Challenges and Potential of Perovskite Solar Cells

Anil Kumar Verma*

Department of Physics, Faculty of Science and Technology, The ICFAI University, Raipur, Chhattisgarh, India.

***Corresponding Author:** anilverma@iuraipur.edu.in

Abstract

A solar cell is a device that converts sunlight into electricity. There are different types of solar cells but in this literature mainly focuses on a type of new dominant solar cell material that has the name organo-metal halide perovskite, namely known as perovskite solar cells, in shortly PSCs . In this respect, the efficiency of power conversion is taken into account to replace the dominancy of traditional and second generation solar cell fields by perovskite solar cells. Perovskite solar cell is a type of solar cell including a perovskite structure, usually a hybrid organic-inorganic lead or tin halide- based material. In this review, a comprehensive study of the perspective challenges and their potential has been highlighted for their future application. There are rigorous research efforts in aspects of device engineering, including physical and chemical passivation, and the use of a wide variety of organic and inorganic additives to develop the advanced PSCs.

Keywords: Solar cell, Perovskite solar cell, Photovoltaic, Substrate, Energy.

Introduction

Solar energy is an alternative source to traditional resources such as coal and fossil fuel for the present growing energy demand. In this perspective, developing solar cells is one of the best approaches to convert solar energy into electrical energy based on the photovoltaic effect. Over the years, silicon-based cells have been used for industrial purposes due to their efficient solar to power generation (~30%), particularly crystalline silicon. However, the cost of Si-based photovoltaic cells is relatively high and difficult to utilize in large-scale industries [Green, M. A., et al. (2001) and Bhattacharya, S., et al. (2019)]. An alternative to silicon solar cells is third generation excitonic photovoltaic devices, which have been developed based on various dye sensitizers, organic and hybrid (organic–inorganic) materials; and these reach a photovoltaic efficiency up to ~15–20%. Among these materials, perovskites (organic–inorganic) have reached top position (~20.1%) within ~5 years, due to substantial improvement of power conversion efficiency and low processing costs. Significant aspects of perovskites are synthetic feasibility, strong optical absorption, charge recombination rate and ease of fabrication. Moreover, hybrid perovskites can be prepared by simple synthetic methods and are easy to capitalize when compared to the existing excitonic photovoltaic technologies such as dye sensitized solar cells (DSSCs), organic solar cells (OSCs) and quantum dot solar cells (QDSCs) [Verma, A.K., et al. (2017), Sahu, S., et al. (2017) and Patel, M., et al. (2017)]. Another important aspect is high charge-carrier mobility, which is more useful for developing high-performance solar cell devices. However, toxicity of lead is a major concern which easily degrades on exposure to humidity and ultraviolet (UV) irradiation. Present day research mainly focuses on the commercialization of perovskite solar cells by controlling degradation and toxicity. In this review, we highlight the fundamental aspects of perovskites and recent status about its potential and challenges for the design of perovskite-based solar cells. Still, there exist some issues which need to be resolved in the commercialization of perovskites. The rapid improvement of perovskite solar cells has made them the rising star of the photovoltaics world and of huge interest to the academic community. Since their operational methods are still relatively new, there is great opportunity for

 DOI: 10.52228/JRUB.2023-35-2-6

further research into the basic physics and chemistry around perovskites. Furthermore, as has been shown over the past two years - the improvement in engineering of perovskite formulations and fabrication routines has led to significant increases in power conversion efficiency (with recent devices reaching over 22%) [Roy, P., et al. (2020) and Shukla, N., et al. (2022)]. The terms "perovskite" and "perovskite" structure are often used interchangeably. Technically, a perovskite is a type of mineral that was first found in the Ural Mountains and named after Lev Perovski who was the founder the Russian Geographical Society. A perovskite structures any compound the same structure as the perovskite mineral. True perovskite (the mineral) is composed of calcium, titanium and oxygen in the form $CaTiO_3$. Meanwhile, a perovskite structure is anything that has the generic form ABX_3 and the same crystallographic structure as perovskite (the mineral). However, since most people in the solar cell world aren't involved with minerals and geology, perovskite and perovskite structure are used interchangeably. The perovskite lattice arrangement is demonstrated below. As with many structures in crystallography; it can be represented in multiple ways. The simplest way to think about a perovskite is as a large atomic or molecular cation (positively-charged) of type A in the center of a cube. The corners of the cube are the occupied by atoms B (also positively-charged cations) and the faces of the cube are occupied by a smaller atom X with negative charge (anion).

