

Structure affects perovskite/silicon solar cells

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Abstract. Contemporarily, the power conversion efficiency of monolithic perovskite/silicon series solar cells has been significantly improved. Starting with the structure of solar cells, this paper discusses the reasons for the power growth of perovskite/silicon series solar cells. Subsequently, the main advantages of perovskite/silicon series solar cells are summarized. Afterwards, the bottlenecks and limitations encountered in the current state-of-art scenarios of solar cells are evaluated detailly, and future prospects for the further exploration are demonstrated. By comparing perovskite/silicon cells with different structures and designs, the idea is proposed of breaking through higher power, and through the discussion of bottlenecks. The direction of progress of perovskite/silicon solar cells for a long time in the future is clarified accordingly. These results shed light on development of the Perovskite / silicon series solar cell.

Keywords: efficiency, perovskite, solar cells, structure.

1. Introduction

Human development is inseparable from energy. As a kind of clean energy with abundant reserves, the development and utilization of solar energy has attracted extensive attention. In recent years, researchers at home and abroad are paying attention to this problem. At present, silicon-based solar cells account for the highest proportion in the global photovoltaic market, reaching more than 90% [1, 2]. Thereinto, perovskite/silicon series solar cell is regarded as the one that possesses the highest efficiency and price competitiveness. This series method achieves 29% efficiency in a short time. Of course, such working efficiency is inseparable from the structure of this solar cell [3]. The initial solar cells were mainly organic structures. Later, scholars gradually found more structured batteries, which have higher efficiency.

In December 2020, the conversion efficiency of perovskite/silicon solar cells makes the development prospect of solar energy brighter. The battery is composed of a layer of silicon and a layer of synthetic perovskite film in series, with an area of 1.1^2 cm^2 [4]. It has passed the independent test certification of the NREL in golden, Colorado, with a conversion efficiency of 29.52% [4]. The application of perovskite in solar photovoltaic is timely, because after decades of improvement, it has encountered a major bottleneck in continuing to improve the conversion efficiency of silicon cells; Photovoltaic materials have a limit in converting solar energy into electricity. The level of this limit depends on their “band gap”, i.e., the energy required for electrons to be released from materials and become charge carriers to flow in the circuit. Since the band gap of crystalline silicon is 1.1 eV, the photons from the sun with energy less than 1.1 eV cannot release electrons, and photons higher than 1.1 eV can still produce charge carriers, but some photon energy exceeding 1.1 eV will be wasted in the form of heat energy. The band gap of perovskite film covered on silicon battery can reach 1.7 eV to supplement the lower band gap of silicon. In this way, more photons can be captured from more sunlight spectra, more electrons can be released and more energy can be generated. The theoretical conversion efficiency of the two materials is 43%.

The rest part of the paper is organized as follows. The Sec. 2 will introduce the structure and design of perovskite / silicon solar cells are introduced. The Sec. 3 will show the current research advantages of perovskite / silicon solar cells. The Sec. 4 will clarify the research limitations and current research

bottlenecks of perovskite / silicon series solar cells are described. Eventually, a brief summary will be given in Sec. 5.

2. Perovskite/silicon tandem for solar cell

Sahli et al. proposed a new battery design and envisaged the structure of the battery [5]. They have developed a top-level battery deposition process. The steady-state efficiency of a series of devices using silicon heterojunction unit and nanocrystalline silicon composite junction is 25.2%. The method of top cell deposition at lower temperature is developed, which can prevent the degradation of silicon heterojunction bottom cell. The mixed deposition method of sequential co evaporation is used. The battery structure they designed is shown in Figure 1.

Another group of researchers combined MACI and mah2po2 in the precursor to carry out grain engineering in order to enhance the efficiency [6]. Because they found that the material in the precursor can change the grain morphology of the wide gap, so as to improve the work efficiency. Moreover, these substances have synergistic effects, which can be passivated through the grain boundary of perovskite, and can effectively reduce the non-radiation recombination of the outside world. The cell structure they designed is made of broadband gap materials. Solar cells are stacked on silicon cells with a near ideal band gap and can be used as a bottom light absorber for series solar cells. We can see the structural characteristics of the battery as sketched in Figure 2.

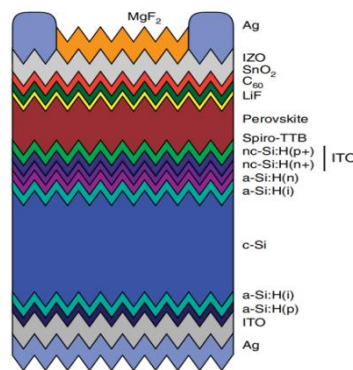


Figure 1. A sketch of perovskite top battery on textured SHJ bottom battery [5].

