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Enhancing efficiency in a-Si:H/μc-Si micromorph tandem solar cells through advanced light-trapping techniques using ARC, TRJ, and DBR

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Abstract

In this study, the performance of a-Si:H/μc-Si:H tandem solar cells was comprehensively assessed through two-dimensional numerical simulations. Our work involved optimizing the layer thicknesses and exploring advanced light-trapping techniques to enhance photogenerated current in both sub-cells. To reduce surface reflections on the top cell, we proposed a two-layer antireflection coating, composed of SiO_2/Si_3N_4. Additionally, we implemented a 1D photonic crystal as a broadband back reflector within the solar cell. In order to balance the current density between the sub-cells and prevent carrier accumulation at the interface, we introduced a tunnel recombination junction (TRJ). This TRJ consisted of n-μc-Si:H/p-μc-Si:H layers with a thickness of 10 nm. Under global AM 1.5G conditions, our proposed cell structure exhibited impressive electrical characteristics, including an open-circuit voltage of 1.38 V, a short-circuit current density of 12.51 mA/cm^2, and a fill factor of 80.82%. These attributes culminated in a remarkable total area conversion efficiency of 14%.

Keywords Micromorph solar cell, Tunnel recombination, Junction, Light trapping, a-Si:H

Introduction

Amorphous tandem solar cells have emerged as a pivotal technology in the pursuit of high-efficiency photovoltaic devices. These solar cells utilize a tandem structure, where multiple sub-cells with different band gaps are stacked in series to effectively harness a broader spectrum of solar radiation. Recent advancements have underscored the significance of band engineering and material optimization in enhancing the performance of these cells.

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Multi-junction structures in thin-film technology offer a practical solution to mitigate loss mechanisms and optimize solar spectrum utilization for enhanced photogenerated carrier collection (Madaka et al. 2021). One significant loss mechanism affecting solar cell performance is the thermalization effect (Fahr et al. 2010), which results from the mismatch between photon energy and the electronic bandgap (Eg) of the absorber material, leading to the conversion of photon energy into heat.

The simplest multi-junction structure consists of two sub-cells, with the top cell featuring a higher bandgap than the bottom cell. Consequently, photons with low energy ($h\upsilon < Eg$) that cannot be absorbed by the top layer are transmitted to the bottom cell for absorption.

Thin-film solar cells based on hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H) as absorber layers have gained prominence due to their non-toxicity, abundant raw materials, and cost-effective manufacturing (Fang et al. 2016). However, a-Si:H solar cells face two significant challenges. Firstly, they exhibit a short diffusion length of minority carriers within the absorber layer (Söderström et al. 2010). Secondly, they are susceptible to light-induced degradation caused by the Staebler-Wronski effect (Staebler, 1. L., & Wronski, C. R. 1977). While reducing the absorber layer's thickness can alleviate these issues, it can lead to lower efficiency due to reduced current generation. Consequently, the thickness of the a-Si:H absorber layer is typically limited to a few hundred nanometers.

To address these challenges and improve the efficiency of hydrogenated amorphous silicon solar cells, tandem "micromorph" cells have been developed (Kouider and Belfar 2020). Micromorph solar cells combine a-Si:H with a bandgap of ~ 1.8 eV as the top layer and μc-Si with a bandgap of ~ 1.1 eV as the bottom layer. The top cell, a-Si:H, plays a critical role in determining the total current density in micromorph tandem solar cells.

The primary goal to maximize efficiency in micromorph solar cells is to enhance current density, achievable by increasing the optical path length of incident light (Bai et al. 2014) and improving light absorption in intrinsic layers with specified thicknesses. Advanced light management techniques are essential for this purpose.