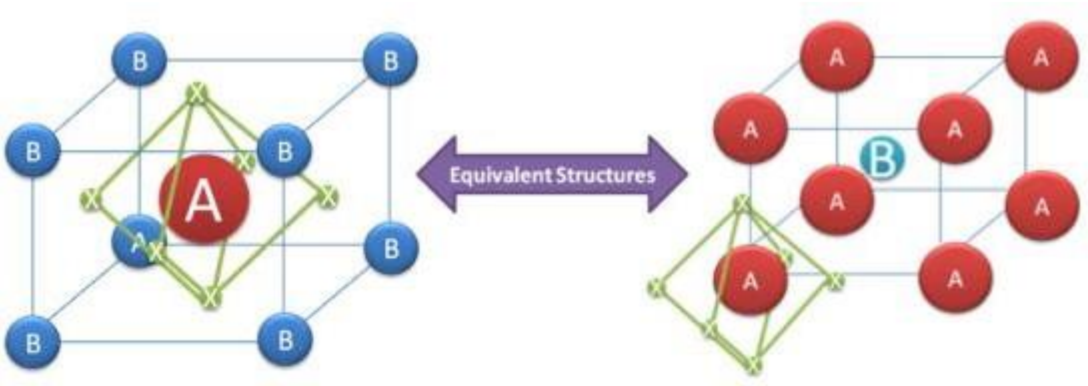

Figure 1. Structure of Perovskite material.

B=A big inorganic cation-usually lead (II) (Pb^{2+})

X_3=A slightly smaller halogen anion–usually chloride (Cl-) ori-odide (I-)

Since this is relatively general structure, the perovskite-based devices can also be given a number of different names, which can either refer to a more general class of materials or a specific combination. As an example of this, we've created many names can be formed from one basic structure.

Figure 2. Perovskite material

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Device Structures and Materials:

Basically, the Perovskite solar cells device consist of variety of mixture of donor-acceptor active material with electron hole transport layer, hole transport layer sandwich between bottom and top contact electrode. The type of material selected as the ETL in PSCs can tune the photovoltaic performance of the device [Verma, A. K., et al. (2020)]. In general; the ETL plays an important role in the extraction and transportation of photo-generated carriers in PSCs. Moreover, the thin layer of ETL eliminates electrical shunts between the transparent electrode and perovskite layers. Currently, titanium dioxide (TiO_2) is most commonly used as an ETL in planar hetero-junction solar cells due to its suitable band alignment with the perovskite layer and good transparency to visible light. However, in the presence of UV light, the TiO_2 ETL behaves as an excellent photo-catalyst, which decreases the stability of the PSCs. In addition, TiO_2 contains a high surface defect density and intrinsically low mobility, which limits the photovoltaic performance of devices. These issues can be resolved by coating the original TiO_2 surface with another ultrathin TiO_2 using atomic layer deposition (ALD) or chemical bath deposition (CBD). Recently, various medications of the TiO_2 surface have been proposed, such as (1) doping treatment with metal or non-metal ions or (2) passivation using a fullerene self-assembled monolayer, (3) graphene-based material, or (4) organic or inorganic self-assembled monolayer.

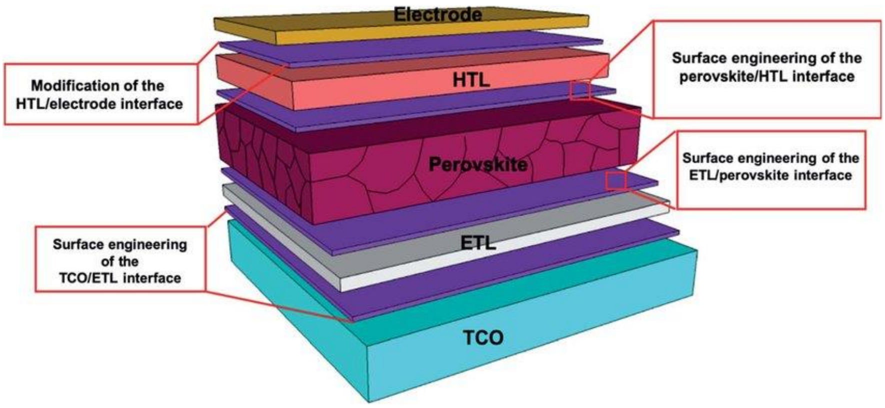

Figure 3. Multilayer device structure of Perovskite Solar Cells (PSCs)

