

Perovskite-Silicon Tandem Solar Cells for High Efficiency Photovoltaics

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Abstract. Over the past few decades, solar cell research has undergone a shift from silicon to richer materials and richer structures. The increase in Power Conversion Efficiency (PCE) and industrial application is the most concerning issue. Perovskite-Silicon Tandem Solar cells (PSTSC) have emerged as a promising pathway to surpass the Shockley-Queisser efficiency limit of single-junction photovoltaics. The highest PCE of PSTSC reported from NREL is 34.85%, done by LONGi, Xi'an, China. This review comprehensively analyzes recent advancements in device architectures, interfacial engineering, and stability optimization, while discussing challenges for commercialization and making the discussion of the general view about the future development of the PSTSC. Recent progress in device architectures, interfacial engineering, and stability optimization has significantly enhanced their performance and reliability. Key innovations—such as triple-halide perovskite with piperazinium iodide modification, ultrathin amorphous IZO interlayers, and nanotextured interfaces—have addressed critical challenges in charge transport, optical losses, and recombination. As PSTSCs continue to evolve, their integration into existing silicon PV manufacturing lines could accelerate the transition toward next-generation, high-efficiency solar technologies, ultimately contributing to a sustainable and decarbonized energy future.

Keywords: Perovskite, Solar cell, Power Conversion Efficiency, Interface engineer

1. Introduction

The increasing global energy demand and the urgent need to mitigate climate change have driven the exploration of carbon-free energy sources. Photovoltaic (PV) solar cells are a key technology for achieving a decarbonized economy, as solar energy is abundant, inexhaustible, and environmentally benign. While the cost of PV modules has significantly decreased over the past decade, non-module costs—such as balance-of-system (BOS) expenses—remain area-dependent rather than power-dependent. Therefore, improving the PCE of solar cells is essential to further reduce the levelized cost of electricity (LCOE). Thus, the tandem solar cells enter the public's view. Tandem solar cells (TSC), which stack multiple semiconductor layers with complementary bandgaps, offer a promising solution to surpass the Shockley–Queisser (S–Q) efficiency limit (~33.7%) for single-junction solar cells (e.g., Si) [1]. Theoretical PCE for two-junction (2J), three-junction (3J), and infinite-junction TSCs under standard illumination (AM 1.5G) are 46%, 50%, and 86.8% (under concentrated sunlight), respectively [2]. Perovskite materials (ABX_3 , where $A=MA^+$, FA^+ , Cs^+ ; $B=Pb^{2+}$, Sn^{2+} ; $X=$

I, Br, Cl) exhibit exceptional optoelectronic properties, including high absorption coefficients, long carrier diffusion lengths, and tunable bandgaps (1.17-3.10eV). These characteristics mean that they are ideal for the material in the tandem applications, particularly as top cells paired with silicon (Eg). Except for those characteristics, perovskite also has an advantage in manufacturing. Unlike the III-V/Si tandems which need rigid lattice-matching, the PSTSC can tolerate the structural mismatches via Goldschmidt tolerance factor (t), enabling solution-processed fabrication at <200°C—critical for preserving silicon heterojunction (SHJ) integrity. The Goldschmidt tolerance factor is defined as follows [3]:

$$t = \frac{r_A + r_B}{\sqrt{2}(r_B + r_X)} \quad (1)$$

The record PCE of crystalline silicon cells is 27.3% [4], approaching the theoretical limit of 29.5% [5]. The record PCE of PSTSC is 34.85% [4]; obviously, it is a promising research direction. Although the PSTSC has lots of advantages, it still has problems to be solved. How to improve the PCE and the stability; the challenges in commercialization, and the future of the PSTSC. This review is focusing on the recent research about those issues and making a summary.

