The Latest Progress in Effect Factors and Related Applications of Perovskite Solar Cells

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Abstract. In recent years, the perovskite solar cells have attracted wide attention for its increasing power conversion efficiency (PCE), simple manufacturing process, low cost material components, light and simple wearable abilities and simple using conditions. Many researchers cooperate to improve the stability, efficiency, universality and operational repeatability of the perovskite solar cells. These efforts have taken a huge step forward in the field of perovskite solar cells and achieved a maximum PCE of 26.11%, which greatly encouraged staffs in the relevant fields. However, there are many factors restricting the continued development and practical application of perovskite solar cells. In this paper, the development and structure of perovskite solar cells are introduced, and different factors for its performance are carefully summarized including surface modification, electrolyte solution, working temperature and spectrum absorption. Moreover, its application in outer space, quantum dots and working temperature are also briefly presented. This work could provide some current practical application situation of perovskite solar cells. Finally, the development prospect of perovskite solar cells is briefly discussed.

Keywords: PCE, stability, perovskite solar cells.

1. Introduction

Electricity, as a form of energy to express, is playing an increasingly important role in the current energy oriented's energy-intensive human society. There are many kinds of green energy today, which including the wind, hydro, geothermal, tidal and so on. But most of them will be restricted by the environmental factors. Solar cells, especially the perovskite solar cells, as a kind of remarkable tool for power generation, has attracted unprecedented attention. Because the working part of perovskite solar cells, a kind of organometallic halide light absorption semiconductor, has a relatively excellent photoelectric conversion performance and electrical conductivity. At first, the surface metal electrons were excited by corresponding light. Then the electron-hole pairs will be born and electrons will move under the controled of material properties. The electric current will be excited and it realizes the direct conversion between light energy and electric energy to low down the energy loss in the processing of energy conversion. The optical properties that promote perovskite solar cells to have advantages are its 1.55 eV band, weak binding energy of nearly 0.03 eV and absorption coefficient of 104 cm^{-1}, etc [1, 2]. In recent years, perovskite battery has been recommended as one of the future of mainstream solar cells for has low-cost, high charge carrier mobility, wide working temperature range and suitable energy absorption band gap. Liu and co-authors have adjusted crystal defects to enhance the stability, Asgharizadeh et. al have combine the perovskite solar cells with two-dimensional graphene materials to accelerate charge transfer and surface modification has also been employed to enhance light utilization [3, 4].

Herein, it has roughly reviewed the recent progress of the perovskite solar cells on structure development, surface modification, electrolyte solution, working temperature and spectrum absorption expansion. It is hoped that this review will provide outstanding changes in perovskite solar cells in recent years and help readers to understand the latest developments in relevant fields. So this review can assist relevant researchers with their research.

2. Development and Structure

In 2009, with the categorical power conversion efficiency (PCE) of 3.8%, Miyasaka et. al firstly added perovskite materials (a synthetic material) to solar cells [5]. Due to its excellent performance, low cost and huge commercial value, perovskite solar cells quickly enter researchers' vision, leading to a new ways for the next generation of photovoltaic (PV) technology. In 2014, You et. al used the low-temperature solution-processed to make the perovskite solar cells under rigid substrate devices with the PCE of 11.5% [6]. In 2021, Liu et. al used the multi-active-site Lewis base ligand (i.e., (5-mercapto-1,3,4-thiadiazol-2-ylthio) acetic acid (MTDAA)) to modify the surface. They not only enchance the working lifespan, but also improve the PCE to 21.92% [7]. In 2022, Aditi et. al using SCAPS 1D modelling software to modify the structure of n-i-p form of perovskite solar cells with the PCE of 26.11% [8]. Shortly speaking, 14 years after the birth of the perovskite solar cells, its working efficiency increase in a high speed, and its huge potential has been continuously developed.

As shown in Figure 1 the perovskite solar cells generally consist of electron conductive glass substrates, sensors (FTO), electron transfer layer (ETM), perovskite photoabsorption layer, electron-hole transmission layer (HTM) and metal electrode layer (usually are Ag or Au) [9]. After perovskite solar cells loses electrons due to photoelectric effect, it tends to obtain electrons by exchanging through the electrolyte solution filled with the material. As a semiconducting material, perovskite solar cells uses p-n junction to transfer electrons to ETM and gain electron from HTM. Finally, HTM material lose the electron and regain electron from metal electrode layer. Then a directional current is formed in the unit. This is essentially the energy flow caused by the potential difference formed in the photoelectric effect.

