Perovskite Cells Based on Carbon Quantum Dots: Structure, Optimization

Jiaqi Liu [1, *]

[1]University of Science and Technology of China, Hefei, China

*Corresponding author: tt1314hh@mail.ustc.edu.cn

Abstract: Perovskite ($CH_3NH_3PbX_3$) photo voltaic cells (PSCs) based totally on blended perovskite minerals have attracted lots interest on the grounds that their inception. Due to its giant absorption coefficient, low cost, and convenient preparation, many researchers have conducted enormous lookup on it and explored whether or not exceptional buildings and supplies can enhance the performance of PSCs. Through the continuous efforts of researchers, the effectivity of PSCs has expanded from 3.8% when it was first born in 2009 to 25.5% now.Perovskite cells do, however, also have a number of flaws and room for development, including ility, insufficient photovoltaic performance, and perovskite skinny film crystal defects.Researchers have additionally tried many methods to enhance them, and one of the more tremendous techniques is to use carbon quantum dots (CQDs) as correction layers to enhance their performance. In this paper, the performance enhancement of CQDs on perovskite cells will be comprehensively confirmed from factors such as electron transport layer (ETL), perovskite thin films and hole transport layer (HTL) and the future PSCs will be prospected based on the modern-day results.

Keywords: Carbon quantum dots, perovskite cells, hole transport layer (HTL), electron transport layer (ETL), thin film passivation.

1. Introduction

In the vogue toward the use of new energy, photo voltaic energy, a clean strength source, occupies a particularly essential part. In the field of photovoltaic-based photo voltaic cells, a lot of research has been invested. One of the solar cells based on perovskite-structured $CH_3NH_3PbX_3$(X represents a halogen element) cloth has won giant interest because its inception [1]. Perovskite photo voltaic cells (PSCs) are the third-generation solar cells.It have the benefits of high-cost performance, simple fabrication process, and high light absorption coefficient. These advantages enable perovskite to be fabricated into low-thickness electron transport layer (ETM) layers, so it can be used to make simple, series, flexible and transparent batteries. Since 2009 Japanese Kojima[2] organized the first perovskite battery for the first time in 2010. The perovskite battery developed rapidly, and the battery efficiency extended from 3.8% to 25.5%.However, PSC also has many problems. Stability, it cannot savings a massive region of peroxide film, the balance is poor, the peroxide is prone to phase transition, and the formal shape is seriously hysteretic. Researchers have also proposed some strategies to optimize its performance, such as interface modification, aspect doping, fabric substitution, and other issues. Among them, the use of quantum dots to alter the interface can effectively enhance the cost transport ability of PSCs, and at the same time optimize the association between layers, and QDs furnish nucleation points. Based on QDs, there are many functions of materials, such as organic-inorganic lead halide perovskite QDs, inorganic QDs, carbon QDs perovskites.Among them, the interface modification of carbon quantum dot film formation has exquisite potential. Because CQDS is low-cost and can effectively improve the associated homes of perovskite, carbon quantum dots have great plausible in the improvement of PSC.So next I will introduce in detail the basic mechanism of perovskite cells, the characteristics of carbon quantum dots and how to use carbon quantum dots to promote the performance of perovskite cells.

2. Basic structure of PSC

PSCs are novel thin-film photo voltaic cells whose buildings are divided into formal and inverted constructions (c). The formal shape is n-i-p arrangement, and the closing shape is p-i-n, and the formal shape is divided into the mesoporous structure (a) and planar shape (b), as proven in Figure 1 [3].

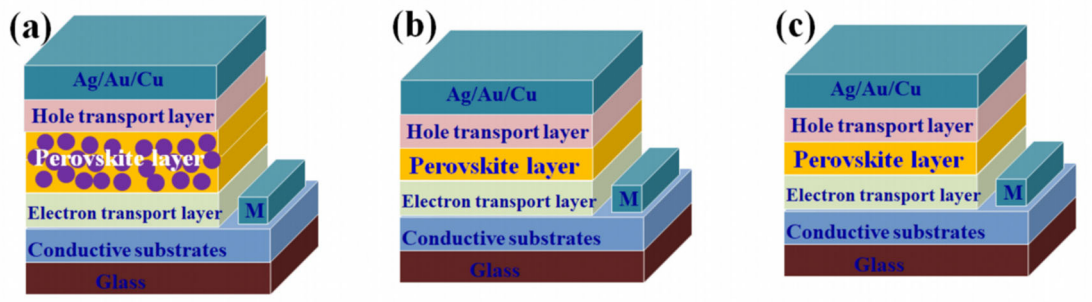


Figure 1. (a) mesoporous upright structure; (b) upright structure; (c) inverted structure.[3]

