ISSN 2616-5880 Vol. 5, Issue 3: 31-36, DOI: 10.25236/AJMC.2024.050305

Research on Structural Optimization to Improve Semiconductor Thin-film Solar Cells Efficiency

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Abstract: *Recently, the severity of the energy crisis and environmental pollution has caused a great threat to people's lives, and solar energy has become the focus of attention due to its abundant reserves and environmental protection characteristics. New thin-film solar cells have attracted much attention due to their light weight, good flexibility, and low manufacturing cost. However, their efficiency and stability issues are still the key factors limiting their commercialization. In this paper, structure optimized measures to improve the efficiency of thin-film solar cells are classified and summarized. Surface modification is to optimize the surface structure by using some special chemicals, such as chlorides and organics. Interlayer optimization, on the other hand, involves the introduction of similar structures, such as distributed Bragg reflectors (DBR), to greatly extend the path length of photons and enhance the absorption of photons in the active region. The new thin-film solar cells have a broad development prospect and are expected to become an important part of the green energy field, providing sustainable solutions for mankind to cope with the energy crisis and environmental challenges.*

Keywords: *Semiconductor Thin-film Solar Cells, Interface Modification, Structural Optimization*

1. Introduction

With the depletion of traditional energy sources and the increasing pollution of the environment, it is urgent to find a new clean and renewable energy source as an alternative. Solar energy can be said to be inexhaustible and is one of the cleanest sources of energy. Solar cells are widely used in various fields because of their long life, low cost, wide distribution and renewability [1].

Solar cells mainly utilize the photovoltaic effect to convert solar energy into electricity, thus realizing the utilization of sunlight. Traditional solar cells mainly include silicon-based solar cells, thin-film solar cells and so on. Silicon-based solar cells have a mature manufacturing process and high stability, but their manufacturing cost is higher, and can bring a certain amount of environmental pollution. Thin-film solar cells have the advantages of thin and light flexibility, and low manufacturing cost. However, its conversion efficiency is low, and its stability is also low. It is difficult to maintain a high efficiency for a long time. Low efficiency means that solar energy cannot be fully utilized, resulting in relatively low energy conversion efficiency. This not only limits the performance of solar cells in practical applications, but also their competitiveness in large-scale applications. Therefore, it is crucial to modify these conventional solar cells to improve their efficiency [2].

Interface modification and interlayer optimization are effective strategies for improving semiconductor thin-film solar cells. The interface modification strategy is mainly to introduce some special substances such as organics or fluorides between the interfaces to realize the optimization of energy bands and defect passivation at the interfaces [3]. It is effective to reduce the density of trap states and the accumulation of charges at the interfaces. Therefore, it improves the efficiency of solar cells. The interlayer optimization strategy is mainly to introduce DBR in the solar cell [4]. It greatly extends the path length of photons and reduces the reflection loss, thus improving the conversion efficiency of the solar cell.

In this paper, structure optimized measures to improve the efficiency of thin-film solar cells are classified and summarized. The results show that interfacial modification is the introduction of new materials to improve the interfacial energy bands or passivate the interfacial defects, thus increasing the photoelectric conversion efficiency. Interlayer optimization, on the other hand, involves the introduction

ISSN 2616-5880 Vol. 5, Issue 3: 31-36, DOI: 10.25236/AJMC.2024.050305

of DBR to greatly extend the path length of low-energy photons, thereby enhancing the absorption of photons and ultimately improving the efficiency of solar cells significantly. Therefore, the new thin-film solar cells have extremely wide application prospects in the energy field.

2. Structure optimized measures

2.1 Surface modification

Thin-film solar cells have multiple interfaces, such as the perovskite/hole transport layer and electron transport layer/perovskite interfaces of PSCs devices. This normally produces various defects thus restricting the efficiency, stability, and optical hysteresis effect of PSCs. But the interfacial modification strategy can effectively reduce the density of trapped states, decrease the accumulation of charges at the interface and inhibit the process of ionic migration to further improve the photovoltaic performance of solar cells.

