

Photovoltaic Effect and Efficiency of Perovskite Solar Cells

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Abstract. Recently, the solar cells have become a hotspot as the solar power is becoming more and more popular. There are many types of solar cells. Perovskite solar cells (PSCs), as a type of solar cell, use perovskite type semiconductors as the light absorbing materials. PSCs exhibit high efficiency and stability. The performance of solar cells could be evaluated by the photovoltaic effect. Therefore, the research on the photovoltaic effect of perovskite solar cells is of importance. This essay gives a brief introduction to the composition and structure of perovskite solar cells. Then, it introduces the photovoltaic effect of perovskite solar cells in two parts which include working principle and efficiency of PSCs. In order to further elucidate the mechanism of PSCs, the influencing factors of photovoltaic effect are discussed. Meanwhile, the limitations and challenges of perovskite solar cells are outlined. Besides, the future development trend regarding these issues is outlined. This work will help to promote further development of this field.

Keywords: Perovskite solar cells; photovoltaic effect; efficiency of solar cells.

1. Introduction

Nowadays, the main energy resources are fossil fuels. However, with the development of industry, this energy is quite limited. The unrenovable fuels decreased rapidly. In addition, the burn of fossil fuels produces lots of greenhouse gases such as carbon dioxide, which cause a lager range of climate change and environmental pollutions. Therefore, people start to focus on some renewable energy source. Solar power, as a kind of renewable energy source, becomes one of the most important renewable energies as its features of clean, sustainable, and environmentally friendly. Because of that, solar cells become the focus of scientific research as a new technology.

Solar cell is also called photovoltaic cell, which is a device that can transfer the solar power to electric energy. The main advantages of solar cells including sustainable and environment friendly. The reason for that is they use the clean solar power which will not produce greenhouse gases.

Perovskite solar cells (PSCs) is one of most popular solar cells [1-3]. It is a new photovoltaic technology that based on perovskite structure materials. It is well known that PSC has high efficiency when it is compared to the traditional solar cells. It also has the advantages of low cost and easy-processing. It is well-known that the efficiency of solar cells is the most significant factor to evaluate its performance. Understanding the mechanism of the photoelectric effect is of great significance for further improving its performance. Therefore, this essay introduces the related details of the photovoltaic effect of PSCs.

2. PSCs

PSCs usually consist of transparent conducting electrode (TCE), absorber layer, electron-transport layer (ETL), hole-transport layer (HTL), counter-electrodes, and protecting layer.

Normally, TCE is made of Indium-doped tin oxide (ITO) or Indium-doped zinc oxide (IZO) which are type of transparent conductive materials. This design allows the sunlight penetrate into the inside of cells. The main working part area of PSC is its absorber layer which is usually made of $\text{CH}_3\text{NH}_3\text{PbX}_3$. The absorber layer is between the ETL and HTL. The electrons and holes will be inserted into n-type and p-type carrier-transporting materials when the sunlight shines to absorber layer of PSC. Then the free charge carriers are generated [1]. ETL transmits the electrons produced in absorber layer to TCE, while HTL transmits the holes produced in absorber layer to counter-electrode and prevents charges flowing. The counter-electrode which is made of gold or silver is used

to collect the holes transmitted from HTL. Afterwards, it forms outside circuit that allows the charges to move. To extend the longevity of PSC, it has a protecting layer that can protect the PSC from some environmental effect such as oxygen and moisture. Protecting layer is made of some transparent materials.

3. Photovoltaic Effect in PSCs

3.1. Mechanism of Photovoltaic Effect

There are three main processes of photovoltaic effect applied in PSC. The first process is light absorption. The second process is production and separation of electron-hole pairs. The third process is transmission and collection of those charge carriers.

