Research Progress of the Light Management for Perovskite-Silicon Tandem Solar Cells

Hanming Zhu

School of Opto-electronic and Communication Engineering, Yunnan Open University, Kunming 650500, China

hivdgzhm@163.com

Abstract

Perovskite/silicon tandem solar cells (TSCs) are attractive for their potential for boosting cell efficiency beyond the crystalline silicon (Si) single-junction limit. Effective light management can improve power conversion efficiency of the perovskite/silicon TSCs. In this article, recent progress in the development of the light management for Perovskite-Silicon TSCs is reviewed. Achievements about optical splitting system, antireflection coating and morphology of TSCs are introduced. At the end of the article, the prospect of light management is presented.

Keywords

Perovskite/Si tandem solar cell, Optical splitting system, Antireflection coating, Morphology.

1. Introduction

Finding suitable bandgap materials to form a series solar cell (TSC) with silicon solar cells is an effective method to improve the efficiency of silicon-based solar cells. Perovskite is a material with high carrier mobility, long diffusion length, strong light absorption, tunable bandgap width, and excellent fault tolerance for structural defects, which has attracted widespread attention[1-2]. Choosing this material as the top sub cell of a silicon solar cell can fully absorb the solar spectrum and improve the efficiency of the entire solar cell. The theoretical predicted efficiency of perovskite/silicon TSC can exceed 30%, making it a potential stacked solar cell.Researchers at home and abroad mainly improve the efficiency of perovskite/silicon TSC through the following two aspects: (i) design new structure on the basis of existing materials, optimize the growth process, and minimize the defects in the materials; (ii) reduce the light loss on the surface and increase the light absorption of the cell through light management.

In this article, the progress of light management for the perovskite/silicon TSC is reviewed, concentrating on the optical structure and antireflection coating, and some brief outlook is presented.

2. Structure of TSC

At present,there are three main structures of tandem cells: mechanical stacking[4], monolithic integration[5] and spectral segmentation. The mechanical stack combines independently made top and bottom cells to form a series battery devices, a four-terminal cell. Monolithic integration is the sequential deposition of each layer of material of the cell, and the top and bottom cell are connected together through tunnel junction or composite layer, which is called tow-terminal cell. Spectroscopic splitting is similar to mechanical stacking, except that a layer of wavelength-selective mirrors is inserted between the two cells so that the incoming light is absorbed by the appropriate cells and the top cells do not have to be transparent. Different design structures have different effects on the performance of the cell. The main research structures are tow-terminal and four-terminal tandem cell, both of which have their advantages and disadvantages. The advantage of the four-terminal device is that it is simple to manufacture and easy to synthesize, so as to avoid the shortage of current or voltage matching capability of the top and bottom cell, as well as the effect generated by the lack of tunnel junction, ensuring that the optimal performance of the top and bottom cell can be better reflected. Compared with four-terminal device, two-terminal device have higher PCE and lower production cost.

3. Light management

The spectral response band of perovskite cell is 300~800nm, which mainly absorbs visible light. The spectral response band of silicon cell is 800~1200nm,which mainly absorbs near-infrared light. Effective light management can reduce surface light reflection and increase photon absorption, and further improve PCE of the perovskite/silicon TSC.

3.1. optical splitting system

In order to achieve very high PCE for a full spectrum the perovskite/silicon TSC, H. Uzuan et al.[6] reported an optical splitting system as shown in Fig. 1. (a). An optical splitter is a dichroic mirror that manages the spectral reflectance and transmittance directing the photons of different wavelengths to the most appropriate solar cell. The cells in the system are individually measured; therefore, the current for each cell does not need to be matched in contrast to standard tandem solar cells and they can be fabricated independently without any additional process constraints. This allows us to have a broader choice of materials and design options for the optical management of the systems. Through the application of this optical splitting system, the a-Si and the perovskite cells contribute to the performance of the system in the shorter wavelength range(Fig.1.(b)), the active-area PCE of 28% have been achieved for the perovskite/silicon TSC, From this approach, the potential of optical splitting system towards high PCE is shown,and the improvement of the top cell will lead to PCE over 30%.

