

The recent progress and state-of-art designs of Multi-junction Solar Cells

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Abstract. Multi-junction solar cell is of great significance for increasing energy utilization, reducing environmental pollution and improving social and economic benefits. This paper will focus on the methods to improve the conversion efficiency of multiple solar cells based on information retrieval and literature analysis. Specifically, some of the significance milestones of the state-of-art scenarios will be briefly introduced in the field of multi-junction solar cells primarily. Afterwards, two well-performances state-of-art scenarios will be listed and discussed. The most popular methods to improve the conversion efficiency of multi-cell solar cells are compared and analyzed. Besides, some of the current limitations of multi-cell solar cells are demonstrated and a certain prospect for its future development is proposed. These results shed light on better converting solar energy into electric energy needed by human beings.

Keywords: Multi-junction, Solar Cells, progress and design.

1. Introduction

Solar energy is a clean, renewable, inexhaustible type of energy and there is no waste or discharge to the environment. Contemporarily, photovoltaic panels are the primary device for converting sunlight into electricity. Multi-junction solar cells are of increasing interest in a variety of applications to reduce material costs and increase the efficiency and utilization of solar energy [1, 2]. To date, scholars have conducted many studies for the sake of improving the power conversion efficiency (PCE), but the production in terms of solution-based methods remain an unsolved issue. McMeekin et al. proposed a solution to deal with the task with fully solution-processed absorber, transport, and composite layers for solar cells [3].

In addition to the above method, an in-depth analysis shows the path to improve the efficiency of InGaP-GaAs-InGaAs on Ge substrate solar PVC by incorporating an ultra-thin graphene IML layer. The proposed device is characterized by a low layer resistance, which will result in effective adhesion to the charge carriers. The interface between the IML and the photoactive layer is played an important role in device performance. The adjustable graphene work function (3 eV to 5.5 eV) offers adjustment to different energy levels. The high optical transparency of the graphene interlayer (>80% at 550 nm) allows to collect the maximum number of photons from incident sunlight compared to conductive metal thin films [4].

This article will first briefly introduce the basic structure of multi-junction solar cells and some related knowledge. Afterwards, two methods to improve the conversion efficiency of multi-junction solar cells will be discussed detailly, one is to install anti reflective film [5] while the other is to improve the conversion efficiency by connecting multiple batteries in series. Subsequently, the characteristics of these two methods will be compared to analyze the pros and cons of each method. Then, the limitations of state-of-art multi-junction solar cells and some prospects for future applications will be demonstrated. Eventually, a brief summary is given in Sec. 6.

2. The basic fundamental of Multi-junction solar cells

In general, the multi-junction architecture can be separated to multiple sub-cells to split the solar spectrum and reduce heat losses [6]. Figure 1 exhibits sketch of an InGaP/(In)GaAs/Ge triple junction solar cell, where the compositions of it are marked [7].

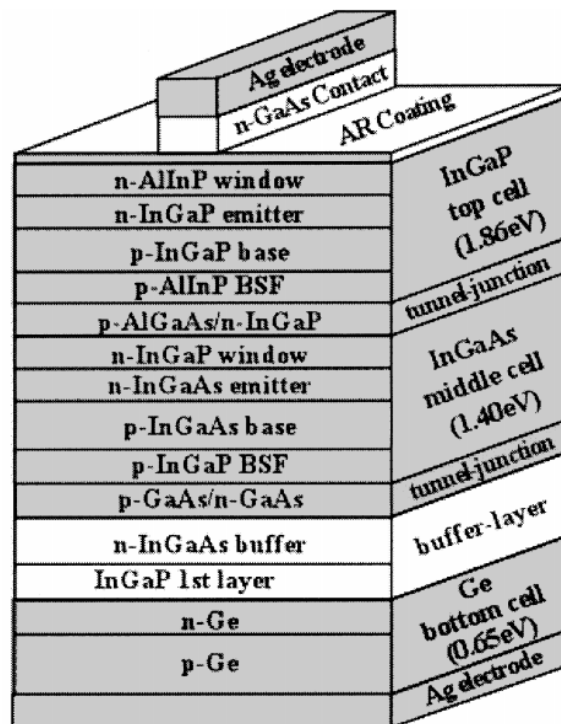


Figure 1. Structure of a triple-junction cell and some methods for improving efficiency [7].

