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A Brief Review on Perovskite Materials: Synthesis, Properties, and Applications

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Abstract

Perovskite materials have emerged as a transformative class of compounds, capturing widespread interest due to their remarkable properties and diverse applications across various fields, including optoelectronics, catalysis, energy storage, and environmental technologies. The synthesis techniques, classification, and unique properties of perovskite materials are thoroughly examined in this paper, which highlights the materials' potential to completely transform a number of sectors. One of the standout features of perovskites is their highly tunable structure, represented by the general formula ABX_3, which allows for the customization of their optical, electronic, and chemical properties. This adaptability has positioned them as strong candidates for high-performance solar cells, with rapid advancements pushing power conversion efficiencies to unprecedented levels. Similarly, their excellent charge transport properties and solution-processable nature have made perovskites integral to next-generation light-emitting diodes (LEDs) and other optoelectronic devices, offering significant advantages in terms of efficiency, cost-effectiveness, and versatility. Beyond optoelectronics, perovskites demonstrate immense promise in catalysis, energy storage, and environmental remediation, owing to their high ionic conductivity, catalytic activity, and structural stability. However, challenges such as long-term stability, sensitivity to environmental factors, and the use of toxic elements like lead must be addressed to ensure their sustainable integration into practical applications. This review underscores the critical role of ongoing research in overcoming these barriers and unlocking the full potential of perovskite materials. By advancing stability, scalability, and environmental safety, perovskite technologies could drive significant progress in energy and environmental sectors, paving the way for innovative, sustainable solutions.

Keywords: Perovskite materials, synthesis methods, optoelectronics, renewable energy, stability challenges

INTRODUCTION

Perovskite, a remarkable class of materials, has gained immense attention in the scientific community and holds tremendous promise for a wide range of applications and have captivated researchers due to their exceptional properties, versatility, and potential for revolutionizing various fields such as solar energy, optoelectronics, catalysis, and more.

The word "perovskite" describes a class of substances that have a particular crystal structure in common. This structure is made up of a cubic lattice of metal cations encircled by oxygen anions. Perovskite materials have the general chemical formula ABX_3, where "A" stands for a large cation, like an organic molecule or an alkali metal, "B" for a smaller transition metal cation, and "X" for an anion, usually oxygen (Figure 1). One of the most notable characteristics of perovskite is its extraordinary optical and electronic properties.

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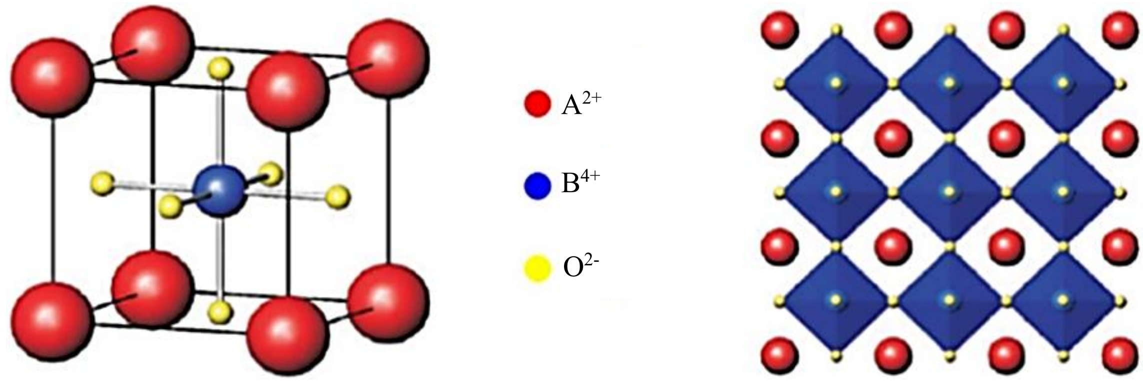

Figure 1. Structure of perovskite [2].

They exhibit a high degree of tunability, allowing researchers to adjust their band gap by modifying their composition or structure, which makes them suitable for various applications. Perovskites have demonstrated exceptional light-absorbing capabilities, making them particularly attractive for photovoltaics and solar cells.

In fact, perovskite solar cells have achieved remarkable power conversion efficiencies within a relatively short period of development.

Perovskite materials also have outstanding charge transport capabilities, which allow for effective electron and hole mobility. This property, coupled with their solution processability and cost-effectiveness, has spurred interest in their utilization of light-emitting devices, such as light- emitting diodes (LEDs) and lasers. Perovskites have exhibited impressive electroluminescence efficiencies and colour, purity, positioning them as potential contenders for next-generation display technologies [1].