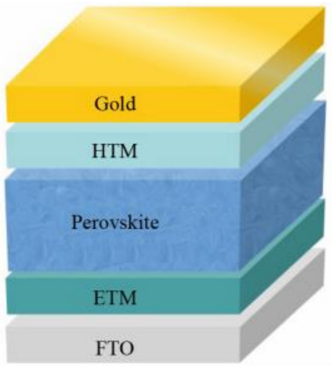

Figure 1. Structure diagram of common perovskite solar cells [9]

3. Factor effect in perovskite solar cell performance

3.1. Surface modification

A passivation strategy has been widely used in semiconductor materials to strengthen the optoelectronic properties of the devices.

The modification strategy used in semiconductor materials are generally passivate the surface molecular layer to enhance the electronic abilities of the devices. And for perovskite solar cells, there are three main ways to passivate the surface: (1) coordination bonds with Lewis acids or Lewis bases; (2) ionic bonds with cations, ions or ammonium; and (3) chemical conversion to broadband material. The purpose of these methods is to reduce the harm caused by the crystal defects.

One of the main reasons that restrict the development of perovskite solar cells and make it difficult to be commercialized should be its low stability. Which also make the work efficiency and lifespan short. In order to improve it, Wang et. al put theophylline, caffeine, and theobromine into the solar cells. In these molecules, the dipoles induced by the hetero atoms work with the conjugated structure to increase the intermolecular interaction. The intermolecular interaction makes it nonvolatile in nature, which is key to the investigation of their interactions with defects in perovskite and long-range stable ability of the devices [10]. By this way, the defect hazard not only can be mitigated, the PCE can also be enhanced. As Figure 2 (a) and (b) show that after modification, PCE will be increased to about 23% and maintain a high level of work.

The passivation Wang do belong to the Lewis acids or Lewis bases passivation. And the second type of ionic passivation tends to form a dense protective film on the surface of crystal. It can make the device withstand harsh working conditions. Pu et. al use the ionic liquid of 1-viny-3-propionate ethyl imidazolium chloride ([PEVIM]Cl) to deal the perovskite photoabsorption layer. Then the non-encapsulated device presents excellent thermal stability, which means it can still maintaining 91% of initial PCE when it had been heated to 85^{o}C in nitrogen atmosphere for 360 h [11].

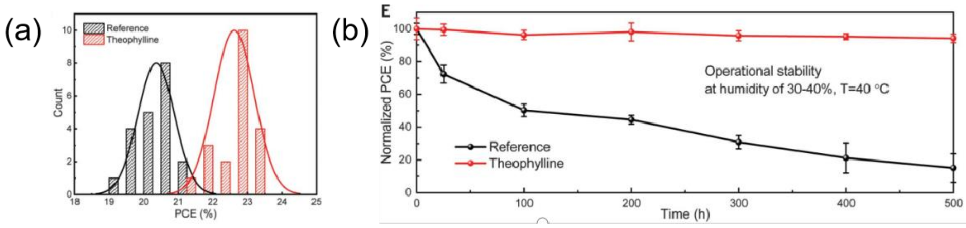

Figure 2. (a) The test of 20 groups of samples; (b) The efficiency maintenance change with the operation hours at 40 oC [10]

3.2. Electrolyte solution

For small area devices, it generally use the recently prepared solution, and the stability of the solution has little effect on the device performance. When it is extended to large area devices preparation and continuous production, the solution service time will be extending inevitably, which will inevitably raise more requirements for solution stability. This requires the electrolyte solution to maintain system stability and reduce system damage caused by evaporation, thermal decomposition, etc. If the stability of perovskite solar cells and its solution can not be ensured, the solar cells will suffer lattice degradation and the obtain energy ability will be dramatically reduced.