Chen Chan used alkali metal fluorides to modify the interface of TiO2 mesoporous layer and MAPbI3 perovskite in the thin-film solar cells, and the side view of perovskite electrode is shown in Fig. 1(a). The modification of TiO2 mesoporous layer by alkali metal fluoride (NaF and LiF solution) can optimize the crystallization and growth environment of perovskite crystals, enhance the crystallinity of perovskite polycrystalline film, and increase the grain size. It improves the quality of the active layer of MAPbI3 perovskite, and makes the conversion efficiency of the solar cell reach 10.74% in Fig. 1(b). To improve the light absorption of the film, the effect of light absorption of the film was explored by changing the holding time as shown in Fig. 1(c). Modification of MAPbI3 perovskite films with alkali metal fluoride (NaF solution) can form stronger chemical bonds as well as optimize the crystal structure. It can enhance the stability of the perovskite crystal structure and improve the crystalline quality of the perovskite films, which enables the NaF-modified solar cells to finally achieve a conversion efficiency of 11.26%. The photovoltaic curves of the PSCs devices prepared based on different NaF contents are shown in Fig. 1(d) [5].

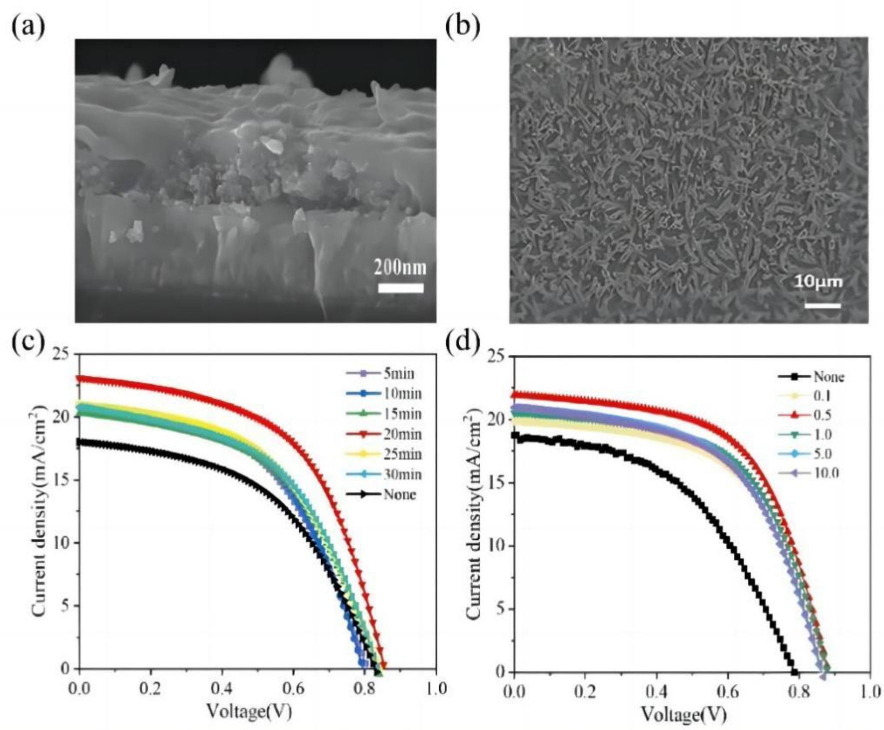

Figure 1: (a) Side view of perovskite thin-film electrode; (b) LiF+ NaF solution modified perovskite thin-film electrode; (c) J-V characteristic curves at different holding times; (d) J-V characteristic curves of PSCs with different NaF content

Pengyu Xu made the fluoride ions in the KF-modified layer directly replace the terminal hydroxyl group of SnO2 by spin-coating a KF-modified layer on the SnO2 layer. It reduces the surface hydrophilicity of SnO2 and makes the perovskite have a better morphology, as shown in Fig. 2(a). The photoelectric performance of KF-modified SnO2 is superior through comparing the J-V test curves of

ISSN 2616-5880 Vol. 5, Issue 3: 31-36, DOI: 10.25236/AJMC.2024.050305

battery devices based on SnO2 and SnO2/KF electron transport layer, as shown in Fig. 2(b) and (c). Their external quantum efficiency curves are shown in Fig. 2(d). In addition, the potassium ions in the KF modification layer can effectively enter the perovskite film during the annealing process of perovskite, which achieves the passivation of the film grain boundaries and the suppression of iodine vacancies. Finally, the photoelectric conversion efficiency of perovskite solar cells reached 20.23% [6].