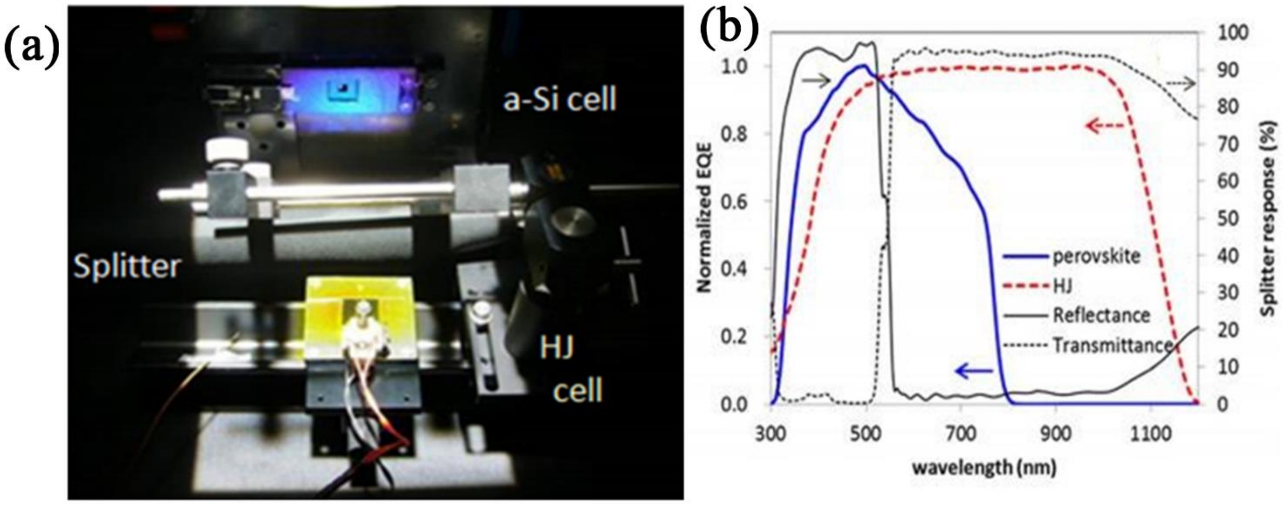

Fig. 1. (a) measurement setup of an optical splitting system. (b) Comparison between normalized EQEs of TSC without splitter and optical properties of splitter.

3.2. Antireflection coating

An important factor that affects the solar cell PCE is the reflection loss of surface incident light on solar cells. In order to reduce the optical reflection loss, a single or multilayer ARC is usually prepared on the surface of solar cells. Since ARCs can promote light entering into the active region of the device, they play an important role in enhancing the PCE of solar cells. Zhao et al.[7]

took the four-terminal TSC (Fig. 2. (a)) as the model and explored the effect of various antireflection materials LiF, MgF_2, SiO_2, and Al_2O_3 on tandem solar cells performance with Silvaco Atlas. They found the PCE with these ARCs were 27.62%, 27.63%, 27.47%, and 26.75%, respectively, much higher than that of the device without the ARC (26.3%). At the same time, they chose Al_2O_3 as the the encapsulation layer, studied the influence of the double ARC on the TSC, and found that the ARC of Al_2O_3 with LiF, MgF_2, and SiO_2 enables PCEs of tandem solar cells to achieve 27.44%, 27.45%, and 27.32%, respectively, total PCE with the double ARC decreased slightly. However, the encapsulation performance of the solar cell was improved significantly because of the existence of Al_2O_3. In addition to numerical simulation, some researchers have prepared LiF, MgF_2 and PDMS ARC on the surface of perovskite/silicon TSC, which reduced the light surface reflection to a certain extent and increases the PCE of the TSC[8-10].

Unfortunately, there are some drawbacks still occurring in these materials. For instance, ARC based on LiF or MgF_2 can only reduce the surface reflections in a specific wavelength region; easily absorb moisture from the environment; and are sensitive to thickness variations. In order to solve this problem, Hou et al.[11] design light management antireflective foils made from polydimethylsiloxane (PDMS) polymer carrying random-pyramidal textures with three different pyramid size ranges (1-3μm, 3-8μm, 8-15μm) for perovskite/SHJ tandem solar cell (Fig.2.(b)). The optical properties, together with the reflection behavior applied to perovskite/silicon tandem solar cells have been systematically studied. One of the PDMS layer exhibited a relatively strong light-scattering property with a high average haze ratio originated from synergistic effect of the appropriate pyramid size and the uneven random pyramid distribution. Consequently, the short-circuit current density of the tandem device was improved by 1.72 mA/cm^2 and thus its efficiency increased from 19.38% to 21.93% as shown in Fig. 2. (c), after laminating the PDMS-based ARC onto the front surface of tandem device.