2. Device architecture

There are typically two configurations in TSCs: mechanically integrated four-terminal (4T) and monolithically integrated two-terminal (2T) configurations [2]. For two-terminal tandem solar cells (2T TSCs), fewer power electronic components (e.g., inverters and wiring) are required. Additionally, the 2T configuration offers advantages in terms of installation and PV system integration due to its potentially lighter weight and lower cost. In contrast, four-terminal tandem solar cells (4T TSCs) feature optically coupled subcells that can be fabricated independently. This eliminates constraints imposed by other subcells regarding processing methods, parameters (such as temperature and surface texture), and cell polarities, allowing each subcell to individually optimize its PCE. Nevertheless, higher optical losses are predicted owing to parasitic absorption and reflection occurring at TCO layers and their interfaces. The complexity of fabrication and assembly, as well as the higher material cost due to the multiple substrates, usually results in higher overall cost. Therefore, 4T TSCs have so far not been found in any industrial applications [2].

3. Technical approach

3.1. Triple-halide perovskite with piperazinium iodide in-terface modification

Pivotal findings of the work by Silvia Mariotti's team, reported in Science in 2023, showcase markedly improved efficiency in perovskite solar cells through innovative interfacial engineering of these materials. Employing a process known as surface passivation using either polyimide (PI) or lithium fluoride (LiF), this technique effectively enhanced not only the open-circuit voltage of the perovskite solar cell but also produced an improved quasi-Fermi level splitting. Both measures indicated better charge separation and lower voltage losses. Adding a C60-based ETL into the system with PI treatments yielded large synergies between the organic passivant, and fullerenes, leading to record-high device performance. These superior results stemmed from two basic phenomena: firstly, dipole-induced interfacial modification, which optimizes energy-level alignments across key junctions; secondly, enhancement of the electronic coupling that allows smoother charge transfers. Finally, two properties limit perovskite devices conventionally: (1)

deficiency in charge selective contacts with a near-ideal band alignment between leads and active layers leading to a low energy barrier for carrier extraction; (2) High nonradiative recombinations due to residual trap states, both weakly- and strongly-bound excitons induced by residual carrier traps, as well as large interface defect densities. Last, strong reductions in the hole collection efficiencies were related to weak hole diffusive rates. Combining the chemical-level molecularly thin-layer surface treatment with tailored material choice is the salient feature of this work and illustrates the advantages of this combination. Not only does it demonstrate a new record efficiency of device performance for perovskite optoelectronic devices, but, more fundamentally, it also provides insight into the design rules of constructing robust and efficient optoelectronic devices from a band engineering viewpoint.

This can produce an impressive VOC of 1.28V (91.5% of the detail balance limit) in p-i-n single junctions and up to 2.00 V in tandems and, most notably, certified power conversion efficiencies as high as 32.5%, which was achieved when using top-quality perovskites combined with PI surface treatments. The tandem devices thus obtained presented decent performance figures. In long-term tests they kept nearly 80% of their original efficiency value of 28.2% after 347 hours, then nearly 75.7% after 478 hours of MPPT. However, it is stated that subcell-specific values obtained from these tandem cells give a pseudo-PCE larger than 33.8% (including a possible further raise up to ~34.3% by improving the double-sided texturing process to reach a relative enhancement of 2.5% upon an estimated increase of JSC of 0.5 mA/cm²) [6].

3.2. Ultrathin (5 nm) amorphous Indium Zinc Oxide (IZO) as the interconnecting TCO layer

In a groundbreaking 2023 study published in Nature, Erkan Aydin and colleagues demonstrated an innovative electrode architecture employing ultrathin transparent conductive oxides (TCO)—specifically 5nm and 20 nm-thick IZO combined with the 2PACz interfacial modification to simultaneously improve the electrical and optical properties of PSCs. Properly varying the TCO layer composition and thickness can precisely control the sheet resistance (R_{sheet}) while ensuring high transmission; as well as control the phase variations due to stacking by utilizing 5 nm layers to minimize optical losses and 20 nm layers to achieve efficient lateral charge transport (LCT). The usage of the 2PACz work-function modifier greatly improves the optimization of electronic/electric properties of the HIA/EVA layer by tuning band alignment, hence greatly reducing recombination losses and increasing charge extraction at critical interfaces. The dual modification concept shows that optimizing materials only with nanoscale thickness or an appropriate molecular interface cannot completely resolve the basic issues of multi-level gain-impaired energy alignment, lower efficiency due to HFDIR, and the conductive thin film needing to be thick enough to guarantee the performance of vertical LCT in conventional PSC architectures; rather, they complement each other well when used together. For instance, such strategic effort has managed to accomplish very large gains from four important loss factors that the photons were impacted by at conventional PSCs, yet perform an efficient VDT operation using extremely thin materials.