Amorphous silicon's high refractive index results in significant light reflection from the cell's surface. Using an antireflection coating (ARC) on the solar cell's surface can mitigate this issue. Experimental studies in 2011 demonstrated that AR/glass/transparent conducting oxide (TCO)/active layers can reduce reflectance by about 3% over the 350–1100-nm range at the air/glass interface, enhancing light absorption (Chang et al. 2011). Various ARC materials, such as ZnO:Al and SnO_2:F, have been simulated and measured (Bai et al. 2014), and novel double-layered antireflection coatings have been experimented with (Zhang et al. 2015).

Another method for enhancing light absorption involves inserting a high-reflectivity material on the backside of the cell, preventing light from escaping and reflecting it back into the cell. The impact of back reflectors on micromorph performance has been widely simulated and measured (Lai et al. 2011; Jovanov et al. 2013). Conventional back reflectors involve silver coating with ZnO (Hüpkes et al. 2008; Müller et al. 2004; Springer et al. 2004; Paetzold et al. 2010). One-dimensional photonic crystals (1DPCs) have been used as back reflectors in amorphous and microcrystalline thin-film silicon solar cells to increase absorption (Biswas and Zhou 2007; Soman and A., & Antony, A. 2018; Krc et al. 2009). A new concept of a modulated one-dimensional photonic-crystal (PC) structure has been introduced for thin-film solar cells (Fahr et al. 2009).

Carrier accumulation between the n-layer of a-Si:H and the p-layer of μc-Si can deteriorate cell performance (Krc et al. 2009). To enhance the recombination rate, a transparent, highly conductive layer is needed between the top and bottom cells. ZnO, as demonstrated in Kateb et al. (2017), acts as both a connector and a transparent oxide that efficiently transfers light to the bottom cell. An alternative solution is the tunnel recombination junction (TRJ), which can reduce carrier accumulation (Madaka et al. 2021; Bielawny et al. 2008). Moreover, the use of a three-dimensional photonic crystal (3D-PC) between the top and bottom cells in micromorph tandem solar cells has been reported (Moreno et al. 2023).

Numerous efforts have also been made to improve the efficiency of copper zinc tin sulfide (CZTS) solar cells. In 2023, the deposition of microcrystalline silicon (μc-Si:H) films produced from silane (SiH_4), hydrogen (H_2), and argon (Ar) mixtures using plasma-enhanced chemical vapor deposition (PECVD) at 200 °C was evaluated (Toniolo et al. 2023). Additionally, two alternative encapsulant polymers, thermoplastic polyurethane (TPU) and thermoplastic polyolefin (TPO) elastomer, were investigated for the packaging of perovskite/silicon tandems into minimodules in 2023, assessing their impact on tandem-module performance and stability through accelerated module stability tests (Vrijer et al. 2022). Furthermore, in 2022, the experimental results of numerous multijunction devices were presented, demonstrating the fundamental mechanisms behind observed phenomena using energy band diagrams obtained through electrical simulations in TCAD sentaurus, focusing on the influence of the thickness and design of the p-layer in the TRJ across different device architectures (Boulmrharj et al. 2022). In 2023, grid-connected photovoltaic systems were modeled based on short-term experimental data, and their performance was assessed over an extended period through various key performance indicators (Cao et al. 2021).

Cao et al. have provided theoretical insights into the high efficiency of triple-junction tandem solar cells through band engineering of antimony chalcogenides, demonstrating promising avenues for efficiency improvements (Cao et al. 2016). Further research by Cao et al. highlights the impact of nonuniform distribution in μc-$Si_{1-x}Ge_x$ on thin film and device performance, emphasizing the need for precise material control to optimize cell efficiency (Cao et al. 2020). The utilization of ultrathin microcrystalline hydrogenated Si/Ge alloys in tandem solar cells has shown potential for full-spectrum solar conversion, as discussed by Cao et al. This approach aims to maximize the absorption of different wavelengths, thereby boosting overall efficiency (Cao et al. 2013). Moreover, hydrogenated microcrystalline silicon germanium has been identified as an effective bottom sub-cell absorber in triple-junction solar cells, further supporting the feasibility of such advanced material systems (Kumar et al. 2023).