Aside from their applications in optoelectronics, perovskite materials have also shown promise in catalysis, energy storage, sensors, and other fields. Their unique chemical and physical properties, including their high ionic conductivity and catalytic activity, have opened up new possibilities for enhancing energy conversion and storage devices, as well as facilitating chemical reactions for various industrial processes.

Despite the tremendous potential of perovskite materials, there are still issues that need to be resolved. Stability problems continue to be a significant worry for their long-term performance and economic viability, especially when exposed to light and moisture. To improve the stability and reliability of perovskite-based electronics, researchers are actively addressing these problems.

Perovskites, which bear the name of Russian mineralogist Lev Perovski, were initially found in the Ural Mountains of Russia in 1839 by Gustav Rose. Numerous synthesized compounds with the distinctive perovskite structure are based on the prototype mineral calcium titanium oxide ($CaTiO_3$) [3].

SYNTHESIS METHODS

Perovskites are synthesized using a variety of sophisticated processes to attain the required structural characteristics, high purity, and uniformity:

Co-precipitation

One technique that is frequently employed for the production of simple oxides is the precipitation of metal salts. After adding a chemical reagent that lowers the solubility limit, precipitation happens. When various cations in a solution precipitate simultaneously, this is known as co-precipitation [4]. The simultaneous precipitation of all cations and the creation of perfect homogeneous products depend on the temperature, concentration, pH, and homogeneity of the solution being controlled. Ammonia, ammonium oxalate, urea, and ammonium carbonate are used for precipitation (Figure 2) [5].

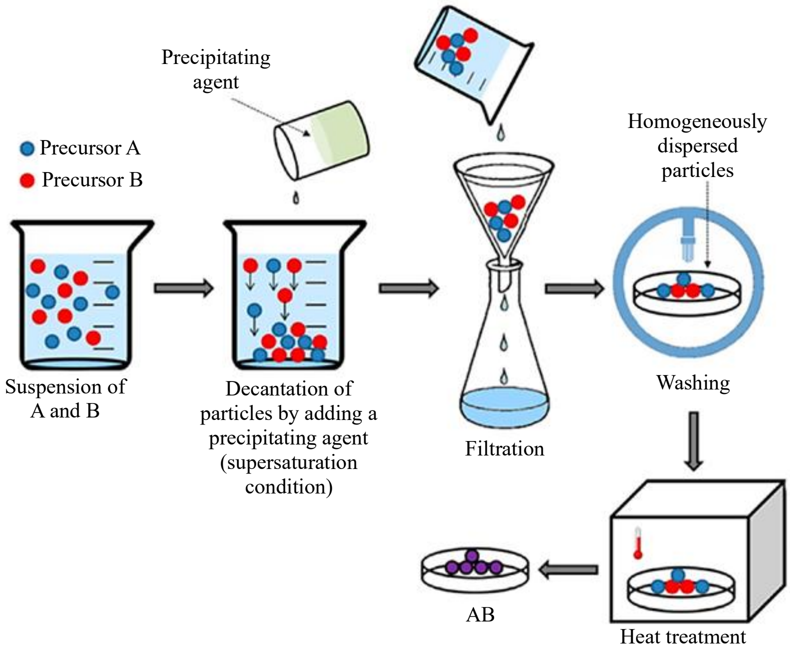

Figure 2. Synthesis by co precipitation method [6].

Solid-State Reactions

All reagents, including carbonates, nitrates, and oxides, can be combined in solid-state reactions according to stoichiometric ratios because the source materials and final products are solid. Perovskites can be created by combining the B-site and A-metal ion oxides or carbonates in the general formula ABO_3 at the necessary ratio and at temperatures greater than 2/3 m.p. for up to 10 hours at a time to produce the final product with the required composition. All of the ingredients are efficiently ball milled in acetone or isopropanol milling media. After being dried at 100°C, the obtained product is allowed to calcinate for 4–8 hours at 600°C while being warmed and cooled at a rate of 2 °C per minute [7]. To guarantee the conformation of a single phase of perovskite, the obtained samples are ground, settled, and then recalcined at 1300–1600°C for 5–15 hours at the same alternating temperature (rate: 2°C/min). Additionally, the obtained samples were settled and ground [8].

Hydrothermal Synthesis

The idea behind hydrothermal synthesis is to mix the precursors at high temperatures and pressures, or to conduct the reaction in an aqueous solution. This process does not require calcination to achieve crystalline particles. Although this technique was initially employed to create and verify the [9] thermodynamic stability of $BaTiO_3$ and other perovskites, it is now possible to modify the particle size and form by adjusting the reaction's temperature, pH duration, and reactant concentration. Recently, this technique has been used to manufacture $BaTiO_3$ at low temperatures by applying an electric field in a hydrothermal shell at particular temperatures (between 100 and 200°C) (Figure 3) [10].