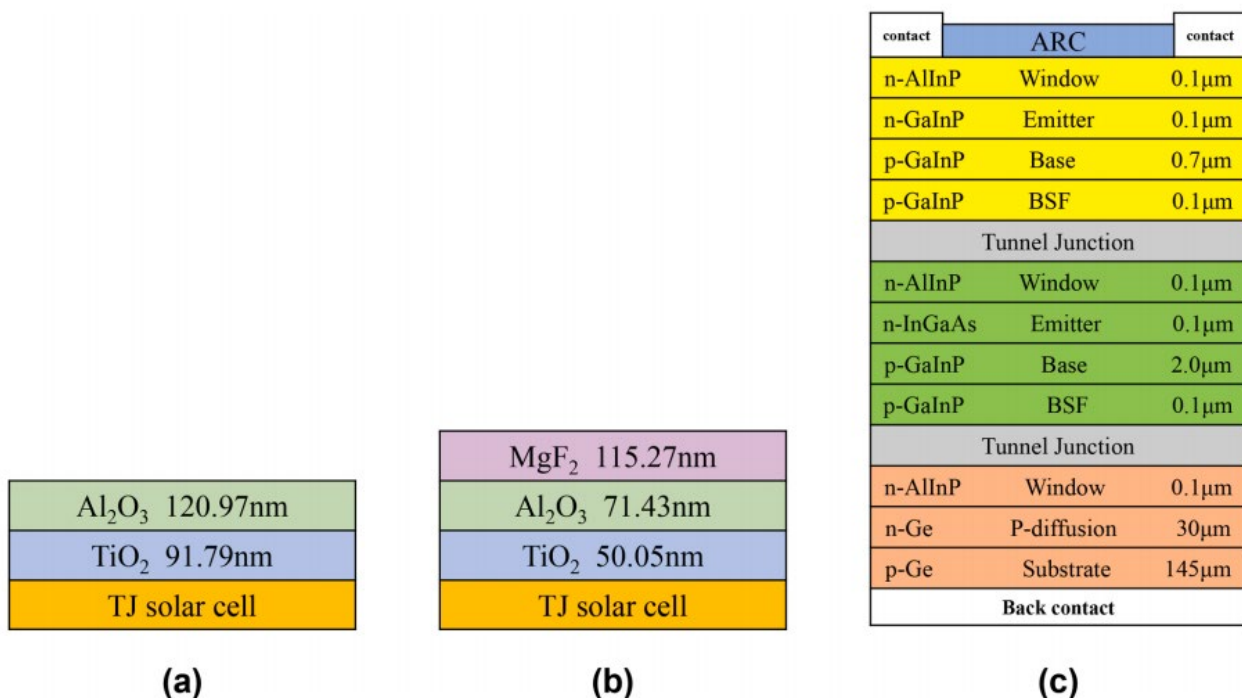


Figure 2. Coating Structure of DLAR (a), TLAR (b) and lattice-matched GaInP/InGaAs/Ge TJ solar cell (c) [8].

3. The performances for different designs

3.1 Multilayer antireflection coating

According to previous literatures, optical losses can be effectively reduced and solar cell performance improved by using multilayer AR coatings with graded-index materials and quarter-

wave ($\lambda/4$) thicknesses. Different fabrication methods have been proposed to prepare these coatings, e.g., electron beam evaporation, magnetron sputtering, sol-gel and atomic layer deposition (ALD), which has achieved remarkable performances. Specifically, $\text{SiO}_2/\text{Ta}_2\text{O}_5$ and $\text{SiO}_2/\text{TiO}_2$ DLAR coatings increase the efficiency of GaInP/GaAs/Ge TJ solar cells by 19% and 31.8%, respectively [8]. Although DLAR coatings have achieved considerable antireflection effects, their broadband antireflection capabilities can still be enhanced. In addition, the three-layer (TL) AR coating is able to substantially weaken the reflectivity in some region and increase the absorption ability of each sub-cell. However, to date, there are few reports on TLAR coatings applied to high-efficiency multijunction solar cells [8]. Nevertheless, the performance of $\text{TiO}_2/\text{Al}_2\text{O}_3/\text{MgF}_2$ TLAR coatings for GaInP/InGaAs/Ge TJ solar cells was quantitatively investigated with and without AR coatings. The optical and electrical properties of solar cells, the effect of TLAR coating on reducing the optical loss of TJ solar cells was investigated, where the numerical calculations tally well with the agreement experimental observations. With this in mind, it denotes that the gradient index TLAR coating has excellent antireflection performance in the broadband region. In other words, it means that the TLAR coating is more appropriate for high-efficiency multi-junction solar cells than the DLAR coating. Figure 2 depicts the structures of DLAR-coated, TLAR-coated and lattice-matched GaInP/InGaAs/Ge TJ solar cells [8].