Addressing the infrared absorption capabilities of perovskite tandem solar cells, Kumar et al. have outlined both the research progress and the challenges, indicating significant potential for future developments (Gupta et al. 2024). Additionally, Gupta et al. have explored the potential of bifacial photovoltaics for indoor light harvesting, presenting a comprehensive review that underscores the versatility and extended application of these technologies (Singh et al. 2012; Das et al. 2019a). Innovative utilization of improved n-doped μc-SiO_x films has been shown to enhance the performance of micromorph solar cells, as demonstrated by Das et al. Such advancements in doping techniques are crucial for optimizing device performance (Kouider and Belfar 2020). Simulation and optimization studies by Kouider and Belfar on a-Si/μc-Si tandem solar cells with thinner active layers have also provided valuable insights into improving efficiency through structural refinements (Islam and Ghosh 2021). Furthermore, Islam and Ghosh have demonstrated performance enhancements in a-Si/μc-Si heterojunction pin solar cells by fine-tuning device parameters, highlighting the importance of parameter optimization in achieving superior performance (Matsui et al. 2015).

These studies collectively reflect the dynamic and multifaceted nature of research in amorphous tandem solar cells, paving the way for the development of next-generation high-efficiency photovoltaic devices.

Among the various strategies explored, the incorporation of narrow bandgap, high absorption coefficient Si-Ge sub-cells has shown significant promise. A comparative analysis of traditional silicon-based thin-film solar cells and those incorporating Si-Ge sub-cells, based on key studies in the field, is disscuced as follows:

1. *Traditional silicon-based thin-film solar cells*

Traditional silicon-based thin-film solar cells, particularly those using a-Si and microcrystalline silicon μc-Si, have been widely researched due to their advantageous properties, such as ease of fabrication and cost-effectiveness. These materials provide a good balance between absorption of high-energy photons and structural stability. However, they suffer from some limitations, such as light-induced degradation and lower absorption in the infrared region of the spectrum. Studies like those by Das et al. have demonstrated improvements in the performance of μc-Si based cells through innovative doping techniques, enhancing their overall efficiency and stability (Kouider and Belfar 2020). Furthermore, Islam and Ghosh have shown that performance enhancement can be achieved by fine-tuning device parameters in a-Si/μc-Si heterojunction pin solar cells (Matsui et al. 2015).

2. *Si-Ge sub-cells*

The use of Si-Ge sub-cells in tandem solar cell structures introduces several benefits, particularly due to the narrower bandgap and higher absorption coefficient of Si-Ge. This enables better absorption of the infrared portion of the solar spectrum, which is not efficiently captured by traditional silicon-based cells. Research by Cao et al. highlights the potential of ultrathin microcrystalline hydrogenated Si/Ge alloyed tandem solar cells towards full solar spectrum conversion, demonstrating significant improvements in efficiency (Cao et al. 2013). Moreover, the work by Cao et al. provides evidence that hydrogenated microcrystalline silicon germanium serves effectively as a bottom sub-cell absorber in triple junction solar cells, enhancing the overall absorption and efficiency (Kumar et al. 2023).

In conclusion, while traditional silicon-based thin-film solar cells offer simplicity and cost advantages, the incorporation of Si-Ge sub-cells represents a significant advancement in photovoltaic technology. By enhancing the absorption spectrum and improving overall efficiency and stability, Si-Ge sub-cells are poised to play a crucial role in the development of high-performance solar cells. Further research and comparative studies will continue to optimize these technologies, paving the way for more efficient and reliable solar energy solutions.