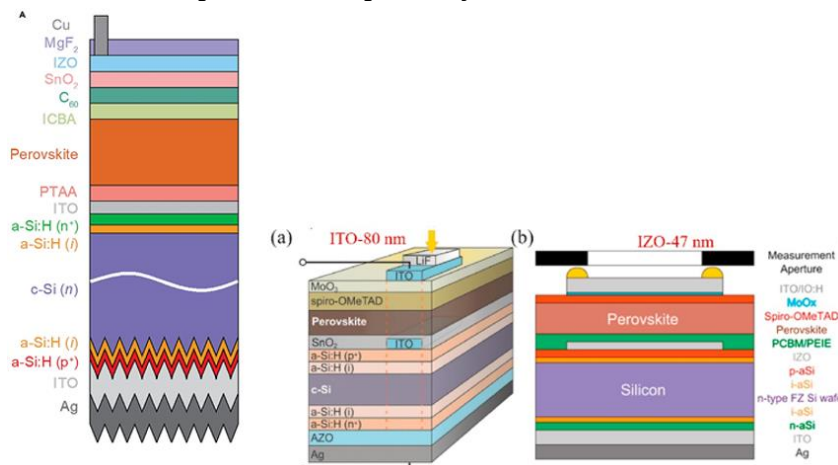


Figure 2. Structure diagram of perovskite / Silicon Monolithic series device and 1.70ev perovskite top battery [6].

Besides, other scholars mainly consider the impact of structure on optical management, since optical management will strongly affect the degree of optical coupling [7]. These structures have micron scale textures on the front and back of c-Si wafer. Regarding to the 4T configuration, the structure consists of planar perovskite SJ solar cells with double-sided texture c-Si SJ on the top. Typically, three types of PV module frameworks are illustrated in Fig. 3.

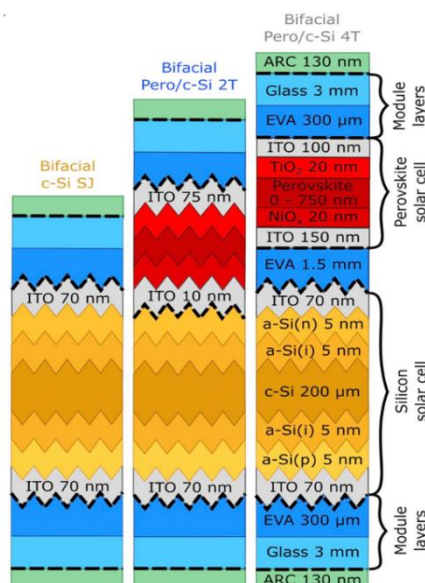


Figure 3. Three types of PV module frameworks [7].

Other researchers focus on the way to combine perovskite with full texture c-Si more efficiently. To overcome the charge collection challenge in micron thick perovskite, the researchers tripled the depletion width at the bottom of the silicon pyramid. In addition, by anchoring a self limiting passivator (1-butanethiol) on the perovskite surface, they increased the diffusion length and further inhibited phase segregation.

Moreover, other proposals tried to connect metal halide perovskite and silicon in series to form a battery, believing that this is the most effective choice to obtain high-efficiency batteries [9]. Based on the analysis, they found that phase stability can be maintained under illumination by rapid hole extraction and minimizing non radiative recombination at the hole selection interface. These characteristics are realized as hole selection layers of perovskite batteries. The extraction of accelerating holes is related to the low ideal coefficient of 1.26 and the single junction filling coefficient of up to 84%, which can achieve a series open circuit voltage of up to 1.92. In this case, it is larger than its own band gap.

Compared with other types, such a series structure requires only half of the battery usage [10]. On account of the light filtering effect, the front and rear sides of the heterojunction of silicon solar cells with inherent thin film are eliminated in the V-shaped series structure. In the meantime, because the VOC of heterojunction and inherent thin-film silicon solar cells can be improved by bilateral illumination. A sketch of the V-shaped perovskite silicon series structure is given in Fig. 4.

