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Exploring the Potentials of Perovskite Solar Cell Technology

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Abstract

The potential of perovskite solar cell technology is explored in this short commentary paper, with special attention to the material's history and origin, physics, benefits over traditional silicon-based solar cells, disadvantages, current deployment locations, and prospects for widespread acceptance as a solar cell material in the future.

Key words: Perovskite materials; Solar cell technology; Futuristic outlook for perovskite solar cell technology.

1. Introduction

Although their long-term stability and commercial feasibility are still being studied, perovskite solar cells are a form of thin-film solar cell that uses perovskite materials as the light-harvesting active layer. They have the potential to be produced at cheap cost and with high efficiency. A family of minerals known as perovskites has demonstrated promise for solar cells with great performance and inexpensive manufacturing costs. Their crystal structure gives them the name "perovskite." Other energy devices like fuel cells and catalysts use these materials. Since they are composed of a mixture of organic ions, metals, and halogens, perovskites commonly used in photovoltaic (PV) solar cells are more precisely referred to as "metal-halide perovskites." In other applications, perovskites may be composed of oxygen rather than halogens and are typically completely inorganic. The primary absorption component, or "active layer," of a perovskite solar cell is made up of metal-halide perovskites. In this potentially low-cost technology, light is absorbed by a thin layer of perovskite, which then excites charged particles known as electrons. Electric power is produced by extracting these excited electrons. Compared to crystalline silicon PV, perovskite cells require much thinner active layers, hence the term "thin-film" [1]. Figure 1 shows the structural composition of Methyl ammonium lead triiodide ($MAPbI_3$) which is one of the more common perovskites in existence.

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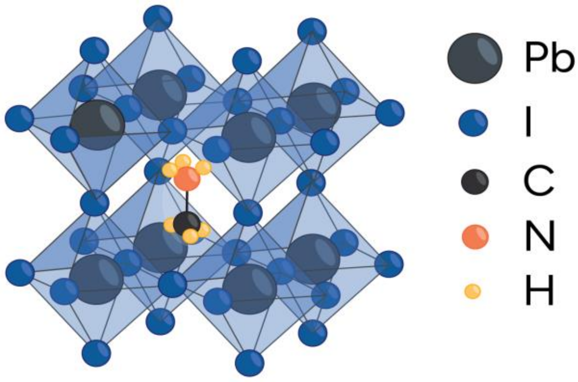

Figure 1: Methyl ammonium lead triiodide ($MAPbI_3$) is one of the more common perovskites; however, researchers are exploring the use of different elements and structures to improve stability.

This is made feasible by perovskite's exceptional absorption of specific light hues. In order to exploit the colors of light that are not absorbed in the perovskite, perovskite absorber layers can also be placed on top of another absorber layer, such silicon. This can theoretically make the cell more efficient than cells built of either material alone. A tandem solar cell is created when two layers are layered in this way. Other materials that are connected to the perovskite absorber in a solar cell "force" electric current to flow through the absorber layer and into the metal contacts in a single direction so that it can be collected as electric current. The efficiency of perovskite solar cells has increased dramatically in recent years, from reports of roughly 3% in 2009 to over 26% presently on small area devices (approximately 0.1 cm^2). Nearly 34% efficiency has been achieved by perovskite-silicon tandem cells. Perovskite PV is not yet produced at scale, and several issues need to be resolved before perovskites may become a viable commercial PV technology, despite the fact that perovskite solar cells have quickly become extremely efficient [2].

2. Some Historical Perspectives and Origin of Perovskite Solar Cells

The mineral perovskite, or calcium titanate ($CaTiO_3$), was the first perovskite material to be found for use in solar cells. In 1839, its discoverer, Gustav Rose, gave it the name “perovskite” in honor of the renowned Russian mineralogist - Lev Aleksevich von Perovski. Later, in 1892, the world's first effective synthesis of a cesium lead halide perovskite substance was accomplished. This is significant since it forms the foundation of contemporary perovskite solar cells' (PSC) chemical makeup. But the perovskite crystal structure wasn't theoretically characterized until 1926, over nine decades later. It took a further 19 years for that theory to be verified in 1945 through X-ray crystallographic analysis of a comparable substance, barium titanate. For decades after 1957, more electric and electrochemical devices, as well as perovskite-structured superconducting materials, have included perovskite materials. However, it wasn't until 1978 that the first organic-inorganic lead halide perovskite material was synthesized, marking the next step toward our current focus in the field of perovskites. This novel semi-conductive material demonstrated a number of intriguing optical and electrical characteristics, including a high relative permittivity and a very high absorption coefficient. The usage of an organic lead-halide perovskite as the main component of a solar cell, however, would not occur until 2009, when an experiment was conducted to try and substitute higher voltage perovskite-based ink with low voltage ruthenium-based inks in dye-sensitized solar cells. Depending on their formulation, perovskite materials can do a wide range of functions, making them versatile in both purpose and capability [3].