This paper delves into three key aspects of tandem solar cells: the front side, the intermediate layer between sub-cells, and the backside. Advanced light management techniques are explored to enhance light absorption in both the top and bottom cells, aiming to achieve a high-efficiency micromorph solar cell. Unlike previous simulations, our proposed configuration results from a comprehensive investigation, wherein each crucial aspect of the tandem cell is separately analyzed and optimized. Furthermore, our simulations are based on optical and electrical parameters derived from validated experimental studies (Bielawny et al. 2008; Liu et al. 2018), affirming the accuracy of our results.

The paper is organized as follows: We will first discuss the numerical models used for simulating the micromorph solar cell. Subsequently, we will conduct simulation studies on two individual solar cells: a-Si:H and μc-Si:H. An introduction to our reference structure, based on prior experimental work, will follow. We will then present different advanced light-trapping methods and introduce our proposed structure, aimed at improving efficiency.

Numerical models and software

Software

In this study, two-dimensional numerical simulations were conducted using the Silvaco Atlas software. Silvaco Atlas is a powerful and versatile simulation tool widely used in the field of semiconductor device modeling and design. It allows for detailed analysis of electronic, optical, and thermal properties of devices, facilitating the optimization of device performance. The software provides a comprehensive set of physical models and numerical techniques to accurately simulate the behavior of complex semiconductor structures.

Silvaco Atlas supports various simulation methods, including drift–diffusion, hydrodynamic, and quantum mechanical models, which are essential for understanding carrier transport, recombination mechanisms, and optical absorption in photovoltaic devices. By using this software, we can simulate the intricate interactions within tandem solar cells, such as charge carrier generation and recombination, and the effects of different material properties and device geometries on overall performance. This capability is crucial for predicting device behavior under various operating conditions and identifying potential improvements to enhance efficiency and stability.

In this work, the two-dimensional simulations allowed us to investigate the performance of the tandem solar cell structure; optimize layer thicknesses, doping concentrations, and material compositions; and evaluate the impact of different design parameters on the efficiency of the solar cell. The insights gained from these simulations provided a solid foundation for the experimental work and guided the development of high-performance tandem solar cells.

Numerical models

In this study, we employ the Shockley–Read–Hall recombination model to describe recombination mechanisms in both (p-i-n) a-Si:H and (p-i-n) μc-Si:H cells. For the interlayer tunnel recombination junction (TRJ), we utilize the trap-assisted tunneling recombination model, which provides a precise representation of the process. In our mobility model, we incorporate a concentration-dependent low-field mobility model to capture the behavior of charge carriers effectively.

The disordered nature of hydrogen and silicon atoms within the amorphous structure introduces many defect states, including dangling bonds, which we model using the defect pool model (Bielawny et al. 2008). In our simulations, we account for the refractive indices with a wavelength-dependent dependence. The tandem solar cell operates under the global standard spectrum, AM 1.5, at a temperature of 300 K.

Simulations and results

Single a-Si:H solar cell

As illustrated in Fig. 1, our initial simulation involves a single amorphous silicon solar cell, composed of ZnO/p-a-Si:H (13 nm)/i-a-Si:H (220 nm)/n-a-Si:H (20 nm)/ZnO/silver/Al (Bielawny et al. 2008). The simulation incorporates electrical parameters, as detailed in Table 1, and defect data retrieved from the literature (Bielawny et al. 2008). The intrinsic layer, situated between the p-doped and n-doped layers, is the absorber layer. ZnO is chosen for the front electrical contact, while the ZnO/Ag/Al layer acts as the back reflector. As indicated in Figs. 2 and 3, the simulation yields the following output parameters: J_{SC} = 14.32 mA/cm^2, V_{OC} = 0.9 V, FF = 82.15%, and conversion efficiency (η) = 10.62%.