This material offers two key advantages over conventional crystalline TCO: exceptional surface potential homogeneity due to its grain-boundary-free structure, and increased density of SAM anchoring sites. When combined with optical enhancements from equally thin IZO rear electrodes and optimized front contact stacks, this approach yielded an independently certified PCE of 32.5%. Among the highest published values for perovskite/silicon tandem cells. The observed relationship of 2PACz SAM coverage with degradation rates suggests that maintaining surface potentials uniform can have a positive effect on stabilization of these devices. Previous work has demonstrated

a relationship between work-function changes and halide migrations within perovskite layers. The uniform surfaces generated by using amorphous IZO demonstrate high operational stability [7].

3.3. Architecture incorporating periodic nanotextured in- terfaces

A groundbreaking 2022 study published in Nature Nanotechnology by Philipp Tockhorn and colleagues demonstrated significant advancements in PSTSC through innovative optical design and nanotexture optimization. Through these studies, we can optimize the thickness of both RDBL and TCO layers. It is able to minimize the optical loss inside the silicon bottom cell while maximizing light use in each structure in the tandem stack. Sophisticated optical engineering is utilized, with 2 primary operating principles considered: ① enhancement of the light-trapping effect due to nano-texturing, combined with the control of electrical loss through optimization of layer thickness. ② The optimization process was able to improve the VOC values by 15 mV, mainly because of the improved optoelectronic properties of the perovskite top cell, as well as reducing the optical reflection losses compared to a planar reference device setup. What's more, even with nanotextured architecture, good process tolerance performance was obtained, which resulted from a significant decrease in its sensitivity to variation of optimal layer thicknesses during fabrication. The result was highlighted by a huge 45% increase in manufacturing yield from 50% to 95%, indicating the importance of ramping up process control at the nanoscale for better product uniformity and consistency in tandem architectures. This demonstrates the benefit of considering both optical and electrical factors when tuning and engineering nanostructures at the interfaces in tandem structures to maximize the overall device efficiency of converting photons to electrons while minimizing carrier recombination loss. The work reveals the ability of optimizing interfaces in tandem cells to solve technological scalability and manufacturability issues in solar technology development. Employing an optical engineering rear reflector, which utilizes a dielectric buffer layer to prevent parasitic absorption, we aim to eliminate near-infrared spectral absorption. All the improved materials of all the combinations succeed in achieving 29.8% power conversion efficiency of tandem solar cells [8].

3.4. Identification and mitigation in nonradiative recombination losses occurring at the interfaces of pstsc

In 2023, the work of Xin Yu Chin and colleagues reported in Science marks another milestone achievement in PERSC aimed at addressing the interfaces recombination losses in industrial-grade microtextured polysilicon substrates in a systematic fashion, which develops a perovskite wafer in which parallel planar n-type thin film transistors are mounted. They systematically tailored micrometric-textured c-Si wafers with good optical matching to industry-standard microtextured silicon (M-Si), using Me-4PACz to reliably passivate the perovskite/HTL heterojunction, decreasing Voc loss, together with FBPAc doping during perovskite deposition, to enhance the quality of the perovskite/C60 heterojunction, and improve perovskite micropatterning morphology and crystal size via fast formation of subsequent crystallization-induced geometric barriers and forming artificially fluctuating superstructures. Utilizing advanced atomic spectroscopy, such as SIMS and XPS to study the underlying charge transport and doping profile, they found that the coordination between phosphonic acid in FBPAc and Pb-containing defects on perovskite generated tunnelling pathways, thereby being able to provide deeper understanding on its passivation mechanism. Its success lies in the following three technological breakthroughs: preserving the optical characteristics of standard industrial c-Si micrometric textures for light trapping; developing a hybrid two-step deposition

method that can uniformly deposit high-quality 1 μ m-thick perovskite absorbers over these textures and adopting phosphonic acid-based passivation over both interfaces of the perovskite layer. The resultant tandem, independently certified at a power conversion efficiency of 31.25%, established a new barometer to measure textured-silicon-based tandems. More importantly, this work illustrates an optimal path to transform existing silicon PV lines by upgrading industry-standard c-Si M-Si cells with micron patterning into >30% efficient tandem devices through a combination of interface modifications and a well-engineered deposition process without interrupting/misaligning silicon photovoltaic production technology [9].