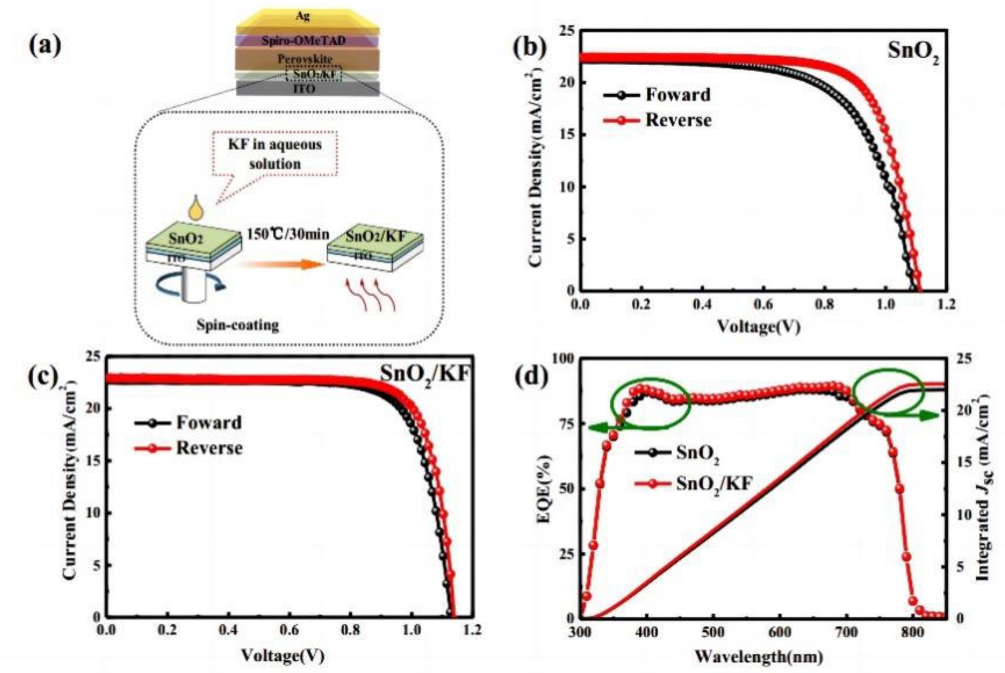

Figure 2: (a) Schematic structure of the perovskite cell; (b) Forward and backward swept J-V curves of perovskite solar cells; (c) Forward and backward swept J-V curves based on the SnO_2/KF electron transport layer; (d) Exogenous quantum efficiency test curves based on SnO_2/KF and the perovskite solar cells

Yali Liu et al. greatly improved the performance of perovskite solar cells by modifying the surface of perovskite with 2-thiophene ethylamine (TEA). The amine group of TEA interacts favorably with uncoordinated Pb2+ through Lewis acidic coordination, and the thiophene ring, with its electron-rich thiophene, assists in the interaction by acting as an electron donor. It is a synergistic effect that effectively passivates the defects in the film and enhances the charge carrier lifetime. And improves the charge carrier lifetime. In the end, the TEA-modified perovskite solar cell ultimately achieved 21.3%, which is a full 2% improvement over the control [7]. Weihuang Wang et al. treated the TiO2/Sb2Se3 interface with SbCl3 to form a Sb2O3 intercalation. It enhanced the carrier transport properties and reduced the conduction band offset (CBO) at the TiO2/Sb2Se3 interface from 0.57 eV to 0.20 eV, effectively reducing the interfacial composite and the device's open-circuit voltage deficit. Moreover, the interfacial bonding at the TiO2/Sb2Se3 interface was improved, resulting in an efficiency of 5.82% for the Cd-free Sb2Se3 solar cell [8].

Interface modification strategies are mainly used to improve the efficiency of semiconductor thin-film solar cells through both energy band optimization and defect passivation at the interface. Energy band optimization can improve the matching of interfacial energy levels, so that carriers can pass through the interfacial layer smoothly, thus improving charge collection. Defect passivation can reduce the number of defects at the interface and eliminate the ion migration path, thus effectively inhibiting ion migration. Combined with the above, the interface modification strategy can effectively enhance the photovoltaic effect of solar cells [9].

