

The Recent Progress and the state-of-art applications of Perovskite Solar Cells

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Abstract. With the awareness of using clean and sustainable energy, the utilization of solar power is of great importance in human society. Following the trend, solar cells are required to have higher and higher power conversion efficiency. Contemporarily, perovskite materials, as a new type of materials for construction of solar cells, exhibits great potential to have high efficiency. This article focuses on the methods on improving power conversion efficiencies of perovskite solar cells and discusses the limitation of recent technologies and industrial applications, and the future prospect of perovskite solar cells. To be specific, all the methods are focusing on the selection of materials suitable for cells design, from CsSnI₃ to lead-based organic materials, the efficiencies have increased significantly. The method of stacking perovskite solar cells to make tandem solar cells improved efficiencies among all the methods. Meanwhile, the toxicity, low stability and difficulties in large-scale application are the main limitations for perovskite solar cells. For the future studies, it is important to search for materials with low toxicity and high stability. The technology for improving efficiency of large-scale solar cells is also required. These results provide a guideline for the future study in perovskite solar cells.

Keywords: Energy, Perovskite, Solar power.

1. Introduction

Energy is of great importance in human society, regarding the significant impact on technical innovation and economic evolution. The population and economic growth of worlds nowadays lead to the increasing demand of energy. The left panel of Fig.1 illustrates the world energy consumption of the past few years and provides us with some prediction of energy consumption in the future [1, 2]. With the great demand of energy and rising awareness of hazards of tremendous emissions of carbon dioxide and depletion of fossil fuels brought by the traditional energy generation source, burning of fossil fuels, the usage of sustainable and clean energy is increasingly demanded. Due to the ever increasing require for clean energy sources, the trend of escalating utilization of solar power can be observed, especially in electric power sector (seen from right panel of Fig. 1).

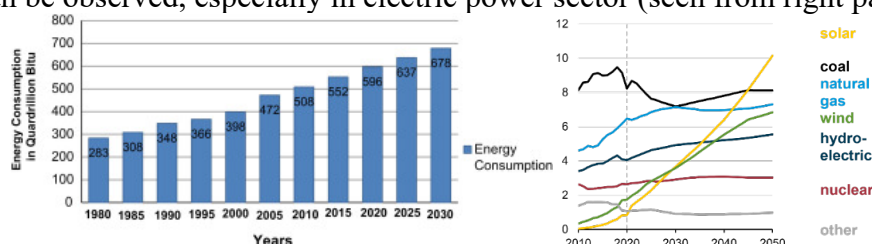


Figure. 1. World energy consumption (left panel) and electricity generation (right panel) [2].

Solar power offers an easy solution to generate electricity in a clean and sustainable way owing to its easier accessibility that can be directly converted into electrical energy. Meanwhile, the innovation and improvement of the devices which convert solar power into electrical power, known as solar cells, are of great importance in energy generation industry. The selection of materials determines the key features for the cells. Currently, new emerging materials, perovskites, are widely used in photovoltaic technology for their good performance and relatively easier and cheaper fabrication process [3]. With the potential of achieving even higher efficiency, perovskite solar cells became attractive in photovoltaic industry. Therefore, much research had been conducted on the efficiency improvement

of solar cells while maintain their long-term stability. Nowadays, the organic-inorganic hybrid halide perovskites materials are commonly studied, such as lead based hybrid materials $\text{CH}_3\text{NH}_3\text{PbX}_3$.