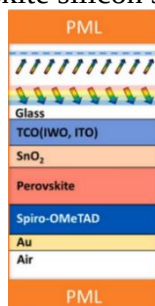


Figure 4. V-shaped perovskite silicon series structure diagram [10]

3. Performance

For each structure discussed in the section 2, their performances are demonstrated as follows. As for the research team of Sahli et al who assess the optical quality of the structure they had designed [5], they have measured the external quantum efficiency (Fig. 5a) from $\lambda=360\text{nm}$ to 1200nm . It is

based on a thickness of 440nm perovskite with 1.6eV bandgap (best), for $20.1\text{mA}\cdot\text{cm}^{-1}$ generated in perovskite and $20.3\text{mA}\cdot\text{cm}^{-1}$ in SHJ. Figure 5b shows the J-V characteristic curve recorded with the velocity 100mVs, which prove that the fully textured monolithic perovskite/SHJ tandem cells featuring an nc-Si:H recombination junction can provide an V_{oc} about 1.788V on an area of 1.42cm^2 . And it's η_{MPP} reach to 25.24%, which is a fairly high efficiency four years ago.

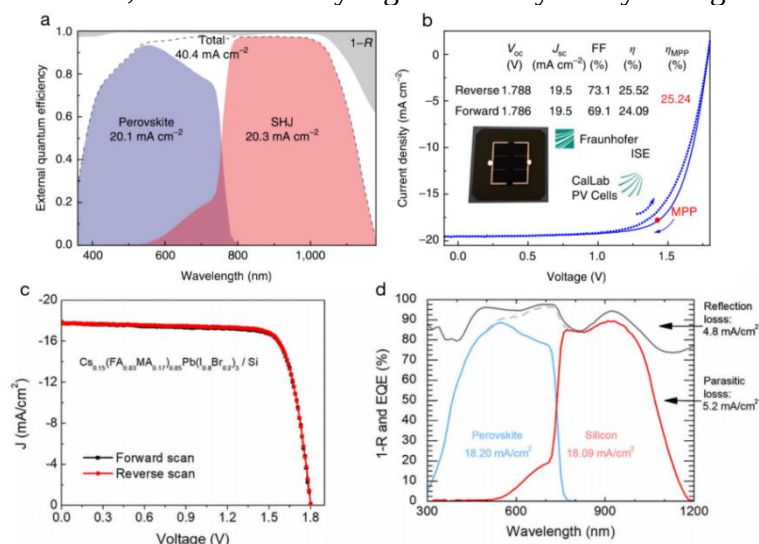


Figure 5. The performances of Refs. [5, 6].

The research team of Chen et al., pays attention to changing bandgap and reducing the trap density at grain boundaries [6]. They have found that $\text{Cs}_{0.15}(\text{FA}_{0.83}\text{MA}_{0.17})_{0.85}\text{Pb}(\text{I}_{0.8}\text{Br}_{0.2})_3/\text{Si}$ performing the best, thus this material are chosen to measure the EQE and J-V curve. The researchers have measured the J-V curve (seen from Fig.5c) using the optimized perovskite composition we have mentioned above and MACl/MAH2PO2 as additives, which shows that the solar cells can reach to a high PCE of 25.4% with V_{oc} of 1.80 V, J_{sc} of 17.8 mA/cm^2 , and FF of 79.4%, which can prove that the additives can continuously improve the photovoltaic performance of the tandem devices. Besides, they measure the external quantum efficiency (as illustrated in Fig.5d) at the absorption edge of the perovskite top cells from $\approx 300\text{nm}$ to 1200nm , indicating the reflection losses and parasitic losses. Besides, they find that the V_{oc} deficit of 0.49 V for a 1.64eV bandgap perovskite is small compared with other reported perovskite solar cells, which prove that 1.64eV bandgap is a wise choice. However, this bandgap performs the highest efficiency rather than the lowest V_{oc} deficit. Therefore, there is still a lot of room for improvement while base on other similar architectures.

For another research, the outstanding contribution is that they consider the impact of the environment on the performance of perovskite/silicon tandem solar cells, and provide suitable bandgap upon the research [7]. According to the structures mention above, the research team, J. Lehr et al., measure the Energy Yield (EY) on different area. Based on the analysis of the research, they calculate the optimum tilt angle in Daggett (California) and Portland (Oregon) as depicted in Figs. 6c and 6d, respectively. The two sub-figures show that the bifacial pero/c-Si 4T structure has the highest EY with the bandgap between 1.55eV to 1.72eV. The bandgap of PVK has decreased with the increase of albedo (seen from Figs. 6a, b). According to the evaluations, they can achieve relatively enhancement for EY 24–38%. All in all, the optimal bandgap of metal-halide perovskites gradually shifts with RA, which points out the importance of choosing bandgap appropriately.