Fabrication and Characterization:

In device fabrication and characterization a glass wafer/ PET functions as the substrate of the Perovskite solar cell. The bottom electrodes like ITO/FTO are patterned onto the wafer substrate by photolithography steps and metal deposition. Around 3 nm layer of titanium is deposited to increase the adhesion of the 80 nm aluminum electrode. On top of the aluminum electrode a 20 nm thick layer of Ti is deposited. This layer acts as an anti-oxidation layer for the aluminum layer. Aluminum oxide decreases the conductivity of the aluminum electrode and thus the PCE of the PSCs. A thin layer of titanium oxide (TiOx) forms naturally on top of the 20 nm titanium layer and acts as an electron transport layer (ETL). Then the active layer is deposited, which consists of solution mixture of Perovskite of electron donor and electron acceptor material. On top of the active material a layer of HTL layer is deposited. Finally a layer of silver/ aluminum is applied for top electrode contact.

The synthesis of lead halide perovskites (CH3)4NPbI3-xClx with quaternary ammonium cations has prepared for solar cell applications. The UV-Vis spectroscopic studies revealed that the optical band gap of synthesized perovskite is 2.61 eV. (CH3)4NPbI3-xClx based Perovskite solar cell was

DOI: 10.52228/JRUB.2023-35-2-6

fabricated in ambient conditions by using TiO2 as electron charge transport material and a PEDOT: PSS as hole transport material. The architecture of fabricated solar cell is conventional n-i-p type device structure is shown in Figure 4. Figure 5 shows the preparation of active layer using one step coating process. Open-circuit voltage (V_{oc}), short circuit current density (J_{sc}) and efficiency of FTO/ c-TiO2/ (CH3)4NPbI3-xClx / PEDOT: PSS/ Al are measured respectively. The electrical and optical characteristics of Lead halide perovskites with quantum efficiency can be determine.