2.2 Interlayer optimization

The device efficiency and transparency of thin-film solar cells are usually negatively correlated, which does not satisfy the requirement of high efficiency and high transmission at the same time. Embedding DBR in the middle layer of the solar cell can selectively reflect light in the ultraviolet or near-infrared region, make it reflect to the active layer and be absorbed, and improve the transmittance of the device in the visible region, thus obtaining a high-performance semi-transparent solar cell.

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Waqas Farooq et al. optimized the material of the active layer by using the DBR technique. It enhances the absorption of light in the active region and reduces the reflection loss. After comparative experiments, it can be obtained that the performance parameters of the solar cell were significantly improved after the introduction of DBR, the conversion efficiency increased by 0.91% and photovoltaic conversion efficiency of 23.29% was achieved. In addition, the optimized structure was tested at different operating temperatures to examine its thermal stability against high temperatures. The rigorously optimized layer design proposed in this study could be a good choice for solar cell technology [10]. Margaret A. Stevens et al. used a fast epitaxial growth method to integrate an epitaxial DBR, by possessing the layer structure of a cell with the post-junction structure of a DBR and a conventional shallow-junction structure as shown in Fig. 3(a) and (b). With a solar cell increasing the optical path length near the band edges and enhancing the photon recycling. It resulted in a significant enhancement of the reflectivity near the band edges allowing for an up to 96% external quantum efficiency, ultimately achieving a conversion efficiency of up to 24.3%, an approach that significantly improves solar cell performance by extending the photon path length, as shown in Fig. 3(c) and (d) [11].

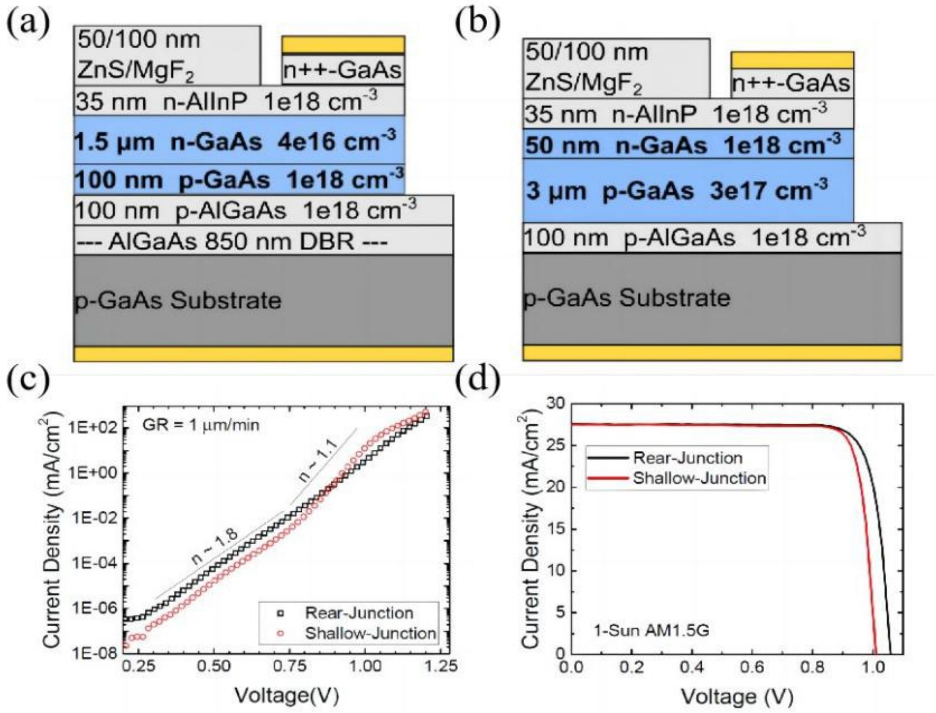

Figure 3: (a) Rear-junction solar cell with DBR; (b) Optimized substrate solar cell with conventional shallow-junction structure; (c) J-V curves of solar cells with shallow- junction and rear-junction structures; (d) J-V curves of solar cells with shallow-junction and rear-junction structures