The fundamental structure of perovskite photo voltaic cells with mesoporous shape is metal electrode,HTM layer,perovskite layer, TiO_2 mesoporous layer,FTO conductive glass. ETL is typically SnO_2, TiO_2, ZnO, C60 (buckminsterfullerene), and BCP (bathocuproine). HTL is normally CuSCN, PEDOT:PSS (poly(4-butyl phenyl diphenylamine), poly(3,4-ethylene dioxythiophene polystyrene sulfonate), PTAA (polytriarylamine), and Spiro-OMeTAD (2,20 ,7 ,70-tetrakis-(N,N-di-4-methoxyphenylamino)-9,90-spirobifluorene). The inverted planar PSCs has the shape of FTO/HTL/perovskite/ETL/metal electrodes. Hysteresis results have been said to be drastically weaker for PSCs with inverted buildings than for those with formal structures, and the corresponding filling thing (FF) exceeds 0.8, greater than for most cells with formal structures. However, the PCE of traditional PSCs is still increase than that of inverted PSCs.

The operation of PSCs can be divided into three parts: generation, collection, and transport of charge and holes. When the PSCs obtain daylight in the formal structure, the perovskite layer absorbs the photons and produces electron-hole pairs at the beginning. Then the uncompounded electrons and holes are gathered respectively through the HTL and ETL. Finally the electrons are amassed by the conductive glass FTO and the holes are using the metallic electrode. When the FTO is related to a steel electrode, the circuit starts to operate, producing a photocurrent. The contemporary course of the PSCs in the inverted structure is the opposite of the formal one; holes waft towards the pre-conducting glass and electrons flow towards the metallic electrode.

3. Basic information of Carbon Quantum Dots(CQDs)

QDs are tiny particles or nanocrystals in a diameter of about 2 to 10 nanometers, which are semiconductor materials.. It is normally prepared by using the chemical answer boom method, epitaxial growth method, and area confinement method. Quantum dots have the benefits of lengthy fluorescence lifetime, slender symmetrical emission spectrum, wide-band and continuous excitation spectrum, selectable color adjustment, and high photochemical stability. The unique homes of QDs are based on their quantum effects. When the particle measurement enters the nanoscale, the dimension confinement will purpose the Coulomb blockade effect, quantum dimension effect n,d multi-exciton effect. Among them, CQDs have many benefits such as extraordinary optical properties, exact water solubility,low price and so on. Carbon-based particles with CQD diameters of about 2–10 nm have many practical companies on their floor that function via their cooperation with the layer surface, and the exclusive ratios of these companies on the surface determine their properties. [4] According to Zhang et al., tailoring allows us to obtain the functioning of the electrodes and the charge distribution and quantity of their transport layers at a lower price. So we can get the most efficient configuration with the highest efficiency. This method is often used in special types of

devices, allowing the use of carbon dots for the first time to increase the efficiency of light-emitting diodes.

4. Different methods for CQDs to improve the performance of PSCs

4.1 CQD-modified electron transport layer(ETM)

The ETM is a particularly important layer for enhancing the efficiency of PSCs, which requires high electron mobility. Only materials with a conduction band minimum below the perovskite can make ETM, because this can facilitate the acceptance of electrons transported by the perovskite layer and transport them to the FTO electrode. Now,many perovskite solar cells have Mesoporous $TiO_2$was used as ETM.During transport, once the carriers are trapped by defects in the perovskite ETL, the PCE of the device is severely degraded. To facilitate charge transfer, improve perovskite crystallization, and delay carrier complexation, researchers extensively introduced QDs at interface between the perovskite layer and the ETL .We can also use CQDs as layers to modify the interface between the perovskite layer and the ETL . CQDs are able to optimize the energy level alignment between the interface of the perovskite layer and the ETL and facilitate charge transport. On this basis, they can also play the role of the nucleation centers to assist the crystallization of perovskites.

In 2018, Ding et al studied all-inorganic $CsPbX_3$ (X = I, Br) perovskite photo voltaic cells[5].

The cellphone efficiency is increased by putting intermediate energy-bridging electron transport of CQDs at the $TiO_2/CsPbBr_3$ interface. The matched WFs (work function) and intermediate electricity tiers drastically reduce charge recombination. The electricity conversion effectivity of the WF-tuned all-inorganic perovskite photo voltaic mobilephone was once 7.17%, compared with 6.10% of the pristine device, which used to be similarly improved to 7.86% by CQDs modification.