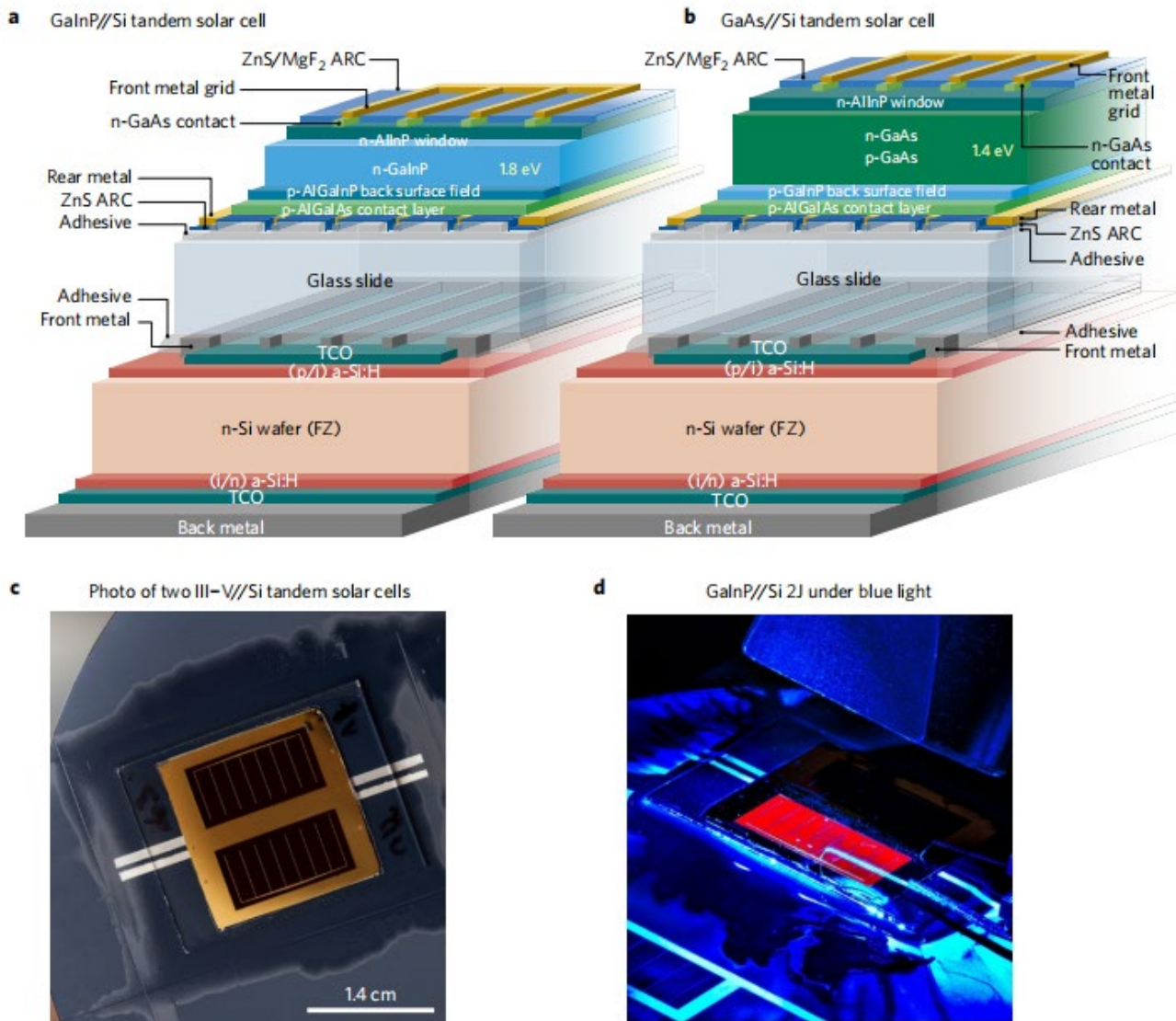


Figure 3. The sketch diagram for the III–V//Si tandem solar cells (a, b), snapshots of the f dual-junction solar cells (c) a well as the GaInP//Si tandem solar cell under illumination with blue light (d) [9].