The absorb layer of PSC has a larger range of absorption spectrum, which allows it capture a larger portion of solar power. When the sunlight comes to the PSC, photons in the sunlight are absorbed by electrons in the absorb layer. In this process, the energy of photons is transferred to electrons then the electrons obtain the enough energy for them to enter conduction band from valence band. At the same time, electron-hole pairs, which are also called excitons, are produced. The electron-hole pairs need to be separated into free electrons and free holes so that they can move through the cells. It is worth noting that it uses an inside electric field to achieve this separation. Carrier charges with different concentration and electrodes with different work function can produce electric field. The electric field helps to push the free electrons and free holes to different electrodes, which can prevent the combination of them. Those free charge carriers will release light energy or heat energy if they are destroyed in the motion. Once the process of separation finished, the free electrons and free holes will arrive to their own electrodes through the absorber layer. Electrons move through the ETL to the cathode, while holes travel through the HTL to the anode. They are collected at electrodes, creating electric current in the outside circuit [2, 3].

In summary, PSC uses the energy absorbed from photons to push electrons to generate electron-hole pairs. Then it uses the electric field to separate those charge carriers. Those charge carriers are collected by electrodes, producing electric current. Finally, it finishes the change from solar power to electricity.

3.2. Influence Factors of the Photovoltaic Effect

There are lots of factors affected the photovoltaic effect of PSC. It includes the composition of perovskite materials and the materials chosen for making ETL and HTL. In addition, it is also related to the environmental conditions in manufacturing processes. Researchers have explored a lot of work to improve photovoltaic efficiency.

The efficiency of light absorption and the ability of charges transmission are closely linked to the photovoltaic effect of PSC. They are decided by the composition and crystal structure of PSC itself. Therefore, one method of improving photovoltaic effect of PSC is materials composition adjustment. Positive ions including MA^+ , FA^+ , and Cs^+ can be used to achieve this component adjustment. Meanwhile, halides such as Cl^- and I^- can also be used to adjust the components [4]. The materials which are chosen for ETL and its thickness are also of importance. They directly influence the efficiency of separation and transition of charges. For instance, Lu et al. made special ETL with different type of TiO_2 successfully through adjust the concentration of KOH solution delicately when they deal with the $TiCl_4$ water solution. Then they investigate the effect of different type of TiO_2 used in ETL on cells ability. The power conversion efficiency of the device based on C- TiO_2 , N- TiO_2 , NF- TiO_2 are 15.3%, 18.5%, 19.1% respectively [5]. The situation of HTL is same as the ETL. Choosing suitable materials for HTL can also enhance photovoltaic effect. Some organic small molecules are the most common HTL material. The reason for that is the HTL made of it have a better performance on holes transitions [4]. For example, Du et al. found that it is a good choice that using spiro-OMeTAD: Sb_2S_3 to make HTL. The PSC which is made of Sb_2S_3 has higher power conversion efficiency (~22.13%) when it is compared to the PSC without Sb_2S_3 (~19.29%) [6]. Besides,

environmental conditions are also important. Perovskite materials is sensitive to humidity and oxygen, which may cause the destroy of materials so that affect the photovoltaic. High temperature also increases the speed of PSC degrading so the photovoltaic effect will have negative influence when the temperature is very high.

In summary, materials property, structure of PSC, environmental conditions all affect the photovoltaic effect of PSC. Through optimizing those factors, the efficiency and stability of PSC can be improved.

4. Efficiency Analysis

4.1. Recent Advances in Efficiency

PSC has high efficiency on the change between light energy and electric energy. Current research show that researchers optimize the composition of perovskite materials, improve the engineering interface, and increase the ability of charge transition layer. They improve the efficiency of PSC to 25% successfully [7]. In research published in 2023, researchers demonstrated the pin PSC. It has a power conversion efficiency of 24.6% on 18 mm². Interestingly, the power conversion efficiency is 23.1% on 1 mm². It has the efficiency of 96% at 25°C. When the temperature rises to 75°C, it still keeps the efficiency of 88% [8]. In addition, another silicon-perovskite tandem solar cell creates a new world record with 34.6% efficiency. To achieve it, the researchers not only optimize the deposition processes, but also defect passivation materials with high-efficiency. The current research show that the main trend in the future is using semitransparent carbon electrode without HTM to make silicon-perovskite tandem solar cells. The four main advantages of it are high-efficiency, simple, stable, and lower cost [9]. In the future, the main application of photovoltaic technology is PSC for the reason that it has high efficiency and the potential of decreasing cost. If people want to make PSC had higher ability and stability, the main researching direction is managing the interface between perovskite absorber and charge transport layers more delicately [10].