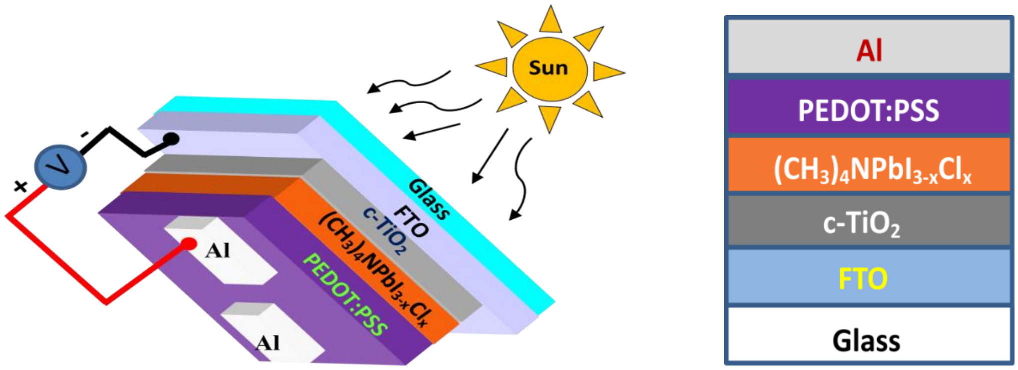

Figure 4. Solar Device and Device Structure

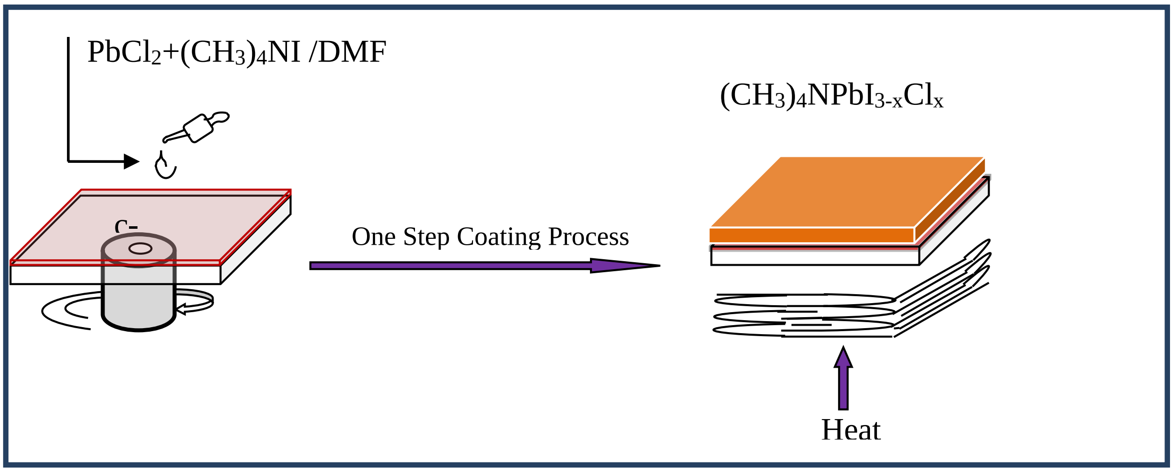

Figure 5. One step coating process for making active Perovskite layer

Result and Discussion

There are two key graphs which demonstrate why perovskite solar cells have attracted such prominent attention in the short time since their breakthrough paper of 2022. The first of these graphs (which uses data taken from NREL solar cell efficiency tables) demonstrates the power conversion efficiencies of the perovskite-based devices over recent years in comparison to emergent photovoltaic research technology and also traditional thin-film photovoltaics.

DOI: 10.52228/JRUB.2023-35-2-6

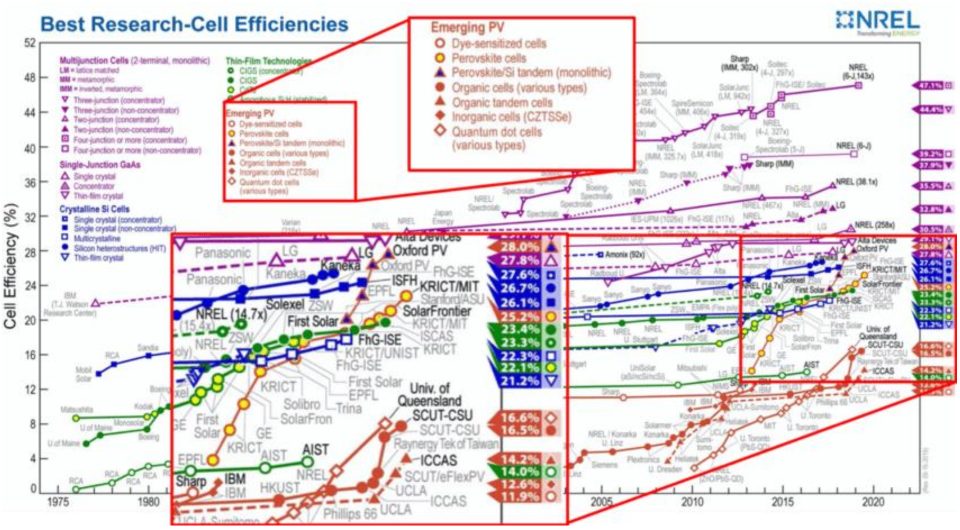

Figure 6. NREL solar cell efficiency chart, perovskite solar cells are highlighted and enlarged.