3.2 Design of the III–V//Si tandem solar cells.

Another method will mention to improve the conversion efficiency of multi-junction solar cells is to connect multiple multi-junction solar cells in series. In such a configuration, it overcomes the efficiency limitations of a single multi-junction solar cell. In fact, the highest solar-to-electrical conversion efficiencies have been achieved with III-V semiconductor multijunction solar cells, allowing efficiencies as high as 38.8% in the case of a solar cell and as high as 46% in concentrated sunlight. Nevertheless, the current high cost of III-V solar cells has limited the commercial usage in the state-of-art applications. To use multijunction architectures for single-sun terrestrial photovoltaics, tandem cell devices with silicon bottom cells appear on the roadmaps of many silicon photovoltaic companies. A key challenge in the development of such cells is to demonstrate that a device containing multiple tandem multijunction solar cells will perform better than a single one. Two pictures a and b in Figure 3 show us two different tandem solar cell designs respectively, and c and d show the physical pictures of tandem solar cells in different environments [9].

4. Comparison of multi-junction solar cells with different design

As for the case on anti-reflection coatings, the Essential Macleod Program and Crosslight Apsys software is used to study TiO₂/Al₂O₃/MgF₂ broadband index distributed TLAR coatings for GaInP/InGaAs/Ge lattice matched TJ solar cells, respectively. This software performs analytical and numerical solutions of AR. According to the analysis, the TLAR coating has a better antireflection effect than the TiO₂/Al₂O₃ DLAR coating in the wavelength range of 300 to 1800 nm, reducing the average reflectance of TJ solar cells by 25.57% to 3.37%. In addition, the TLAR coating grown by electron beam deposition has excellent omnidirectional antireflection properties, which have been improved by 29.44% and 28.98%, respectively. The results of external quantum efficiency spectroscopy show that the TLAR structure leads to an increase in the current density of the GaInP and InGaAs subcells. The TLAR coating outperformed the DLAR coating in reducing the light loss of high efficiency TJ solar cells [8].

In the tandem cell design, the conversion efficiency of the top GaInP cell is good. The 1.81eV GaInP top cell has a back-heterojunction design similar to the bibliography and is transparent to visible light near the GaInP bandgap. With a fill factor (FF) of 87.0% and an ERE of 5%, the single sun efficiency is 19.95%. This is only 1.4% lower than LG's record GaInP cell with a single metal back reflector of 21.4%. It should be noted that the good news is the high average reflectance from the middle layer. The SHJ cell at the bottom of the Si device achieves an efficiency of 12.5%, and the cumulative efficiency of the 2J cell is (32.5 ± 0.3) %. This is significantly higher than the 29.8% previously reported for a similar GaInP/Si 2J cell design. It is also not difficult to find that this tandem cell structure can also be used to further improve the conversion efficiency by adding the anti-reflection coating method as mentioned before. Then, Table. 1 is given to summarize the comparison of the two methods [9].

To sum up, it is not difficult to witness that the increase of the conversion efficiency of multi-junction solar cells by adding an anti-reflection film will be higher than that of a simple series connection. Nevertheless, the series connection is indeed a simpler and easier way, and it can also be compatible with many others to improve the conversion efficiency.

Table. 1. Comparison of methods to improve battery efficiency

Comparison	Efficiency improvement	Difficulty and cost of implementation
Multilayer antireflection coating	about 29% [8]	More difficult and expensive

Design of the III–V//Si tandem
solar cells.

about 13% [9]

Easier and cheaper

5. Limitation and future prospects

In general, Multi-cell solar cells are also facing plenty of limitations. To be specific, since the current manufacturing technology is not mature enough, a large number of materials have not been able to find good and cheaper alternatives, resulting in a relatively high overall construction cost. Similarly, the application of multi-cell solar cells is not very wide, hence the overall market price has not yet normalized. It is believed that with the improvement of technology and the expansion of construction scale in the future, the overall price should be able to reduce, which is suitable for the public in commercial usage. In addition, the heat dissipation of the device is also one of the biggest drawbacks of multi-cell solar cells. It is undeniable that when the sunlight touches the battery itself, a large amount of heat can be generated. Most of the energy consumed in the process of energy conversion is also dissipated in the form of heat energy, which leads to the inevitable heating of the entire multi-junction solar cell device. On this basis, the increase in resistance will result in the increase of the temperature. The efficiency of converting light energy into electrical energy is further reduced. Therefore, how to control the temperature is also one of the key points to improve the conversion efficiency of multi-section solar energy. The current heat dissipation technology has not been able to solve this problem well, and it may be necessary to change the heat dissipation in the future. This problem can be better solved by replacing the material with better heat dissipation [10]. Finally, there is the issue of material replacement. On account of the concentration of high-intensity light, the receiver plate of multi-junction solar cells also needs to choose materials with better tolerance, so that more light can be absorbed by the cell itself.