Pechini Method

The Pechini method, sometimes referred to as the polymeric precursor method or the method of mixed liquids, is a synthesis technique that makes it possible to synthesize oxides while exhibiting excellent control over the stoichiometry of the reaction products, as well as high reproducibility and homogeneity of the reaction mixture [11]. The main idea behind this approach is to react modified cations with a carboxylic acid to produce a chelate, which is then added to the system as soluble salts. The resulting solutions comprising metal salts and citric acid yield a clear solution when heated to 80–100°C in conjunction with a chosen ethylene glycol. When heated to a higher temperature (150–250°C), a condensation reaction involving COOH and OH groups occurs, which also results in the formation of a polyester "resin" with uniformly distributed metallic cations throughout the resin mass [12].

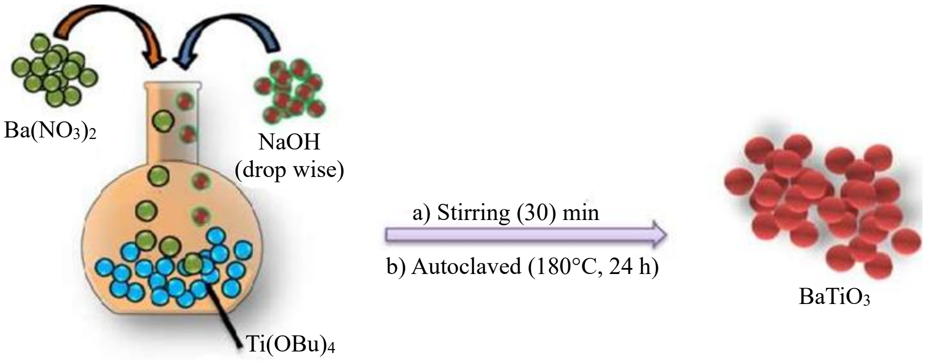

Figure 3. Synthesis by hydrothermal method.

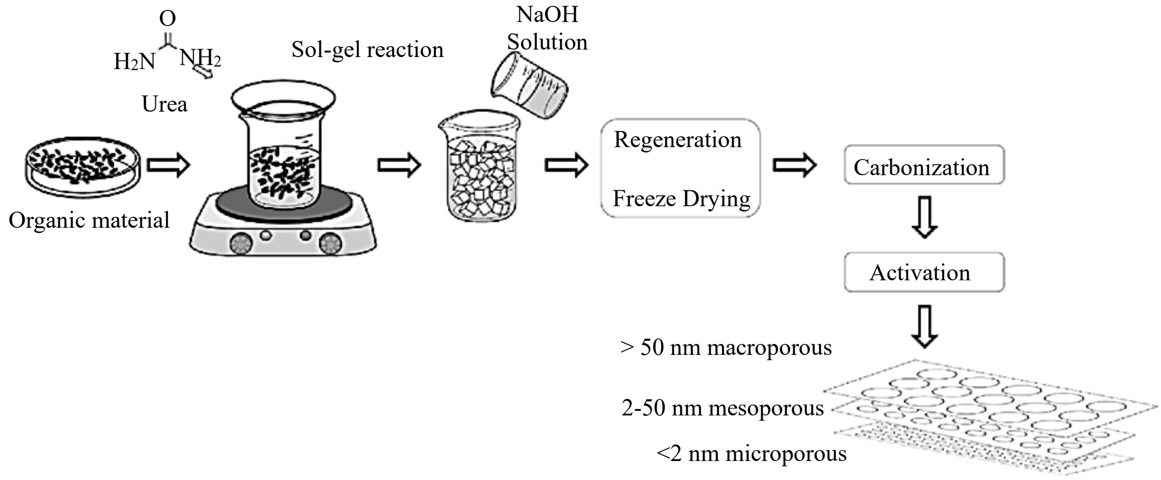

Figure 4. Sol-gel method.