In 2020, Liu et al organized graphitic carbon nitride quantum dots (g-CNQDs) to facilitate charge transport and minimize defects in PSCs and photodetectors (PDs). [6]The 2D polymer cloth in the interlayer of g -CNQDs is used to alterSnO_2 layers in ambient PSCs and PDs. It used to be used as a SnO_2 interface via spin-on deposition. The introduction of g-CNQD layers improves the crystalline excellent of non-stop perovskite absorbers with high section purity, fewer grain boundaries and suppressed charge carriers because of the inherent cross-linkable homes and surprisingly clean surfaces of the g-CNQDs complex. The utterly air-treated PSC achieves a energy conversion effectivity of 21.23% with negligible hysteresis, and PD has a enormous overall performance boost. Furthermore, the modified PSCs confirmed right balance in ambient air, conserving more than 90% of their preliminary overall performance after 30 days of exposure.

4.2 CQD-modified hole transport layer(HIL)

As a hole transport layer, HTM needs to be in close contact with the perovskite layer. Now, the spiro-OMeTAD is most widely used HTM layer material .It has a small molecular structure which can maintain good contact with the perovskite layer and can more easily achieve hole transport.. CQDs are currently used as an interface between perovskite and HTL to passivate film defects, optimize energy level alignment, and contribute to the crystalline layer of perovskite, thereby improving device stability.

In 2017, Zhou et al. first confirmed a method to fabricate CQD sensitized all-inorganic $CsPbBr_3$ perovskite inverse egg (IO) motion pictures by template-assisted spin coating. [7] The basic structure of high-efficiency PSCs is FTO/TiO2/CQD-$CsPbBr_3$ IO/spiro-OMeTAD/Ag.

Embedding CQDs in the IO framework broadens the mild absorption vary and improves the charge switch process. Applied to perovskite photo voltaic cells, sluggish photon impact of $CsPbBr_3$ in contrast to planar $CsPbBr_3$The combined use of IOs and CQDs resulted in a substantial increase in both conversion efficiency (PCE) and incident photon-electron conversion efficiency. IO greatly improves the utilization of light, and at the same time, CQDs promotes the electron extraction and air injection process, prolonging the carrier lifetime, allowing us to obtain 8.29% double PCE and up to 76.9% incident photon electrons conversion efficiency.

In 2019 Wei et al synthesized ultrafine flake carbon nitride QDs (EgC3N QDs) by H_2SO_4 intercalation and NH_3 exfoliation. [8] The acquired EgC_3N_4 incorporates a massive range of NH or OH groups, which can spontaneously entangle from nanosheets into nanoparticles through hydrogen bonding, forming an interfacial layer between peroxide and HTL. EgC_3N QDs are passivated to do away with floor defects, and the remaining PCE is 15.8%, which is 35% greater than that of the reference cells.

In 2019, Benetti et al. constructed inverted planar heterojunction (PHJ) PSCs. [9] The use of CQDs has resulted in a substantial increase in the performance of PHJPSCs, which is a very typical structure of PSCs. In this basic structure, light is typically transmitted from the P-side, through a junction glass/ITO/HTL/perovskite/ETL/metal in sequence, acting in a superstrate configuration. In this way, the HTL is critical to achieve excessive VOC and normal excessive performance. The efficiency of PSCs has been improved by introducing CQDs on graphene oxide (GO) to form composite HILs.The addition of C-dots reduces the work characteristic of GO, will increase the hole injection rate, and reduces charge recombination, thereby extensively enhancing the collection of photogenerated charges. In addition, with suited UV absorption and CQDs as a shielding film on the outer aspect of PSC, the stability in opposition to UV radiation can be elevated by greater than 20%; PCE is ingrained in C-dots, a film on the outer aspect of PSC, the balance against UV radiation can be accelerated through extra than 20%; PCE is elevated to 16.8%.

4.3QDs passivated perovskite films

Photovoltaic overall performance and long-term stability are essential indicators for judging the performance of PSCs, and perovskite videos have a widespread influence on these two properties, so it is specially necessary to gain superb perovskite motion pictures with few defects. Due to the migration of many dopant particles of PSCs, many particles easily destroy the crystal structure of perovskite films, forming a large number of defects on the bottom surface and grain boundaries, so that their photovoltaic performance deteriorates and needs to be replaced. Therefore, how to repair grain boundaries and surface defects is a key issue for the preparation of high-performance PSCs. It has been tested that the problem can be effectively solved by incorporating CQDs into the perovskite precursor solution. CQDs can passivate the film surface, reduce the defect density in the film to a considerably lower level and reduce nonradiative recombination and crystal defects. The overall photovoltaic performance of PSCs may be more ideal with the addition of CQDs.