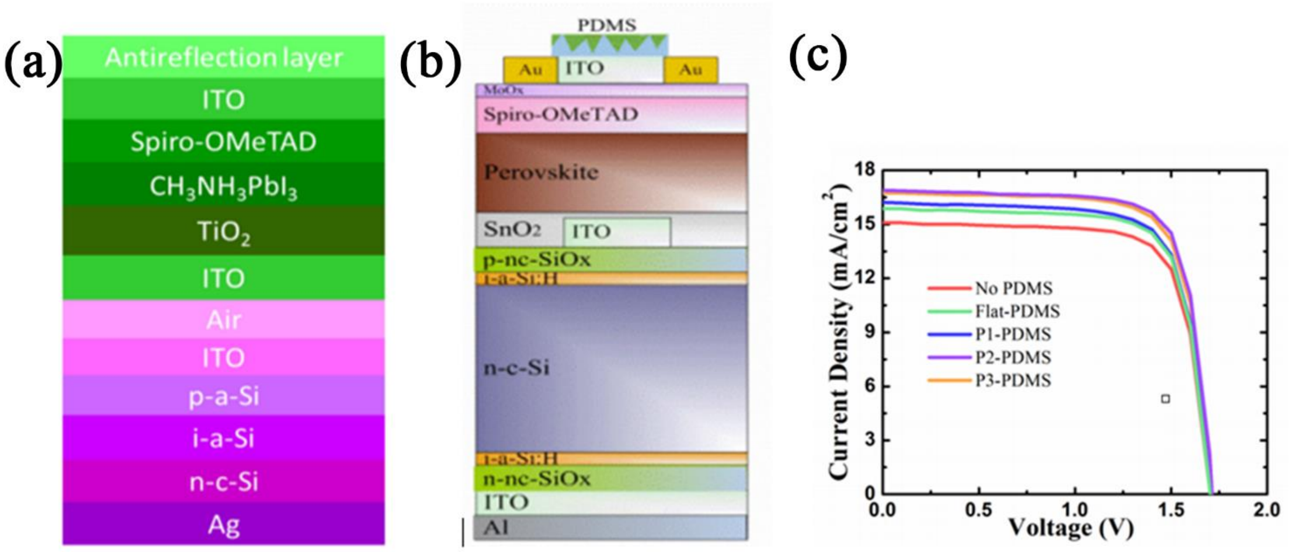

Fig. 2. (a) Schematic device structure used for the simulation. (b) The structure of monolithic perovskite/SHJ tandem solar cell. (c) J–V curves of perovskite/SHJ tandem solar cell with Flat-PDMS, P1-PDMS, P2-PDMS and P3-PDMS ARCs.

3.3. Morphology of TSC

The different morphology of TSC can further alter the path of light, thereby altering the amount of photons entering the TSC. Introducing rear texture,front texture and double-side texture into the perovskite/silicon TSC can decrease parasitic absorption and improve short-circuit current density[12]. Nogay et al.[13] demonstrated the first front texture tandem solar cell featuring a p-type bottom cell (Fig. 3. (a).) based on such contacts. In brief, a p-type float-zone (100) c-Si wafer, which is flat on its rear and textured on its front, is capped on both sides by a ~1.2 nm SiO_x layer grown by UV-O_3 exposure. Doped silicon-rich silicon carbide (SiC_x) layers are deposited by plasma-enhanced chemical vapor deposition (PECVD) over the full area. SiC_x is doped with boron on the rear side (SiC_x(p)) to form the hole contact. The front is doped with phosphorus to provide electron selectivity (SiC_x(n)). A single annealing step at 850 °C then triggers the partial crystallization of the doped SiC_x and the diffusion of dopants from the doped layers into neighboring wafer regions, lowering both contact resistivity and parasitic absorption. The perovskite absorber is processed using the hybrid deposition method, which ensures a conformal deposition of the absorber on the micrometer-sized Si pyramids for optimum light management. The method combines the coevaporation of CsBr and PbI_2, before spin-coating an organo-halide solution and crystallizing the photoactive phase through an annealing step at 150 °C. Tandem cells with an active area of 1.42 cm^2 are then finalized by depositing a SnO_2/IZO/Ag front electrode by atomic layer deposition, sputtering, and evaporation, respectively, as well as an MgF_2 antireflection coating by evaporation. The TSC achieved a steady state efficiency of 25.1%. In the same year, Mazzarella et al.[14] reported a monolithic perovskite/SHJ tandem cell with rear texture, and introduced an optimized nc-SiOx:H interlayer between the top and bottom cell in monolithic perovskite/silicon-hetero junction tandem cells, which significantly increased bottom-cell current density. The best tandem device reached a certified conversion efficiency of 25.2%.