Perovskite materials-based cells were evolved from the dye-sensitized solar cells. The two organolead halide perovskite materials, $\text{CH}_3\text{NH}_3\text{PbBr}_3$ and $\text{CH}_3\text{NH}_3\text{PbI}_3$, were used as sensitizer on TiO_3 based solar cells for their outstanding band-gap absorptions. They were found to have a efficiency of 3.8% in 2009 [4]. In 2013, Liu et al. replaced the mesoporous TiO_2 with mesoporous Al_2O_3 and observed a great improvement in efficiency in the devices which they termed “meso-superstructured solar cells” [5]. Furthermore, the removal of Al_2O_3 layer was proofed to result in more than 12% efficiency in solar cells. So fat, the organic-inorganic hybrid halide perovskites materials are widely investigated, e.g., lead based hybrid materials $\text{CH}_3\text{NH}_3\text{PbX}_3$ with a bandgap of about 1.55eV and $\text{NH}_2\text{CHNH}_2\text{PbX}_3$ with a bandgap between 1.48 and 2.33eV [6]. Besides, tin-based perovskite materials (e.g., $\text{CH}_3\text{NH}_3\text{SnI}_3$) can be an alternative for lead based solar cells due to the concern of potential toxicology of lead [7]. Further study has shown that perovskite based multi-junction revealed even higher efficiency than single junction solar cells, due to good optoelectronic properties and low voltage loss of perovskite [8].

Currently, the major challenges of perovskite solar cells are improving efficiencies, while maintaining long-term stability, and removing the hysteresis effects [9]. In this paper, the section 2 will introduce the basic structures and features of perovskite solar cells. Subsequently, several recent developments on improving the solar cells’ efficiencies of Perovskite Solar Cells will be discussed and compared in the Section 3. Afterwards, in the 4th section, limitations and future outlooks the limitations such as stability and cost, and the future prospect on improving solar cells’ performance and focus will be discussed. At last, a summary will be presented in the section 5.

2. Perovskite Solar Cells

Perovskite was first used for calcium titanium oxide (CaTiO_3). Contemporarily, it is used to describe the materials with the same specific crystal structure as CaTiO_3 , which are usually expressed as ABX_3 formula, where A and B are cations, such as metal ions and organic cations, and X are anions, such as oxides and halides [10]. Fig. 2 shows the crystal structure sketch of perovskite materials.

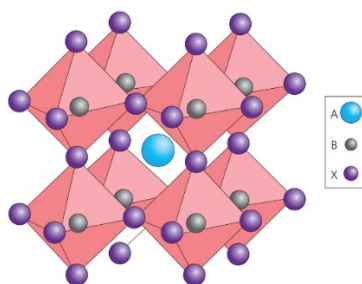


Figure. 2. Basic crystal structure of perovskite materials [11].

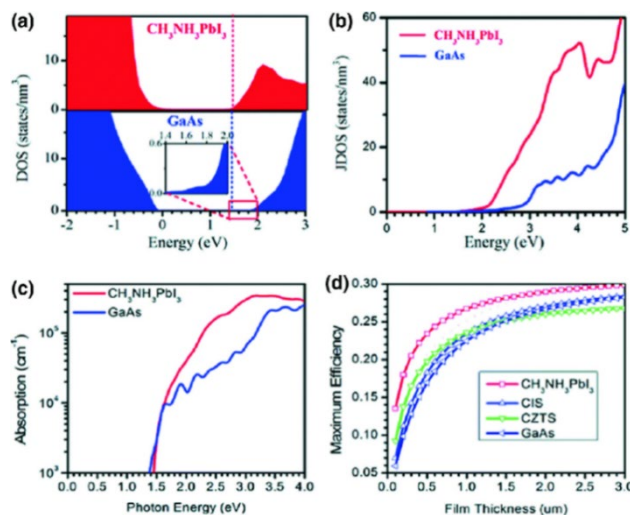


Figure. 3 DOS, JDOS, absorption and maximum efficiency of two materials [13].

Perovskite materials have outstanding unique optical and electrical properties along with relatively low cost and large area device processibility, compared with traditional silicon and germanium solar cells. Perovskite materials are direct bandgap semiconductors, which ensure much higher transition possibility. Taking MAPbI₃ and GaAs as an example, though they both have direct bandgap, the difference on the electrical structures of both materials makes their electrical properties different [12], where the comparison results is shown in Fig. 3 [13].