Single μc-Si:H solar cell

In this case, the configuration of the μc-Si:H solar cell is identical to the single a-Si:H cell, except a thicker intrinsic layer, as depicted in Fig. 4. The layer thicknesses in this structure are as follows: p-μc-Si:H (20 nm), i-μc-Si:H (2500 nm), and n-μc-Si:H (15 nm), which have been adopted from the literature (Bielawny et al. 2008). The simulation results provide the following electrical parameters: J_{SC} = 20.1 mA/cm^2, V_{OC} = 0.4 V, FF = 66.97%, and conversion efficiency (η) = 5.31%. The corresponding J-V curves and quantum efficiency are presented in Figs. 5 and 6, respectively.

a-Si:H/μc-Si:H tandem solar cell

The choice of a-Si for the top cell and μc-Si for the bottom cell in our tandem solar cell design is driven by several factors. Firstly, a-Si has a higher bandgap (~1.7 eV) which makes it well-suited for absorbing the high-energy photons from the solar spectrum. On the other hand,

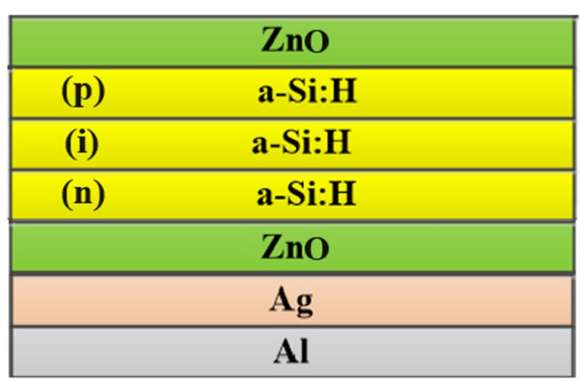

Fig. 1 Schematic of a simulated single a-Si:H solar cell

Table 1 Electrical parameters of the proposed structure

Layer properties	a-Si:H (top cell)			μc-Si:H (TRJ)		μc-Si:H (bottom cell)		
	P	*i*	*n*	*n*	*P*	*P*	*i*	*n*
Thickness (nm)	13	220	20	5	5	20	2500	15
N_D (cm^{-3})	-	-	10^{20}	10^{20}	-	-	-	10^{20}
N_A (cm^{-3})	3×10^{19}	-	-	-	3×10^{19}	10^{20}	-	-
E_g (eV)	1.71	1.71	1.71	1.16	1.16	1.16	1.16	1.16
N_C (cm^{-3})	10^{21}	10^{21}	10^{21}	3.5×10^{20}	3.5×10^{20}	3.5×10^{20}	3.5×10^{20}	3.5×10^{20}
N_V (cm^{-3})	10^{21}	10^{21}	10^{21}	3.5×10^{20}	3.5×10^{20}	3.5×10^{20}	3.5×10^{20}	3.5×10^{20}
χ (eV)	3.89	3.89	3.89	4.05	4.05	4.05	4.05	4.05
ε	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9
μ_e (cm^2/V.S)	1	1	1	20	20	20	20	20
μ_h (cm^2/V.S)	0.6	0.6	0.6	4	4	4	4	4