In the future, multi-junction solar cells will have a wide range of applications. Owing to its excellent energy conversion performance and no environmental pollution, it may become one of the main ways for human beings to utilize solar energy in the future [11]. In life, it will replace old-fashioned fuel power generation and other inefficient and polluting power generation methods. Moreover, different from water conservancy and wind power generation, its conversion efficiency will be higher. Besides, it will not be affected by common natural factors because sunlight will be stably delivered to it. In addition to light energy, multi-junction solar cells will also play an irreplaceable role when humans explore the space field in the future. Since it is difficult to obtain other forms of energy supply in space, sunlight (or other strong intensity photon fluxes with wide bandwidth) has almost become the only. Therefore, the level of multi-cell solar cell technology will directly determine the difficulty of our exploration in space, which will also become one of the most solid backings for mankind in the universe.

6. Conclusions

In summary, this paper discusses multi-junction solar cells from the perspective of energy conversion efficiency improvements. First of all, according to enumerating some classic studies of predecessors, improving the conversion efficiency of multi-junction solar cells is one of the more popular research issues contemporaries. Afterward, this paper focuses on describing two methods to improve the conversion efficiency of multi-junction solar cells. They are adding anti-reflection film to the battery and connecting multiple batteries in series to improve the conversion efficiency of the battery. For comparison, these two methods have their own advantages and disadvantages. Adding anti-reflection film can greatly improve the conversion efficiency of the battery. Improving the conversion efficiency will also lead to more expensive costs. Simply connecting multiple batteries in series may not significantly improve the efficiency, but it is more convenient and cheaper to implement.

Based on these characteristics, one can choose specific ones according to different construction needs. In the future, the application of multi-junction solar cells will be applied more and more extensively. With the improvement of technology and the discovery of new materials, more approaches will be proposed to improve its efficiency. Solar cells will also play a more important role in future energy utilization. Overall, these results offer a guideline for some reference standards for choosing the scheme to improve the conversion efficiency of multi-junction solar cells, and also provides some directions and goals for further improvements of this field.

References

- [1] Green M, Dunlop E, Hohl-Ebinger J, et al. Solar cell efficiency tables (version 57) [J]. *Progress in photovoltaics: research and applications*, 2021, 29(1): 3-15.
- [2] Zhang W, Hu K, Tu J, et al. Broadband graded refractive index TiO₂/Al₂O₃/MgF₂ multilayer antireflection coating for high efficiency multi-junction solar cell[J]. *Solar Energy*, 2021, 217: 271-279.
- [3] McMeekin D P, Mahesh S, Noel N K, et al. Solution-processed all-perovskite multi-junction solar cells[J]. *Joule*, 2019, 3(2): 387-401.
- [4] Chawla R, Singhal P, Garg A K. Design and analysis of multi junction solar photovoltaic cell with graphene as an intermediate layer[J]. *Journal of nanoscience and nanotechnology*, 2020, 20(6): 3693-3702.
- [5] Oh G, Kim Y, Lee S J, et al. Broadband antireflective coatings for high efficiency InGaP/GaAs/InGaAsP/InGaAs multi-junction solar cells[J]. *Solar Energy Materials and Solar Cells*, 2020, 207: 110359.
- [6] Valdivia C E, Hinzer K. Segmented multi-junction solar cells: A new opportunity for cell design & optimization[C]. 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC). IEEE, 2019: 0045-0048.
- [7] Takamoto T, Kaneiwa M, Imaizumi M, et al. InGaP/GaAs-based multijunction solar cells[J]. *Progress in Photovoltaics: Research and Applications*, 2005, 13(6): 495-511.
- [8] Zhang W, Hu K, Tu J, et al. Broadband graded refractive index TiO₂/Al₂O₃/MgF₂ multilayer antireflection coating for high efficiency multi-junction solar cell[J]. *Solar Energy*, 2021, 217: 271-279.
- [9] Essig S, Allebé C, Remo T, et al. Raising the one-sun conversion efficiency of III–V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions[J]. *Nature Energy*, 2017, 2(9): 1-9.
- [10] Wang Z, Zhang H, Dou B, et al. Theoretical and experimental evaluation on the electrical properties of multi-junction solar cells in a reflective concentration photovoltaic system[J]. *Energy Reports*, 2022, 8: 820-831.
- [11] Kwak J I, Nam S H, Kim L, et al. Potential environmental risk of solar cells: Current knowledge and future challenges[J]. *Journal of Hazardous Materials*, 2020, 392: 122297.