The basic structure of perovskite solar cells consists of 6 layers: metal electrode/ETL/Perovskite/HTL/TCO/Glass. ETL, which means the electron transfer layer, usually uses titanium dioxide or aluminum oxide. HTL, which means holes transfer layer, is usually deposited on FTO (fluorine-doped tin oxide) coated on the glass. In addition, the perovskite layer is deposited on the HTL and annealed, then a layer of ETL is deposited. Finally, a thin layer of metal electrode, usually Au or Ag, is coated on the top.

Under such structure, the choices of materials are of great importance. Zhou et al. demonstrated that different materials for each layer has led to significant increase in efficiency. In the research, the fluorine-doped tin oxide layer was replaced by poly-ethyleneimineetholated-modified ITO. For the electron transfer layer, yttrium-doped titanium dioxide was used. These change in the materials increased the power conversion efficiency significantly by 19.3% in planar geometry [14]. Research carried out by the team of Jeon et al. showed an efficiency of 17.8% was achieved when they combined formamidiniumlead iodide (FAPbI₃) with methylammonium lead bromide (MAPbBr₃) to form a composite (FAPbI₃)_{0.85}(MAPbBr₃)_{0.15} as the main absorber layer [15]. Furthermore, the addition of I⁻ solution has been proofed to have the effect on increasing of the efficiency [16].

3. Performance

Based on the previous literature, there are several ways to enhance the efficiencies of perovskite materials. With regard to single-junction solar cells, the choice of materials determines the electrical and optical properties, i.e., influences the efficiency and performance of solar cells. At first, CsSnI₃ is used for hole conduction in TiO₂ based dye-sensitized solar cells [17]. The research conducted by Chung I. et al revealed that the doping with SnF₂ of CsSnI₃ which formed CsSnI_{2.95}F_{0.05} had a bandgap of about 1.3 eV, which surprisingly enhanced the visible light absorption. This method also improved the photocurrent density, as shown in Fig. 4. The optimal efficiency of the solar cells is approximately 10.2%.

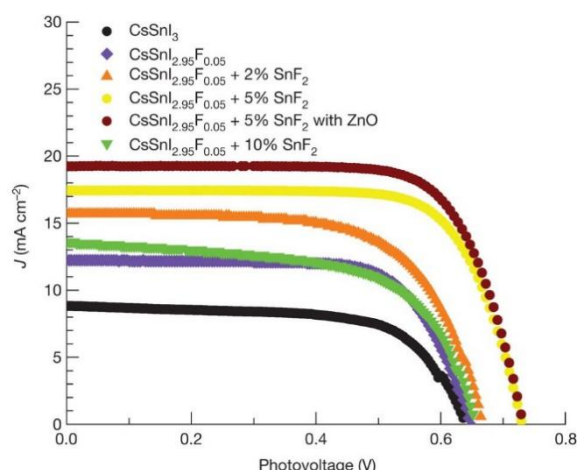


Figure. 4. Photocurrent density-voltage characteristics under 100 mW cm^{-2} AM1.5 sunlight [17].

The first apply of perovskite materials had illustrated the advantages of such materials in photovoltaics applications. The further study clarified that the lead based organic materials had much higher efficiencies. Recently, plenty of studies have focused on the methylammonium lead trihalide perovskite (MAPbX_3), which has a band gap of about 1.55 eV or greater. Furthermore, the formamidinium lead trihalide perovskites (FAPbX_3) can be formed, which has a band gap between 1.48 and 2.23 eV, where 1.48 eV is more suitable for single junction solar cells. The organic based perovskite materials have relatively lower bandgap and higher short-circuit currents, which leads to higher power conversion efficiencies of about 14.2%. Moreover, these kinds of perovskite solar cells are easier to form at low temperature by solution processing, which results in other advantages of the materials of lower fabrication cost [6]. Nevertheless, on account of the poor stability of the organic components, the organic lead-based perovskite materials are easy to decompose, when facing higher light concentration and higher temperature. Therefore, the method of replacing the cations in the perovskite crystals with various pure inorganic cations was applied to obtain stable perovskite solar cells [18]. Started with CsSnI_3 , a significant increase in the efficiency could be observed when Sn cations were replaced by Pb cations. Fig. 5 demonstrates the evolution of inorganic perovskite solar cells.