4. Challenges in commercialization

The development of perovskite/silicon tandem solar cells faces three critical stability and reliability challenges that must be addressed for commercial viability. First and foremost, the establishment of comprehensive stability testing protocols and industry standards (such as IEC and ISO) is essential, as standardized accelerated stress tests are urgently needed to accurately predict long-term performance degradation and build confidence among potential investors. Second, significant material and structural challenges persist, including the inherent brittleness of perovskite films, thermal expansion coefficient mismatches with silicon substrates, and phase segregation issues in wide-bandgap perovskite compositions - all of which contribute to performance degradation over time. At the molecular level, encapsulation difficulties, reverse bias effects under partial shading conditions, and interfacial delamination risks demand thorough reliability investigations. Third, interface and architectural limitations present substantial hurdles: while heterojunction (HJT) silicon bottom cells impose strict temperature constraints on perovskite processing, tunnel oxide-passivated contact (TOPCon) designs offer greater thermal budget flexibility. Although 4-terminal (4-T) tandem configurations could potentially allow for easier perovskite module replacement, their economic feasibility requires careful cost-benefit analysis considering balance-of-system expenses [10]. These multifaceted challenges underscore the need for coordinated research efforts across materials science, device engineering, and reliability testing to develop commercially viable perovskite/silicon tandem photovoltaic technologies.

5. Future prospect

PSTSC research should prioritize optimizing the PCE of PSTSC via interface engineering and other advanced ways, and improving the stability of PSTSC. Machine learning (ML) is beneficial in speeding up the finding of the best material composition and presenting the physics mechanism. For example, ML models can mine big data in published literature to forecast possible exciting perovskite compositions as well as optimize device structure, including both common (n-i-p) and inverted (p-i-n). In addition, ML models can recognize key properties of materials affecting efficiency like bandgap, carrier mobility, and crystallinity, etc., facilitating targeted experimenter verification. Furthermore, machine-learning-guided strategy helps people better comprehend complex phenomena, such as charge transport and recombination that allow for designing more stable tandem solar cells. With ML consolidating experimental synthesis together, researchers can uniformly handle difficulties like interface defects and environmental corrosion problems so that high-efficiency PSCs and PSC/Si tandems would quickly enter commercial markets [11].

6. Conclusion

PSTSC represents a transformative advancement in photovoltaic technology, offering a viable pathway to surpass the Shockley-Queisser efficiency limit of single-junction solar cells. With a record power conversion efficiency (PCE) of 34.85% achieved by LONGi, PSTSCs demonstrate immense potential for high-performance, cost-effective solar energy conversion. Recent progress in device architectures, interfacial engineering, and stability optimization has significantly enhanced their performance and reliability. Key innovations such as triple-halide perovskite with piperazinium iodide modification, ultrathin amorphous IZO interlayers, and nanotextured interfaces—have addressed critical challenges in charge transport, optical losses, and recombination. Despite these advancements, several hurdles remain for commercialization, including long-term stability under operational conditions, material compatibility, and scalable manufacturing processes. Standardized testing protocols and improved encapsulation techniques are essential to ensure durability. Additionally, economic feasibility must be evaluated, particularly concerning balance-of-system costs and the trade-offs between two-terminal (2T) and four-terminal (4T) configurations. Future research should focus on further optimizing PCE through advanced interface engineering, defect passivation, and machine learning-guided material discovery. Enhancing stability via robust encapsulation and degradation-resistant materials will be crucial for real-world deployment. As PSTSCs continue to evolve, their integration into existing silicon PV manufacturing lines could accelerate the transition toward next-generation, high-efficiency solar technologies, ultimately contributing to a sustainable and decarbonized energy future.

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