At present, it is believed that there are three main types of side reactions maybe existing in solution. The first is deportation reaction, which is the most easily occurred. Such reactions include the deprotonation of methylamine iodide (MAI) and formamidine iodide (FAI) to produce methylamine (MA) and formamidine (FA), respectively. In addition, polar solvent systems commonly used in perovskite solutions (such as dimethyl sulfoxide) can also promote the deprotonation reaction. The second type is the reaction between solutes caused by deprotonation of iodide. Such reactions mainly include the self-condensation reaction of triazine, a by-product generated in formamidine perovskite solution; the trans methylation reaction of dimethylamine (DMA) generated in methylamine perovskite solution. And the transform reaction of N-methylformamide iodide (MFAI) produced methylamine in formamide compound perovskite solution between methylamine and formamide iodide. The third type of reaction is the side reaction between the deprotonated iodide and the solvent, such as the demethylation reaction between the MA molecule and the solvent N, N^{-} dimethylformamide (DMF) to generate DMA, or the deprotonated hydroiodic acid (HI) to generate DMF solvent acid hydrolysis to generate dimethylamine iodide (DMAI) and formic acid The occurrence of the above side reactions will not only change the stoichiometric ratio of the components in the perovskite precursor solution, but also generate larger organic ions, significantly increasing the density of defect states in the perovskite film, which will inevitably have a fatal impact on the efficiency, life and consistency of the device. In order to solve the above problems, we may need to realize the synergistic effect of electrolyte solution and surface passivation to reduce the impact of crystal defects or adjusting the production mode. Remeika et. al achieve fine-tuning of the coating properties of the perovskite precursor by the adsorption sequence conversion of the perovskite layers and the highly controlling of the electrolyte solution addition process [12].

3.3. Working temperature

Working temperature works important to the performance of the solar cells. With the development of perovskite solar cells, the maximum PCE is getting higher and higher. However, its limited thermal stability has been a major problem puzzling relevant workers. Because equipment working at high temperature often suffers efficiency loss, and it will low down around 12.3% [13]. Majority of the solar cells perform outstandingly at low temperature (300 K) than elevated temperatures. From Figure 3, it can be believed that the PCE of the cell is reducing with the increase of the working temperature. This decrease in batteries performance is due to the reverse saturation current on the temperature reverse saturation current changing significantly with temperature. With the rising of operating temperature, the PCE decrease at each size [14]. Considering the change of normal working temperature, the decrease is too large to hold on.

It is believed that temperature will affect the internal recrystallization process of perovskite solar cells. Wu et. al make a high crystalline quality of perovskite and the durability of PCE and perovskite solar cells are improved. After 500 h of operation under 85^{o}C, the working efficiency remains 80% [15]. Therefore, the influence of working temperature on stability and efficiency can not be ignored.

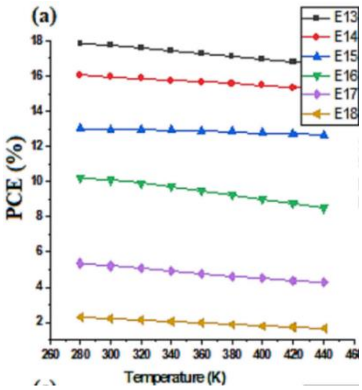

Figure 3. The effect of temperature on PCE with the different degree of poly crystallinity. E13 is 1x1013, E14 is 1x1014 and so on [14]

3.4. Spectrum absorption

As a kind of typical solar cell, perovskite solar cells mainly absorbs the energy in visible light band.

Guan et. al changed the $MAPbI_3$ ($CH_3NH_3PbI_3$ a kind of perovskite) layer thickness in nano degree to modify its structure with the help of optimized periodic poly (methyl methacrylate) (PMMA) nano texture. The thickness of $MAPbI_3$ move from 31.25nm to 2um. And the special outcome is that the ultimate efficiency significantly improved by 11.5%–32.8%. when thickness is 125nm, the PCE will be 24.3%, there is relatively 32.8% efficiency more than normal perovskite solar cells [16].

It is a method to thicken the perovskite photoabsorption layer to make more photons will be captured. But it can also be an excellent way choose to add a special layer between the structure of HTM and perovskite photoabsorption layer. Bipin et. al use one-dimensional photonic crystals to enhance the light harvesting efficiency and photo-current density. It means that Bipin improve the working efficiency of the light absorption layer. And they make a short circuit current with the density of 21.52mA/cm^2 [17].