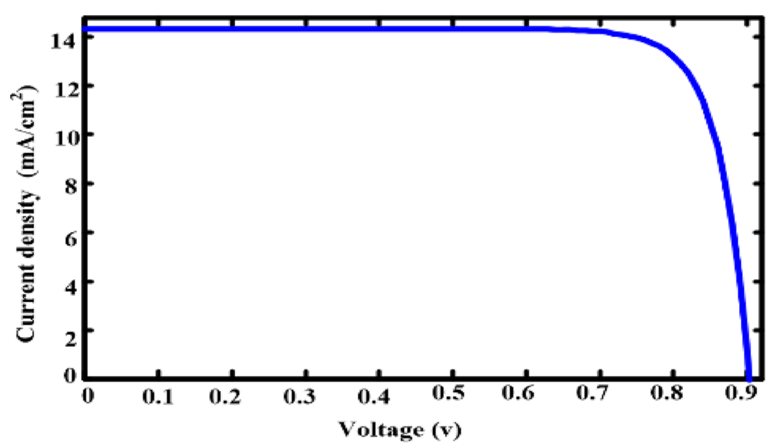

Fig. 2 J-V characteristics of a single a-Si:H solar cell

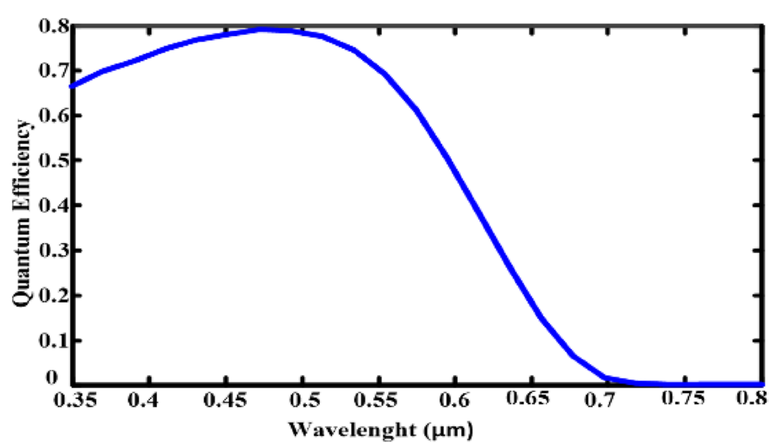

Fig. 3 Quantum efficiency of a single a-Si:H solar cell

μc-Si, with its lower bandgap (~ 1.1 eV), is more effective in absorbing the lower-energy photons that pass through the top cell. This complementary absorption range allows the tandem structure to utilize a broader spectrum of sunlight, thereby enhancing the overall efficiency of the solar cell.

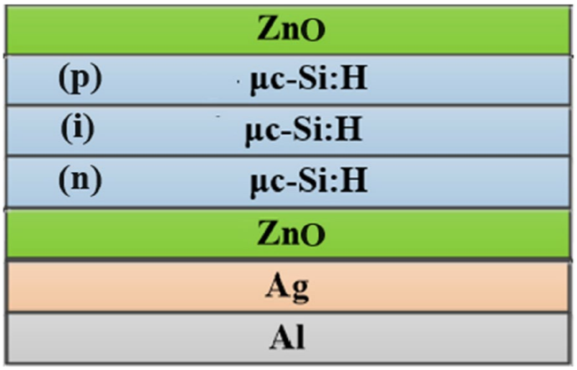

Fig. 4 Schematic of a simulated single µc-Si:H solar cell

Additionally, a-Si is known for its excellent light absorption properties and ease of deposition on various substrates, which makes it an ideal candidate for the top layer in tandem structures. However, it suffers from light-induced degradation (Staebler-Wronski effect), which can reduce its efficiency over time. The incorporation of µc-Si as the bottom cell helps to mitigate this issue, as µc-Si is more stable and less prone to degradation under illumination. The microcrystalline structure of µc-Si also allows for better carrier mobility and reduced recombination losses compared to a-Si.

Furthermore, combining these materials has been extensively studied and proven effective in various tandem cell configurations, achieving high efficiencies and long-term stability. The synergistic properties of a-Si and µc-Si make them a suitable pair for tandem solar cells, offering a balance between high initial efficiency and long-term performance reliability. These material choices are supported by numerous studies that have demonstrated their effectiveness in achieving high efficiency in tandem solar cell configurations.