Gas Phase Preparations

Three types of deposition are used to admit perovskite films with a specific thickness and structure: at the crystallization temperature in a suitable atmosphere (i), at an intermediate temperature between 873 and 1,073 K followed by post-annealing treatment (ii), and at a low substrate temperature followed by post-annealing at a high temperature. These reactions are known as gas phase reactions or transport reactions. One of the Yttrium barium copper oxides, $YBa_2Cu_3O_7{-}x$ films, can be created by co-evaporating Y, Cu, and BaF_2 [13]. These films are then hardened at high temperatures in an O_2 environment and wet with water vapor to reduce the substrate interface and hardening time. Techniques like magnetron sputtering, laser ablation, molecular beam epitaxy, thermal evaporation, dc sputtering, and electron beam evaporation are used for gas phase deposition.

Sol-Gel Method

One well-known technique in the ceramics industry is the sol-gel alkoxide approach. The earliest non-silicate ceramics produced using this method were most likely a number of perovskite phases. For a wide range of metals, metallic alkoxides are commercially available. Reactions with organic compounds produce hybrid materials. The alkoxide pathway of oxide compound processing relies on the poly-condensation and hydrolysis of metallic alkoxides (Figure 4) [15].

Although this technique is widely used to manufacture nanosized material and is typically used to numerous aluminate, titanate, and complicated mixed cation phases, its usage is restricted because of the stability of its precursor system and the difficulty in controlling the chemical composition of complex oxides. More people are using sol-gel processes, especially when it comes to creating thin films at low temperatures. Inorganic salts and chelating agents of polyols or carboxylic acids are used as precursors in the sol-gel process in an aqueous media [16].

Microwave Synthesis

Offers energy-efficient and rapid synthesis for advanced material morphologies.

CLASSIFICATION OF PEROVSKITES

Inorganic Perovskite System

PSC can be produced by methylammonium oxide that has a high open-circuit voltage and the thickness range of the material can be well absorbed with the carrier-based diffusion length and it can further be classified into intrinsic and doped perovskite systems.

Intrinsic Perovskite System

The power conversion efficiency of the intrinsic perovskite system is high when compared to other systems and because of the high-conversion efficiency the stability of the material is very high and long lifetime of more than 72 hours.

Doped Perovskite System

The properties of PSC will depend upon the crystal structure of the perovskite compound thus, doping the perovskite by using lead or halide will increase the power conversion efficiency, stability, and also increase the diffusion length of ions and therefore, the wavelength absorption limit of the compound was improved [17].

Halide Perovskite System

One of the key components in the field of heterostructure-based optoelectronics and microelectronics is halide perovskite material.

This kind of material, which is further subdivided into alkali halide perovskite and organometal perovskite systems, will offer extremely high performance at a reasonable cost.

Alkali Halide Perovskite System

This kind of perovskite offers a larger bandgap, which will make it more affordable for the high-efficiency modules, and low energy loss, which will boost power conversion efficiency and a high open circuit for better response.

Organometal Perovskite System

Because of its direct bandgap and light absorption coefficient, which will boost the system's power conversion efficiency and carrier mobility, organometal PSC is one of the cutting-edge technologies created in recent years (Figure 5).

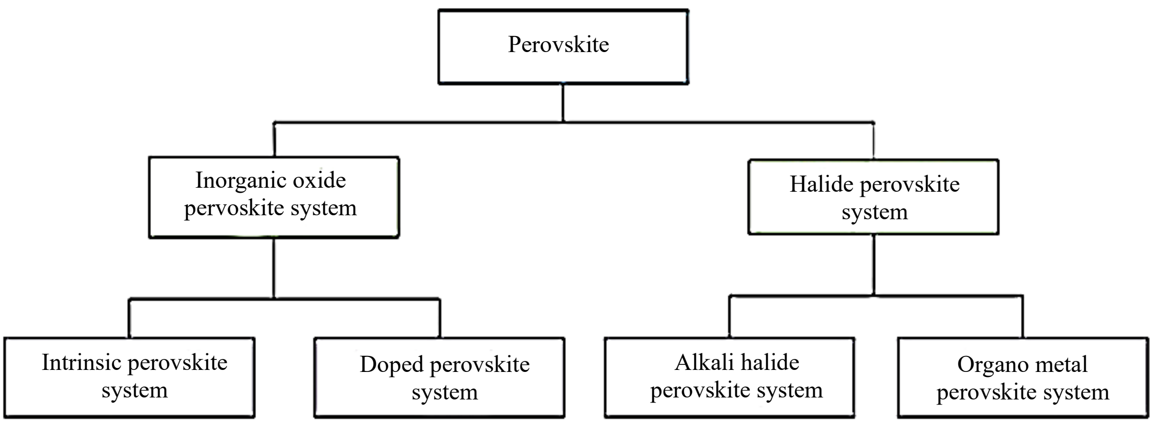

Figure 5. Classification of provskite materials.