The lead-free materials were usually tin-based or germanium-based perovskite materials attributed to their similar low bandgap compared with the Pb based perovskite materials. The Bi- and Sn-based compounds can also be applied because of their good stability [19]. However, when comparing the power conversion efficiency with lead-based materials, the lead-free materials were not able to replace the lead-based perovskite materials, as shown in Fig. 6.

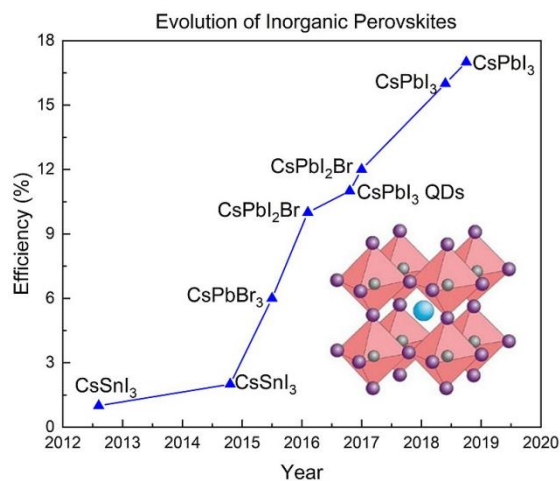


Figure. 5 Evolution of solar cells materials and improvement in the efficiency [18].

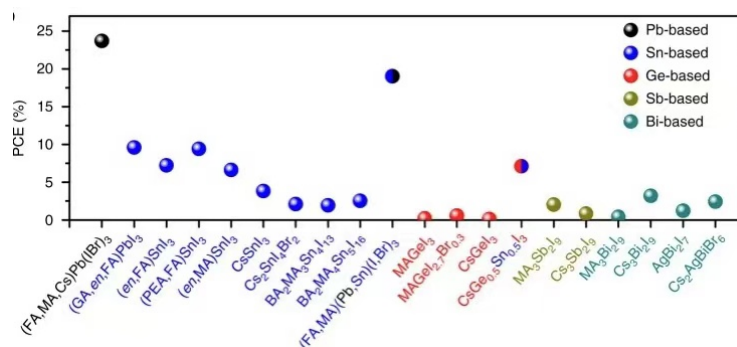


Fig. 6. Comparison of power conversion efficiency of various perovskite materials [19].

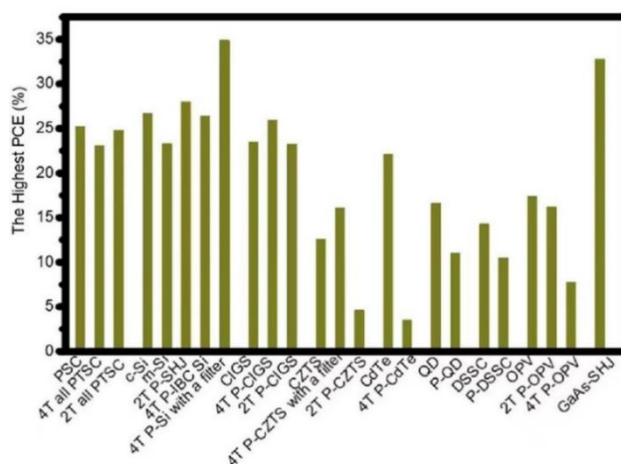


Figure. 7. Comparison of the highest PCE of single-junction and multi-junction solar cells [20].

Meanwhile, making multi-junction solar cells is another way to enhance efficiencies. Perovskite solar cells can be both applied for top and bottom solar cells for their tunable typical bandgap regions [20]. Moreover, because of the good structure and electrical tolerance, perovskite solar cells are more suitable for fabricating tandem solar cells. The first perovskite multi-junction solar cell, perovskite/Si 4T tandem solar cells had an efficiency of 13.4%. The further studies have revealed that the highest efficiency that the perovskite multi-junction solar cells can achieve is about 35%, greatly boosted from that for single-junction perovskite solar cells, which is about 25% according to recent study. Fig. 7 illustrates the comparison. In comparison, the method of applying perovskite solar cells in multi-junction solar cells increased the efficiency the most.