In this section, we present our proposed reference structure for the micromorph solar cell, depicted in Fig. 7. On the front side, we employ ZnO as a transparent conductive oxide with a thickness of 40 nm. Meanwhile, the combination of ZnO (40 nm)/Ag (100 nm)/Al (200

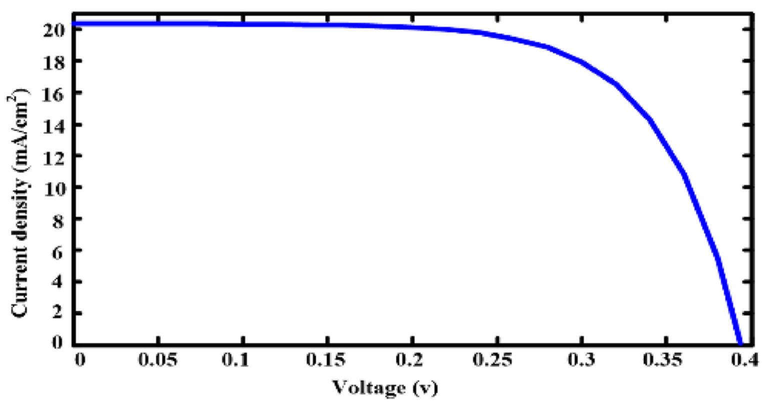

Fig. 5 J-V characteristics of a single µc-Si:H solar cell

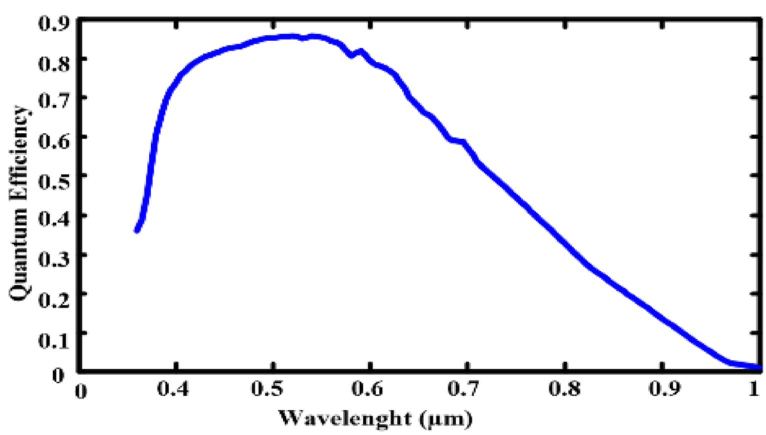

Fig. 6 Quantum efficiency of a single µc-Si:H solar cell

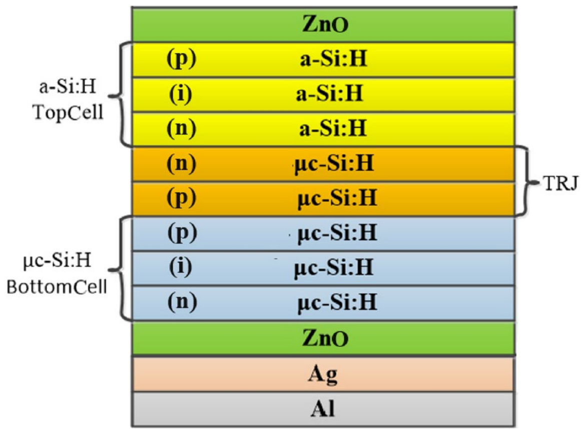

Fig. 7 Schematic structure of an a-Si:H/μc-Si:H tandem solar cell

nm) serves as the back reflector on the rear side of the solar cell.

To enhance carrier recombination between the sub-cells, we introduce the TRJ, which comprises n-μc-Si:H and p-μc-Si:H layers. This TRJ facilitates the recombination of holes generated in the bottom cell with electrons generated in the top cell at the TRJ interface, utilizing tunneling mechanisms due to localized trap states in this region.

In this context, we conducted an investigation to determine the optimal thicknesses for the TRJ by studying the solar cell's electrical behavior while varying the TRJ layer thickness. As illustrated in Fig. 8, our simulation results reveal that reducing the thickness of the TRJ layer leads to an increase in the total current density of the structure. This enhancement in current density results from a higher recombination rate in the interlayer. Consequently, the improved current density leads to an efficiency boost, reaching 12.22%.