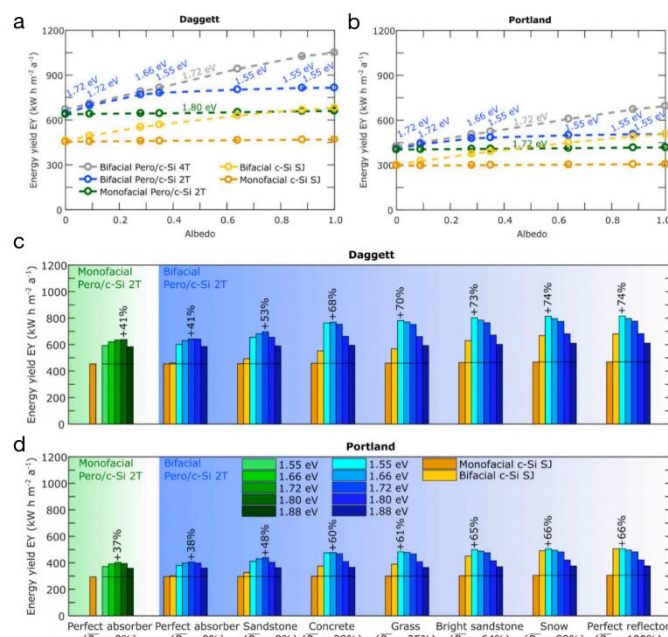


Figure 6. The performances of Ref. [7]

The research team of Hou et al. evaluates the J-V characteristics curve and PCE, EQE performance [8]. For the structure they have designed, measuring EQE for the flat (Fig.7c) and textured (seen in Fig. 7d) devices from =320nm to 1200nm, the certified 19.3 mA/cm^2 value is among the highest values for a single-pass textured device with 1.68eV bandgap perovskites. They find that single-junction devices required a thicker absorber to capture more photons near the band edge comparing with opaque devices. And with time going by, the top cell can absorb more photons, thus the upper limits of efficiency can increase. They show low hysteresis as exhibited in Fig. 7a and high reproducibility shown in Fig. 7b.

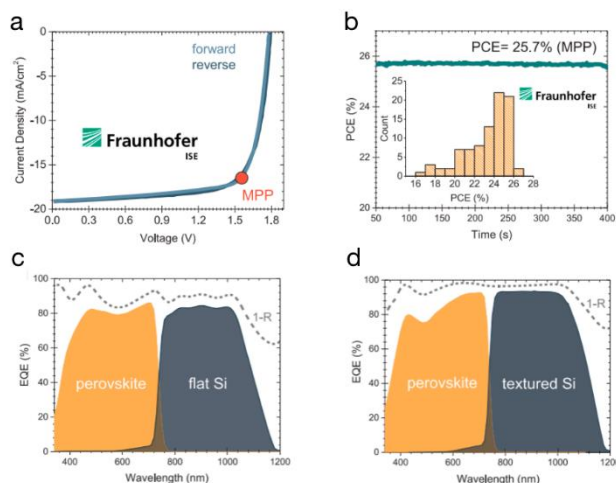


Figure 7. The performances of Ref. [8]

Al-Ashouri et al. invent a structure having a relatively high efficiency reaching to 29.15% [9]. As for the J-V curve illustrated in Fig. 8a, we can see that V_{oc} reach to 1.90V and the cell had a PCE of 29.01%, surpassing any other monolithic 4T tandem solar cell. Figure 8b shows its EQE and reflection, where the current densities J_{ph} in the perovskite are 19.41 mA cm^{-2} and in silicon subcells are 20.18 mA cm^{-2} .