PROPERTIES

Perovskites exhibit a wide range of properties, including:

- *Dielectric Properties:* High dielectric constant and low energy loss, ideal for capacitors.
- *Optical Properties:* Excellent photoluminescence and electro-optical coefficients, making them suitable for displays and lasers.
- *Ferroelectricity:* Spontaneous polarization under an electric field, useful in sensors and memory devices.
- *Superconductivity:* Zero electrical resistance at critical temperatures.
- *Piezoelectricity:* Electric charge generation under mechanical stress, used in actuators and energy harvesters.
- *Multiferroicity:* Co-occurrence of ferroelectricity and magnetism, enabling applications in spintronics.
- *Catalytic Activity:* Exceptional chemical stability and catalytic properties for environmental and industrial reactions.

APPLICATIONS

Perovskites' versatility enables their use in numerous fields:

- *Solar Cells:* High power conversion efficiency and low-cost production make them ideal for photovoltaic applications.
- *Light-Emitting Diodes (LEDs):* High color purity and quantum efficiency for displays and lighting.
- *Catalysts:* Effective in oxidation-reduction reactions and pollution control.
- *Fuel Cells:* Solid oxide fuel cells utilize perovskites for their ionic conductivity.
- *Sensors and Actuators:* Used for environmental monitoring and industrial applications (Figure 6).

Advantages of Perovskite Solar Cells

- High efficiency and low-cost solution-based processing methods.
- Flexibility, lightweight, and semi-transparency for diverse applications.
- Ability to respond to a wide range of light wavelengths for optimal energy conversion.

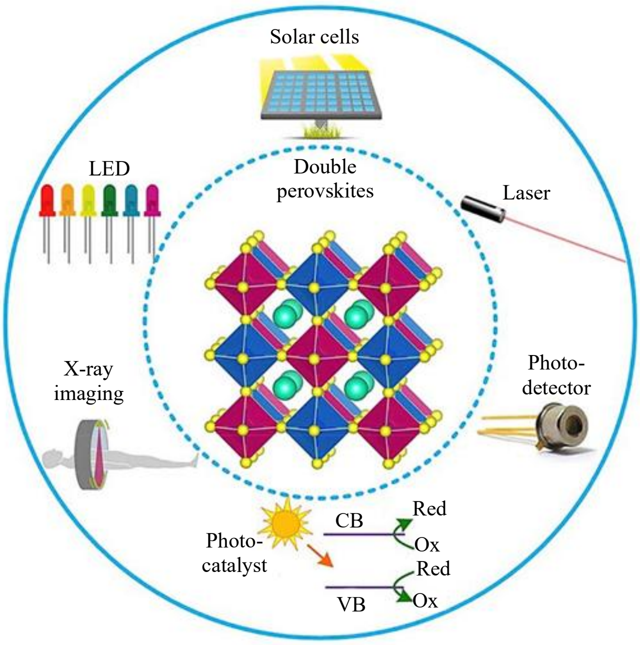

Figure 6. Applications of perovskite materials.

Commercialization

Efforts are underway to commercialize perovskite technologies through:

- Scalable manufacturing processes such as roll-to-roll deposition.
- Standardization and certification for market readiness.
- Cost reduction strategies to compete with silicon-based technologies.

CONCLUSION

In conclusion, perovskite materials represent a transformative class of materials with significant potential to revolutionize renewable energy and optoelectronics. Their exceptional power conversion efficiency (PCE) and compatibility with low-cost, scalable fabrication techniques position them as strong contenders to traditional silicon-based technologies in applications such as solar cells, LEDs, and other optoelectronic devices. To allow for broad commercialization, however, many obstacles still need to be overcome, including those related to stability, durability, and environmental issues. Research efforts aimed at improving the long-term stability of perovskite materials under real-world operating conditions, alongside the development of lead-free or alternative compositions, are critical to overcoming these barriers. Additionally, advancements in understanding degradation mechanisms and implementing robust encapsulation techniques hold promise for enhancing device longevity and reliability. The rapid progress in this field underscores the need for interdisciplinary collaboration to address material, manufacturing, and environmental challenges comprehensively. Continued innovations in perovskite technology, coupled with sustainable practices, have the potential to deliver highly efficient, cost-effective, and eco-friendly solutions that could significantly impact the renewable energy and optoelectronics sectors. By addressing the existing limitations and leveraging ongoing advancements, perovskite-based technologies could play a pivotal role in driving the transition toward a more sustainable and energy-efficient future. This review highlights the importance of continued research to unlock the full potential of perovskites and pave the way for their successful integration into commercial applications.

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