4. Applications

Although perovskite solar cells have not been widely used in the commercial field, we can also infer to explore the relevant potential research using.

4.1. Application for PCE

In order to obtain more energy, the manufacture of the high PCE and practical perovskite solar cells should be the pursuit for researchers, which means that the efficient use of pre light energy under the same working quality.

Hima et. al use the $CH_3NH_3PbI_3$ as the perovskite photoabsorption layer and choose a better structure to reach a maximum 18.16% PCE [18]. And Lin et. al choose a different way. They put the nanoparticles into the perovskite absorption layer and use an anti-reflective coating to the interior and above of the layer [19]. Kumar et. al in 2022 make a special p-i-n configuration structure and reach a maximum PCE of 19.6% [20].

4.2. Application for temperature

The working efficiency of perovskite solar cells will be affected by the working temperature. Therefore, many researchers try to control the working temperature to keep it at a working promoting temperature. Hang et. al make a low-cost Zn/Mn-based battery, which has a negative temperature coefficient to low down the working temperature. And they reach a 23.7% PCE at 25°C and make a 20.1% PCE under normal working temperature 60°C [21]. However, it is undouble that if the energy consumed for temperature control is very high, the behavior of temperature control will lose its significance. This feasible approach needs more research.

4.3. Application in space

Since the launch of the second satellite in human history in US in 1958, various space stations have to dependent on the solar cells for energy. However, due to the high production cost of single crystal solar cells, perovskite solar cells and other kinds of low-cost solar cells are been seeking for the possibility to solve such problems. In 2018, Cardinaletti et. al first launched perovskite solar cells to the stratosphere at a 32 km altitude high as Figure 4 [22]. It shows the future application prospect of perovskite solar cells in space under extreme case like thermal cycling pressure, high vacuum issue and solar flare. Perhaps in the nearby future, the large scale application of perovskite solar cells in space will become a reality.

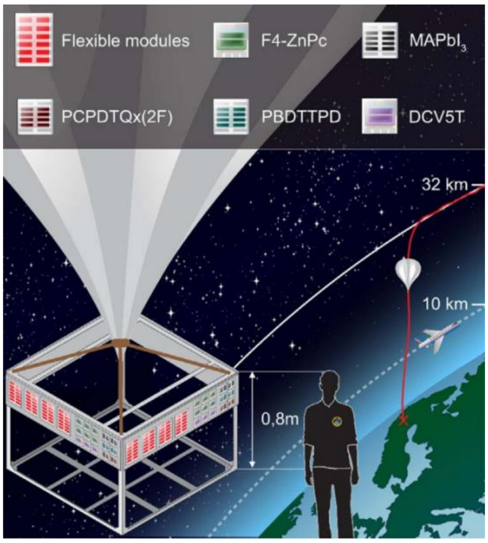

Figure 4. Installation situation and device working diagram of all kinds of solar cells [22]

4.4. Application in quantum dots

As a derivative study of conventional perovskite batteries, application of quantum dots shows a special way to continuing enhance the ability of perovskite solar cells. By this way, researchers can use this tool to optimize the conductivity and stability of ETL and HTL [23, 24]. At the same time, due to the micro size adjustment, quantum dots may also have effects like improving system crystallization and restraining energy transmission hysteresis [25]. The development of this special combination form is not clear enough, but there is still a promising future and we can hope foe it.

5. Conclusions, summary and outlook

In this review, it explains why perovskite solar cells is considered as a promising fresh energy source. This is not only its maximum 26.11% PCE, but also a visible future connected with low-cost and simple processing processes. The low-cost and simple processing processes make it convenient to integrate into the existing solar cell production industry to bring benefits quickly and reduce production pollution.

To summarize, perovskite materials have broad application potential as a semiconductor power generation material with rich physicochemical properties. But the technical capabilities are not mature enough and require more investment in research. We can adapt perovskite solar cells to surface modification, electrolyte solution, working temperature, pectrum absorption, and other different directions to make the performance of perovskite solar cells meet the requirements. Considering the instability of wind energy, tidal energy and other new energy sources and the difficulty of space energy supply, perovskite solar cells may not only be a supplement, but also be a major energy source in outer space.

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