Robert F. McCarthy et al. added reflective structures below the middle and bottom InGaAs subcells to maintain most of the solar cell current. Reflective back structures were placed below the bottom InGaAs subcells, but new wavelength-selective DBR were grown below the middle GaAs subcells. The newly designed solar cell with DBR significantly improves radiation tolerance due to improved current retention. The average cell efficiency even reached 28% with a power retention of 84% for a given energy of 1 MeV [12]. Through comparative tests, Waqas Farooq et al. concluded that the use of DBR pairs improves the photovoltaic parameters and helps in trapping the reflected light back to the active region, and that the solar cells with DBR pair structures have a certain degree of high temperature tolerance. In addition, the use of three DBR pairs achieves an increase in conversion efficiency of 1.076%, resulting in a photovoltaic conversion efficiency of 11.02%. The photovoltaic characteristics of the solar cell after the insertion of DBR pairs are shown in Fig. 4(a) and (b) and (c) and (d) [13].

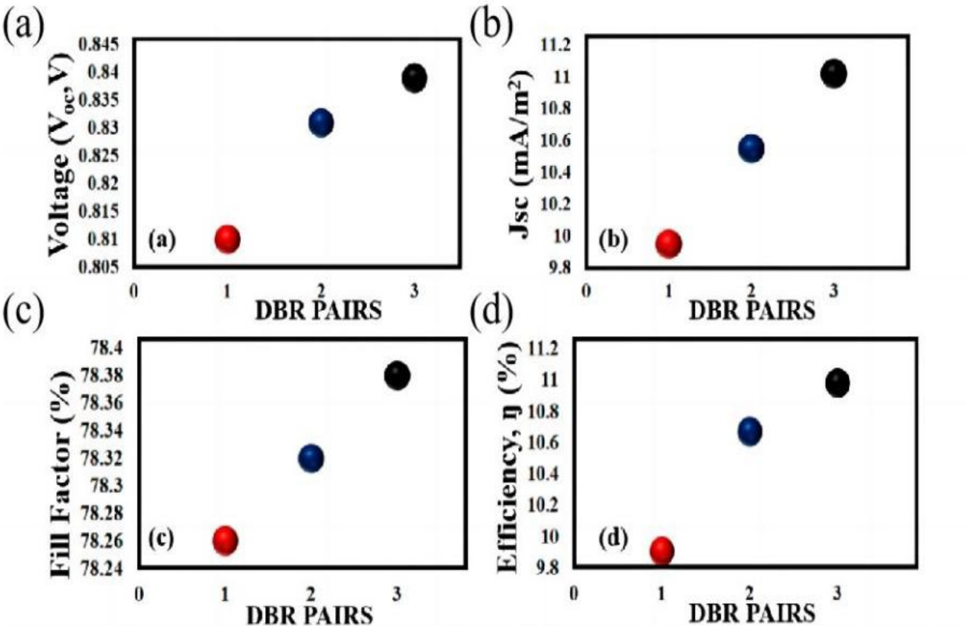

Figure 4: Performance parameters of the solar cell after insertion of DBR composed of ($W0_3$/LiF). (a) Open-circuit voltage Voc; (b) Short-circuit current Jsc; (c) Fill factor FF; (d) Conversion efficiency η

DBR embedded in a solar cell is a reflective structure used in waveguides. The DBR can be very sensitive to wavelength selection due to the multiplicity of light interfering to make the reflection effect obvious. This structure can enhance the absorption of light in the active region, reduce the reflection loss, and can increase the path length of photons, which ultimately greatly improves the conversion efficiency of solar cells. In conclusion, the optimization strategy of the interlayer with the introduction of the DBR structure can significantly improve the efficiency of thin-film solar cells [14].

3. Conclusions

Recently, energy and environmental issues have become more prominent. Solar cells are highly favored for their advantages of environmental protection and energy saving and wide application. The efficiency of the cells can be effectively improved by modification techniques such as surface modification and interlayer optimization. The results show that thin-film solar cells with low efficiency can be structurally optimized to significantly improve the photovoltaic conversion efficiency. As a result, it contributes more to the energy sector and solves environmental problems. In addition, the continued development of solar cells is expected to make a greater contribution to the global energy transition and environmental protection.

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