Moreover, The perovskite/silicon TSC with double-side texture have also been studied. Sahli et al.[15] developed a top cell deposition process that achieves the conformal growth of multiple compounds with controlled optoelectronic properties directly on the micrometre-sized pyramids of textured monocrystalline silicon as shown in Fig. 3. (c). Tandem devices featuring a silicon heterojunction cell and a nanocrystalline silicon recombination junction demonstrate a certified steady-state efficiency of 25.2%. The optical design yields a current density of 19.5 mA cm^{-2} thanks to the silicon pyramidal texture and the PCE of monolithic perovskite/silicon TSC will surpass 30% in the future.

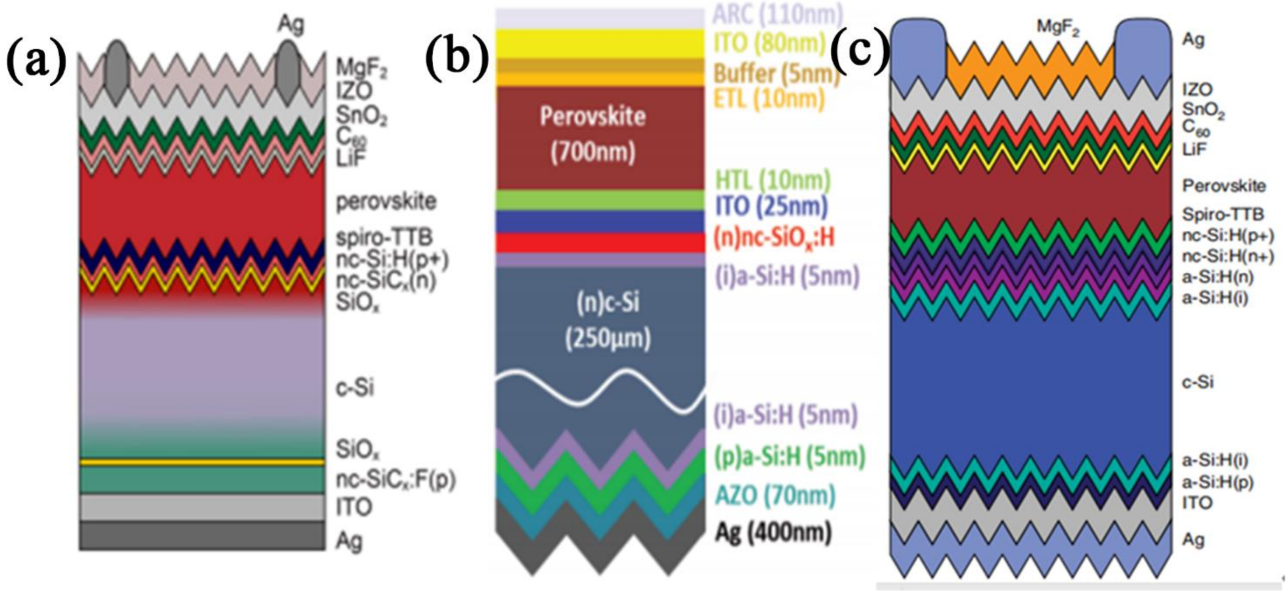

Fig. 3. (a) Schematic view of the perovskite/p-type c-Si bottom cell with front texture. (b) Cross-section of the simulated monolithic perovskite/SHJ tandem cell with rear texture. (c) Schematic view of a fully textured monolithic perovskite/SHJ tandem with double-side texture.

4. Conclusion

Optical splitting system,ARC and morphology in light management technologies can broaden the absorption spectrum and increase PCE of Perovskite/Si TSCs. However, the optical splitting system will raise the fabrication cost of the device, and silicon bottom cell with the textured structure will increase the complexity of fabrication process of perovskite top cell. Therefore,the use of ARC for light management is the focus of future research. Therefore, the use of ARC for optical management is the focus of future research. Research can be carried out from the following aspects: (1) find new materials and design new ARC; (2) improve the deposition process and use the simplest and most stable process; (3) explore more kinds of doped high performance ARC. It is believed that the ARC in light management will have a broad application prospect through in-depth and detailed research.

Acknowledgements

This work was surported by the Yunnan Open University Campus level Research Fund (No. 21YNOU17).

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