The graph (Figure 6) shows a meteoric rise compared to most other technologies over a relatively short period of time. In the space of three years, perovskite solar cells have managed to achieve power conversion efficiencies comparable to Cadmium Telluride, which has been around for nearly 40 years. Although it could be argued that more resources and better infrastructure for solar cell research have been available in the last few years, the dramatic rise in perovskite solar cell efficiency is still incredibly significant and impressive. Currently, the only major unknown in the field of perovskite research is the stability of devices over their operational lifetime. Although lifetime studies of actual devices are limited, research into the stability of these films has shown that there are several reaction pathways leading to degradation that involve water, oxygen, and even the diffusion of electrode materials. Current leading research is focused upon reproducing the high power conversion efficiencies, but with the addition of stabilizing agents such as Cesium and Rubidium. Another issue yet to be fully addressed is the use of lead in perovskite compounds. Though it is used in much smaller quantities than that which is currently present in either lead- or cadmium-based batteries, the presence of lead in products for commercial use is problematic. There is potential for a lead alternative to be used in perovskite solar cells (such as tin-based perovskites), but the power conversion efficiency of such devices is still significantly behind lead-based devices. Finally, there has also been little discussion of the optical density of these materials - which although is higher than silicon, is still lower than other active materials. As a result, the perovskite devices require thicker light-harvesting layers which may cause some fabrication limitations. These limitations apply particularly to solution processed devices where creating such thick layers with high uniformity can be difficult. Over the past two years, the improvements in precursor material blends for the fabrication of perovskite solar cells have led to a significant increase in power conversion efficiency. A key development has been the improvement in processing techniques used. Previously, vacuum-based techniques offered the highest efficiency devices but lately, improvements in solution-based deposition through the use of solvent quenching techniques has shifted the record-breaking devices to solution-based processing. To enable a truly low cost-per-watt will require perovskite solar cells to have the much heralded trio of high efficiency, long lifetimes, and low manufacturing costs. This has not yet been achieved for other thin-film technologies but perovskite-based devices so far demonstrate enormous potential for achieving this. Put simply, perovskite solar cells aim to increase the efficiency and lower the cost of solar energy. Perovskite PVs indeed hold promise for high efficiencies, as well as low potential material & reduced processing costs. A big advantage perovskite PVs have over conventional solar technology is that they can react to various different wavelengths of light, which lets them convert more of the sunlight that reaches them into electricity.

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Moreover, they offer flexibility, semi-transparency, tailored form factors, light-weight and more. Naturally, electronics designers and researchers are certain that such characteristics will open up many more applications for solar cells.

Despite its great potential, perovskite solar cell technology is still in the early stages of commercialization compared with other mature solar technologies as there are a number of concerns remaining. One problem is their overall cost (for several reasons, mainly since currently the most common electrode material in perovskite solar cells is gold), and another is that cheaper perovskite solar cells have a short lifespan. Perovskite PVs also deteriorate rapidly in the presence of moisture and the decay products attack metal electrodes. Heavy encapsulation to protect perovskite can add to the cell cost and weight. Scaling up is another issue - reported high efficiency ratings have been achieved using small cells, which is great for lab testing, but too small to be used in an actual solar panel. A major issue is toxicity - a substance called PbI is one of the breakdown products of perovskite. This is known to be toxic and there are concerns that it may be carcinogenic (although this is still an unproven point). Also, many perovskite cells use lead, a massive pollutant. Researchers are constantly seeking substitutions, and have already made working cells using tin instead. (With efficiency at only 6%, but improvements will surely follow). While major challenges indeed exist, perovskite solar cells are still touted as the PV technology of the future, and much development work and research are put into making this a reality. Scientists and companies are working towards increasing efficiency and stability, prolonging lifetime and replacing toxic materials with safer ones. Researchers are also looking at the benefits of combining perovskites with other technologies, like silicon for example, to create what is referred to as "tandem cells".

Conclusion

Organic–inorganic halide perovskites are significant for research and commercialization of solar cells in the next few years due to high efficiency and durability. Advantages of Perovskite solar cells (PSCs) include low processing cost and simple execution of desirable products such as flexible, transparent or all-perovskite tandem cell modules than existing photovoltaic. PSCs can show better performance if integrated with other cell technologies. However, few problems need to be resolved with respect to commercialization: (1) toxicity of Pb atoms, (2) long-term durability and (3) cost-effectiveness. Until now, the highest efficiency has been obtained only from lead-based perovskites. However, utilization of Pb-based materials in solar cells is restricted due to their toxicity. In order to overcome this issue, majority of research is on lead-free-based materials together with commercialization. Fortunately, Sn-based materials have been developed and reached efficiency of approximately ~22%. The stability of Perovskite solar cells are affected by many factors which fall into two broad categories: Perovskite stoichiometry, ion migration, strength of bonds between cations and anions are Intrinsic factors and another factor called extrinsic factors are degradation due to air, moisture, temperature.

Acknowledgments

The author, Dr. Anil Kumar Verma would like to acknowledge and thank to the Vice Chancellor and Registrar, The ICFAI University, Raipur, Chhattisgarh, India for encouraging and proving the opportunities for preparing this article.

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