adsorb and enrich discharged drugs like antibiotics, exacerbating their environmental hazards (Hale et al., 2020).

Various techniques, including adsorption, filtration, membrane technology, and advanced oxidation methods like ozonation and photocatalysis, have been developed for wastewater treatment. Membranes are preferred over conventional water treatment processes due to their effectiveness and limited environmental hazard. They act as barriers, selectively allowing water molecules to pass through while preventing impurities. However, most commercial membranes are made from non-biodegradable polymers, which are susceptible to fouling. To address this, innovative designs like self-cleaning ultrafiltration membranes incorporating TiO2 nanoparticles and polyvinyl alcohol

hydrogels have been developed. These membranes offer improved hydrophilicity, self-healing properties, and enhanced performance, making them promising materials for sustainable wastewater treatment (Yang et al., 2021).

6.5 Metamaterials and Self-healing Materials:

Artificially structured metamaterials have revolutionized the manipulation of electromagnetic waves, enabling functionalities such as the cloak of invisibility based on coordinate transformation. Unlike other cloaking methods, which are typically limited to subwavelength objects, the transformation method allows the design of devices that render macroscopic objects invisible. This approach is not sensitive to the object being cloaked, and significant strides have been made in designing non-magnetic cloaks operating at optical frequencies. These metamaterials and plasmonic media have garnered significant attention due to their potential applications in various fields, including cloaking. They enable sub-wavelength focusing and "perfect lensing," opening exciting possibilities in camouflaging, low-noise measurements, and non-invasive sensing and probing in medicine, biology, and optics (Monticone & Alu, 2017). At optical frequencies, the combination of metamaterials with plasmonics and nanophotonics has advanced the control of light propagation, radiation, localization, and scattering. Metamaterials enable unprecedented wave manipulation, such as creating artificial plasmas at microwaves, artificial magnetism in optics, and negative refraction. These capabilities are not only paving the way for fascinating research directions but also have direct applications in electromagnetic and optical technology. For instance, directive scatterers and nanoantennas driven by localized nanosources can be used in point-to-point wireless communication at the nanoscale, nano-sensing, nanoscale spectroscopy, and the realization of directive and efficient single-photon emitters (Cai et al., 2007) (Alu & Engheta, 2008).

Product commercialization in industries typically follows key milestones: idea generation, laboratory implementation, pilot line upscaling, and industrial applications. Currently, self-healing materials are mostly in the early stages of development, either at the preliminary or product level, with their broader applications yet to be realized. However, their future potential spans nearly all industries. Presently, the automotive, aerospace, and construction industries are leading the way in applying these materials. For instance, Nissan has commercialized a self-healing clear coat for car surfaces, known as "Scratch Guard Coat," which repairs minor scratches autonomously. Similarly, Bayer Material Science has developed self-healing polyurethane clear coats for aesthetic maintenance. The aviation industry anticipates the use of self-healing composites for aircraft, while the construction industry looks forward to self-healing concrete and corrosion-resistant coatings for long-term structural integrity. Additionally, biocompatible self-healing materials are poised to extend the service life of medical implants like artificial bones and teeth. These advancements demonstrate the broad and transformative potential of self-healing materials across various sectors (Ma et al., 2020).

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