3. Physics of the Perovskite Material

The absorber materials' ABX_3 crystal structure, also known as the perovskite structure, in which X is an anion and A and B are cations, is where the term "perovskite solar cell" originates. It has been discovered that cations with radii ranging from 1.60 Å to 2.50 Å can form perovskite structures. Methylammonium lead trihalide ($CH_3NH_3PbX_3$, where X is a halogen ion like iodide, bromide, or chloride) is the most researched perovskite absorber. Depending on the amount of halide present, its optical bandgap ranges from approximately 1.55 to 2.3 eV. With band gaps ranging from 1.48 to 2.2 eV, formamidinium lead trihalide ($H_2NCHNH_2PbX_3$) has also demonstrated promise. It should be able to achieve greater efficiencies since its minimum band gap is closer to the ideal for a single-junction cell than methylammonium lead trihalide. A dye-sensitized cell employing $CsSnI_3$ as a p-type hole transport layer and absorber was the first solid-state solar cell to use perovskite. Although solar cells made from tin-based perovskite absorbers, like $CH_3NH_3SnI_3$, have been reported, they have poorer power-conversion efficiency. Lead inclusion in perovskite materials is a typical problem [4]. The crystal structure of $CH_3NH_3PbX_3$ perovskites is shown in Figure 2 below.

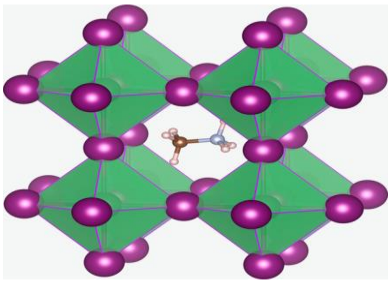

Figure 2: The structure above is a Crystal structure of $CH_3NH_3PbX_3$ perovskites (X=I, Br and/or Cl). The methylammonium cation (CH_3NH_3+) is surrounded by PbX_6 octahedra.

4. Applications: Where Perovskite solar cells are currently used

PSCs, or perovskite solar cells, are a new photovoltaic technology that is finding increasing use all over the world. Despite not being as readily available as silicon-based solar panels, they are utilized in a number of industries, such as:

A. Research and Pilot Initiatives:

In Europe, PSCs are being tested for effectiveness, robustness, and scalability by research institutes and pilot initiatives in nations including Germany, the UK, and Switzerland.
In the USA: Perovskite-based solar panels are being developed and tested by universities and businesses (such as NREL and Swift Solar). China and Japan have made significant expenditures to increase the manufacture and commercialization of perovskites.

B. Indoor Applications & Consumer Electronics:

• **Wearable technology and the Internet of Things**: Perovskite solar cells are being incorporated by businesses into low-power electronics including wireless charging devices, smart watches, and sensors.

• **Indoor energy harvesting**: PSCs can power indoor gadgets since they function effectively in low light levels.

C. **Building-Integrated Photovoltaics (BIPV):**

- **Europe:** Perovskite-based solar windows and facades are being developed in Europe by businesses like Saule Technologies (Poland) and Oxford PV (UK).

• **Asia**: Using perovskite solar panels, China and Japan are investigating BIPV solutions.

D. Space Applications:

NASA & ESA (European Space Agency):

Because PSCs are lightweight and have a high power-to-weight ratio, scientists are now investigating them for use in space missions by NASA and the European Space Agency (ESA).

E. Hybrid Solar Panels: Perovskite and silicon are being combined by businesses such as Oxford PV (UK) to produce tandem solar cells with increased efficiency.

5. Advantages of PSCs to Conventional Silicon based Solar Cells

Perovskite solar cells (PSCs) are an intriguing prospect for future solar technology since they have a number of benefits over traditional silicon-based solar cells. Here is a comparison between them:

1. Potential for Increased Efficiency:

Perovskite solar cells outperform conventional silicon cells (~22-24%) with efficiency above 26% in the lab and have the potential to reach over 30% when combined with silicon.