4. Limitations & Future outlooks

Though perovskite solar cells have higher PCE compared with other kinds of materials, there are some limitations needed to be concerned about. As mentioned in the previous section, the long-term stability of perovskite materials is the main challenge for development. For example, the organic lead halide-based perovskite materials, which are proved to have the highest efficiency in single-junction solar cells. The portion of organic limits the long-term stability because they are more easily to be decomposed facing high light concentration and high temperatures. The other limitation is the toxicity of the materials. The leakage of compound of lead, which is one of the toxin metals, may lead to safety issues. The lead compound cannot be replaced since the lead-free materials fail to offer the same high power conversion efficiency, though they have higher stability compared with the lead-based perovskite materials.

On the other hand, perovskite solar cells also have difficulties to be commercialized. With scaling up of the solar cells' modules, it is difficult to maintain the same efficiencies of small modules. Fig. 8 illustrates the improvement on the power conversion efficiency of different scales of modules. From the graph, with the increase of the device sizes, the efficiency tends to decrease. Therefore, it is difficult

to process large-scale of perovskite solar cells for industrial application which has the same high efficiency as revealed in lab with the recent technology. The high cost for processing, low efficiency for scaling up and low stability all result in the difficulties commercializing perovskite solar cells.

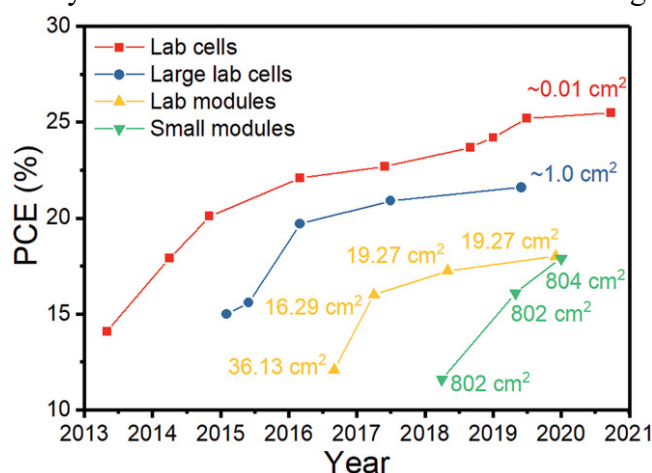


Fig. 8 Evolution of efficiencies of different scales of perovskite solar cells [21].

From those perspectives, the future studies should be focused on the methods for improving perovskite solar cells efficiencies since they have already illustrated their great potential to approach even higher efficiencies, especially for the large-scale applications. Meanwhile, the materials for replacement for lead-based materials are required as well to reduce toxicity. They should have at least similar efficiency as the lead-based materials since they are more stable. Moreover, searching for more stable materials is strongly required.

5. Conclusions

In summary, this paper discusses the state-of-art scenarios to improve the PCE of perovskite solar cells, as well as clarifies their limitations. Contemporarily, the awareness of using clean energy has drawn people's attention on solar energy. As the most recent product, perovskite solar cells have illustrated great potential on account of their rapid growth in power conversion efficiencies compared with traditional semiconductor materials such as silicon. The methods to increase perovskite can be divided into two fields. One is to improve the efficiency of single-junction solar cells, in this case, the choice of materials is of great importance. The other one is to stack perovskite materials with other solar cells to form multi-junction solar cells. In comparison, the application of perovskite materials in multi-junction solar cells improved the efficiencies the most, to about 35%. The limitations are the long-term stability and the toxicity of the materials. In the future, the lead-free materials for perovskite solar cells to reduce toxicity needs more research, and novel approaches for improving the efficiency need to be proposed. Overall, these results offer a guideline for future research on perovskite solar cells.

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