4.2. Challenges and Limitation

PSCs have a potential of high efficiency and low cost. Nevertheless, it has some limitations and challenges. For example, it still needs to be improved in long-term stability and commercialization. Nowadays, the ability of batteries of most of PSC decrease rapidly because of the water and oxygen in the environment. In addition, the high temperatures and ultraviolet light also affect the stability of PSC [11]. Water can dissolve the organic positive ions (MA⁺) in the perovskite layer. PbI₂ and HI are produced after the organic positive ions dissolved. Then the oxygen and ultraviolet light will break down the hydroiodic acid (HI). The productions of this process are water (H₂O), hydrogen (H₂), and iodine (I₂) gas. This process is irreversible [12]. Another challenge is in large-scale production. Although the high efficiency PSC is produced in laboratory, it is still hard to transfer this lab production to large-scale production. In large production, the PSC has some problem in efficiency and uniformity, which cause the challenge in commercial production. Besides, the toxicity of lead in PSC is a problem. Lead is the common material that be used in perovskite. However, it has a risk on environment and human health. Lead will enter the soil and water if the PSC is destroyed, causing pollution. Therefore, researchers are looking for non-lead materials to instead of it. Prashant V. Kamat et al. want to find some materials instead of lead. They research on tin-based perovskites, halides double perovskites, antimony-based and bismuth-based perovskites. These lead-free PSC has lower risk of toxicity [13]. Those materials indeed successfully decrease the risk of toxicity in PSC. Nevertheless, those materials still face the challenges of low efficiency and lack of stability. Therefore, PSC still need to be researched more on the design of materials, improvement of manufacture and environment protection.

5. Future Perspectives and Research Directions

5.1. Potential Improvements

The most important indicator to measure the ability of PSC is its efficiency of photovoltaic. If people want to make better PSC, they should improve its efficiency of photovoltaic effects. The four potential ways to improve it are solvent engineering, material optimization, interface engineering, and tandem solar cells.

About solvent engineering, Guohua Wu. et al. do some related researches. They improve the power conversion efficiency of PSC to 21.32% by using a different additive approach of perovskite precursor solution [14]. The adjustment of composition of materials of PSC can also improve the efficiency of its transformation between light energy and electric energy. Bella et al. find a way to both improve the efficiency of PSC and limit its photo degradation. They use the waterproof fluoridated polymers involved pigment to print the cells. These polymers involved pigment can absorb the ultraviolet light in the environment then re-emit it in the range of visible light [15]. Additionally, interface engineering is another way to improve the efficiency of photovoltaic effect. Decreasing the contraction between ETL and HTL can reduce the energy loss. Zhou et al. improve the photovoltaic efficiency of PSC by controlling charge to generate the formation of films and improve the current transmission to electrodes [16]. Besides, tandem solar cells have a huge potential on efficiency improvement of PSC. Tandem solar cells not only can match and utilize the sunlight spectrum better, but also can limit the energy loss caused by hot carrier relaxation in parallel. These types of solar cells can break through the theoretical Shockley-Queisser (S-Q) limit of single-junction cell [17]. Researching more on those area can improve the efficiency of photovoltaic of PSC and commercialization of PSC could be more possible.

6. Conclusion

PSCs have attracted widespread attention as a new type of energy battery. This essay introduces the photovoltaic effect applied in PSCs in details, which is the principle of its application. Then it introduces the efficiency of PSC in recent researches. It also states the challenges and limitations of PSC that still need to be faced. Finally, it states some methods to improve the efficiency of PSC through analyzing the effects of material structure, interface engineering, and solvent engineering applied on the PSC. In addition, this essay also introduces the tandem solar cells which break the S-Q limit. The future researches will focus on the improvement of material stability which can promote the commercial application of the PSC.

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