2. Reduced Production Expenses:

In contrast to silicon, which requires processing at temperatures of 1000°C and more, PSCs use less expensive raw materials and require simpler, lower-temperature procedures.
Their ability to be coated or printed onto surfaces lowers the complexity of manufacture.

2. Flexible & Lightweight:

PSCs, as opposed to rigid silicon panels, may be manufactured thin, light, and flexible, which makes them suitable for use in portable solar gadgets, wearable technology, and BIPV (solar windows, facades).

4. Improved Performance Indoors and in Low Light Conditions:

Unlike silicon cells, which require direct sunlight for maximum performance, PSCs function well in indirect light, overcast conditions, and artificial indoor illumination.

5. Semi-Transparent & Customizable Designs:

They are perfect for aesthetically pleasing applications like solar windows and integrated electronics since they can be adjusted for various hues or even made semi-transparent.

6. Simpler Integration & Scalability:

Perovskite materials are easy to integrate into a variety of applications because they may be deposited on a variety of substrates, such as metal foils, glass, and plastics.

6. Challenges and Limitations of PSCs

• **Stability Problems:** PSCs deteriorate more quickly than silicon, particularly when exposed to heat and moisture.

• **Toxicity Issues:** Lead is included in certain perovskite formulations, which raises environmental issues.

• **The process of commercialization obstacles**: Silicon dominates the market, and large-scale production is still in its infancy.

7. Futuristic Outlook: The Future of Solar Cell Technology

With a number of developments targeted at enhancing efficiency, affordability, and adaptability, solar cell technology is developing quickly. The following are the main developments and trends influencing solar energy's future:

i). Perovskite Solar Cells (PSCs) – The Next-Gen Solar Tech

• **Tandem Solar Cells:** These cells combine silicon or other materials with perovskite to attain efficiencies higher than 30%.

• **Adaptable & Lightweight Designs:** Perfect for space missions, wearable technology, and building-integrated photovoltaics (BIPV).

• **Increased Stability & Durability:** PSCs are becoming increasingly feasible for long-term use as research tackles lead toxicity and degradation concerns.

ii). Tandem and Multi-Junction Solar Cells

• These have an efficiency of over 45% in laboratory settings and employ numerous layers of various materials to catch a larger portion of the solar spectrum.

• Uses include high-efficiency commercial panels, satellites, and concentrated solar power (CSP).

iii). Nano and Quantum Dot Solar Cells

• To more effectively absorb and transform light, the use of quantum dots, or nanoparticles would take centre stage.

• The possibility of solar cells that is transparent, bendable, and incredibly thin.
• Has the potential to transform consumer electronics and BIPV.

iv. Organic & Dye-Sensitized Solar Cells (DSSC):

These solar cells are lightweight, flexible, and effective at low light levels since they are made of organic materials or dyes.

• Uses include solar-powered sensors, indoor solar panels, and portable gadgets.

v). Solar and Transparent Windows:

Perovskite and organic solar cells can be made semi-transparent, which enables their incorporation into smart glasses and windows.

• Structures could produce power without compromising their aesthetics.

vi). Solar Paint & Coatings:

Research is being done on solar paint that can be sprayed to surfaces like walls and rooftops and contains photovoltaic elements. This revolutionary approach has the ability to transform any surface into a source of energy.

vii) Space-Based Solar Power (SBSP):

Ideas for orbiting solar farms that gather sunlight all day, every day, and wirelessly transmit power to the planet (SBSP) is being intensively studied by space agencies such as China's CNSA, NASA, and ESA.

viii). Intelligent Solar Grids and AI:

• Solar panel maintenance, energy distribution, and placement are all optimized by artificial intelligence (AI).

• Smart grids will increase efficiency and decrease energy loss by more effectively integrating solar energy into power networks.

8. End Note: Projected Future Breakthroughs

The design and technology of solar cell materials are trending in the direction of solar cell solutions that satisfy the following criteria:

• **Cost reduction:** Increasing the scale of new technologies to match silicon in terms of cost.

• **Stability & Longevity:** Ensuring that next-generation materials, such as perovskites, have a lifespan of at least 25 years, comparable to silicon.

• **Recycling & Sustainability:** enhancing the recycling of solar panels and creating environmentally friendly substitutes for lead-based perovskites [5].

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11. Authors Contributions

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