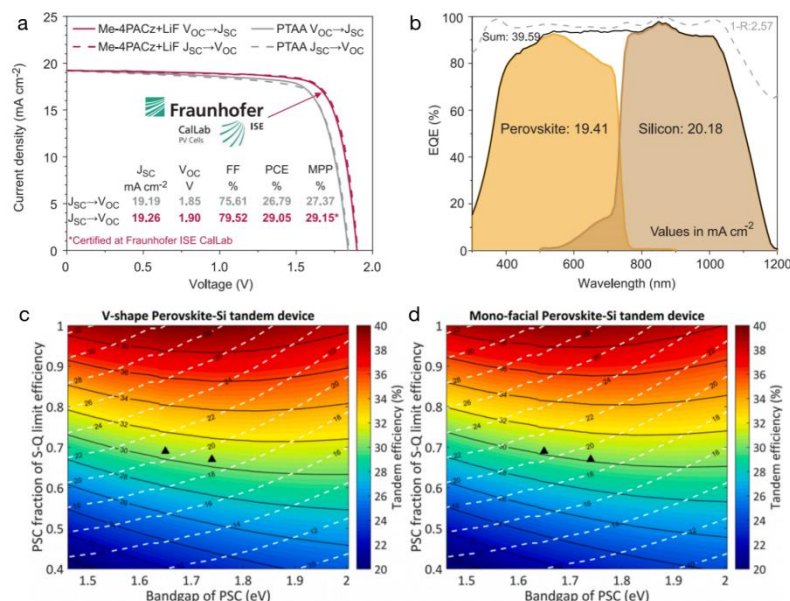


Figure 8. The performances of Ref. [9] (upper panel) and Ref. [10] (lower panel).

Zheng et al. also investigate the performances generally basing on the calculating of ideal efficiency through 4T tandem device [10]. In terms of the PSC model for FDTD simulation, the research team calculate efficiencies of 23%. The configuration is presented in Fig. 8c (V-shaped) and Fig. 8d (mono-facial). Table 1 shows the maximum possible efficiencies of 4T tandem devices pairing a HIT SSC and record PSCs with different bandgaps. The research paper also considers the impact of the PVK bandgap and thickness of the PVK layer, the thickness of the TCO layer, and the thickness of the Spiro-OMeTAD layer.

Table 1. Maximum possible efficiencies of 4-T tandem devices pairing a HIT SSC and record PSCs with different band-gaps.

PSC	E _g (eV)	Efficiency(%)	C	Tandem efficiency
1	1.65	20.7	0.69	30.26% (30.59% with half amount of SSC)
2	1.74	19.1	0.67	30.15% (30.53% with half amount of SSC)

4. Limitations and Future prospects

Perovskite solar cell is a brand-new topic which has become popular contemporarily, many researches have been done on inventing new structures and new materials. However, there are several difficulties that hindering the development of this field:

Perovskite and some other materials are easy to degrade, which can not ensure to work for a long time out of the lab. In addition to considering the perovskite active layer itself, we should pay attention to the design of other functional layers and the packaging technology of devices. The paper mentioned above all test the properties under some extreme conditions (e.g., high temperature, high humidity) to ensure the solar cells can tackle with different weather conditions and extend service life while using. Researchers should guarantee their solar cells can achieve commercialization.

High conversion rate is the goal that pursued by every research about solar cells. The efficiency was only about 3.8% when the first-time perovskite using in solar cells, which and now has reached to 30% for the efficiency of perovskite/silicon tandem solar cells. Nevertheless, it is still not enough comparing to traditional solar cells like multijunction monolithic silicon cells, which efficiency almost reach to 50% in lab.

Another obstacle to the commercialization of perovskite solar cells is the high production cost. One needs to produce large areas of perovskite solar cells to meet demand. However, if the area is enlarged, the film process will change and there will be many defects. Its efficiency and stability will decline.

According to the analysis of the paper, we can consider the improvements from the aspects as follows.

Further reducing the V_{oc} deficit for the perovskite top cell and changing the concentration of halogen ions in perovskite deposit.

Reducing the parasitic absorption loss from the TCO electrode and charge-transport layers as well as replacing the materials in the silicon bottom cell with a better rear reflector to further reduce the near-infrared parasitic absorption.

Fully considering the conditions outdoors and changing the height of the battery from the ground (it may be affected by the reduction of albedo and irradiance due to the ground shadow)

Considering the reflection characteristics of PSC are usually not ideal because of the unnecessary reflections on the surface, interface, and parasitic absorption in different layers. In this case, one can analyze the impact of the specific material and structure of PSC on the reflection characteristics, evaluate the performance of actual V-shaped series devices, and point out the selection and optimization direction of PSC.

5. Conclusions

In summary, this paper discusses the recent progress as well as the state-of-art applications for perovskite/silicon tandem solar cell, introducing its background and research meaning. Then, we discuss 6 important research papers in recent 3 years, pointing out various structures or materials used in inventing perovskite/silicon tandem solar cells and their performances. Finally, the limitations about research nowadays are clarified and some new ideas and improvements suggestions are proposed. Perovskite/silicon tandem solar cells has a great application prospect. Different research teams are committed to improving the efficiency and stability of the solar cells from different perspectives. All these works contribute to the practical application in our daily lives. We can anticipate a future with the popularize of perovskite/silicon tandem solar cells. Overall, these results offer a guideline for the research of perovskite/silicon tandem solar cells in the future.

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