In 2021, Tang et al. Two special-purpose carbon quantum dots (CQDs), A-CQDs and CA-CQDs, have been used to passivate perovskite CH3NH3PbI3 surfaces, respectively, and the effect of substrate ligands created through the two CQDs has been similarly investigated. [10] Both A-CQDs and CA-CQDs were designed to build bulk grains and reduce the defect density of perovskite films, both of which were different and improved the performance of PSCs, in which A-CQDs passivated The PCE of PSCs was 13.97%, while the PCE of PSCs in the CA-CQDs layer was 10.77%. After comparing the PSCs of the control group again, it was finally concluded that the former has the best photovoltaic performance. Further research found that A-CQDs can also well tune the strength level matching of perovskite electrodes and CQD electrodes, thereby achieving environmentally friendly power flow transfer. After being tested by USP, the data show that the use of a passivation layer for A-CQDs can minimize the level mismatch between the MAPbI3 film and the carbon electrode. The energy band between the perovskite film and the carbon electrode is bent upward due to the addition of A-CQDs. Therefore, based on the above changes, we can correctly choose the carrier that needs to be transported. In addition, A-CQDs also showed an important role in resisting the external environment. A-CQD-based PSCs can be stored for 840 hours at 35% humidity, exceeding 80% of normal PCE.

5. Conclusions

This paper mainly introduces the development, basic structure, and optimization method based on CQDs of PSCs. PSCs have great development prospects, but there are still many defects and problems

that cannot be ignored, such as perovskite film defects, insufficient layer-to-layer contact, and low transmission efficiency. CQDs have become one of the best ways to optimize perovskite cells due to their cheap price, easy access, special optics, and quantum properties. CQDs can act on HTL/perovskite interface, ETL/perovskite interface and perovskite layer, respectively. The CQDs modified the interface and optimizing crystal defects in perovskite thin films, which greatly enhanced the performance of PSCs.The future development direction can continue to try to apply CQDs to different layers of PSCs, or to couple CQDs with other materials to form new quantum dots to modify the interface or compensate for film defects.Combining CQDs with other more elements, or changing the solid structure of carbon quantum dots (such as graphene structure) can also be used as an improved form as a modified layer of PSCs to optimize the performance of PSCs. There has been considerable research in these areas but there are some alternative directions for further research.However, its biggest defect,which is significantly degraded when exposed to sunlight for a long time, is no effective solution so far. Perhaps the addition of the improvement layer can solve one of the problems, which needs to be studied in the future.

Referrences

[1] Yao Xin, Ding Yan-Li, Zhang Xiao-Dan, Zhao Ying. A review of the perovskite solar cells[J].Acta Phys. Sin. 2015, 64(3): 038805

[2] Kojima A, Teshima K, Shirai Y, et al. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells[J]. Journal of the american chemical society, 2009, 131(17): 6050-6051.

[3] Zhou Y, Luo X, Yang J, Qiu Q, Xie T, Liang T. Application of quantum dot interface modification layer in perovskite solar cells: progress and prospects[J]. nanomaterials. 2022;12(12):2102.

[4] Xiaoyu Zhang et al, Energy Level Modification with Carbon Dot Interlayers Enables Efficient Perovskite Solar Cells and Quantum Dot Based Light Emitting Diodes[J]. Advanced Functional Materials ,2020

[5] Ding J, Zhao Y, Duan J, et al. Alloy‐Controlled Work Function for Enhanced Charge Extraction in All‐Inorganic CsPbBr3 Perovskite Solar Cells[J]. ChemSusChem, 2018, 11(9): 1432-1437.

[6] Liu P, Sun Y, Wang S, et al. Two dimensional graphitic carbon nitride quantum dots modified perovskite solar cells and photodetectors with high performances[J]. Journal of Power Sources, 2020, 451: 227825.

[7] Zhou S, Tang R, Yin L. Slow-photon-effect-induced photoelectrical-conversion efficiency enhancement for carbon-quantum-dot-sensitized inorganic CsPbBr3 inverse opal perovskite solar cells[J]. Advanced Materials, 2017, 29(43): 1703682.

[8] Wei X, Liu X, Liu H, et al. Exfoliated graphitic carbon nitride self-recognizing CH3NH3PbI3 grain boundaries by hydrogen bonding interaction for improved perovskite solar cells[J]. Solar Energy, 2019, 181: 161-168.

[9] Benetti D, Jokar E, Yu C H, et al. Hole-extraction and photostability enhancement in highly efficient inverted perovskite solar cells through carbon dot-based hybrid material[J]. Nano Energy, 2019, 62: 781-790.

[10] Tang H, Xu T, Qin X, et al. Carbon Quantum Dot-Passivated Perovskite/Carbon Electrodes for Stable Solar Cells[J]. ACS Applied Nano Materials, 2021, 4(12): 13339-13351.