Referring to the simulation results presented in Fig. 8, we have determined the optimal thicknesses for both n-μc-Si:H and p-μc-Si:H in the TRJ, each with a 5-nm thickness. Consequently, the electrical characteristics of the solar cell are as follows: $J_{SC} = 11$ mA/cm^2, $V_{OC} = 1.35$ V, $FF = 81.92\%$, and conversion efficiency $(\eta) = 12.22\%$. Detailed electrical results of the solar cell are depicted in Fig. 9.

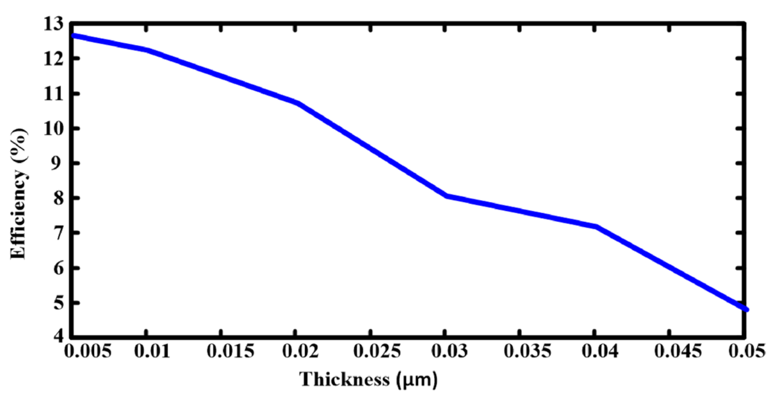

Fig. 8 Efficiency as a function of TRJ layer thickness

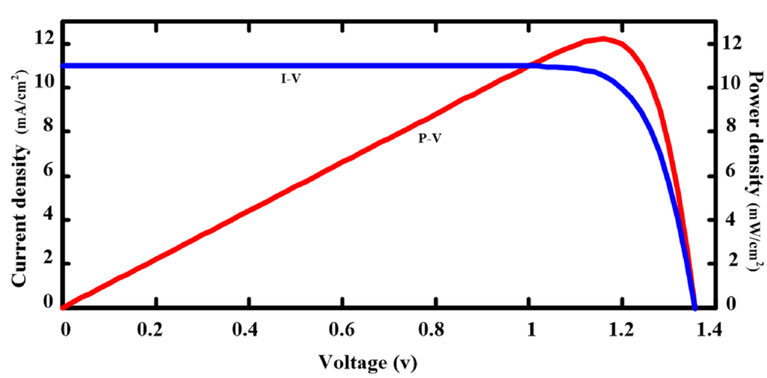

Fig. 9 J-V and P–V characteristics of an a-Si:H/μc-Si:H tandem solar cell

Reference solar cell with proposed anti-reflector

As previously mentioned, to minimize light reflection from the surface of the solar cell, an ARC is commonly employed on the front side. For single-junction solar cells operating within a relatively narrow solar spectrum range, such as 300–700 nm for a-Si:H solar cells, a single-layer anti-reflector like SiO_2 with a quarter-wavelength thickness is typically sufficient. However, in the case of multi-junction solar cells like micromorph, a more complex ARC is required to effectively transmit a broader spectrum of sunlight.

In this study, we introduce a two-layer ARC comprising SiO_2 and Si_3N_4 layers with respective thicknesses of 230 nm and 55 nm. As depicted in Fig. 10, this dual-layer ARC demonstrates the capability to transmit over 90% of incident light into the micromorph solar cell across the wavelength range of 300–1000 nm. The micromorph solar cell equipped with this ARC is illustrated in Fig. 11.

As anticipated, the inclusion of the ARC on the surface of the micromorph solar cell results in increased light absorption, leading to an enhancement in the J_{SC}. While the V_{OC} remains relatively stable, the short-circuit current has improved, reaching 12.093 mA/cm^2, up from 11 mA/cm^2, elevating the overall efficiency to 13.29%. The electrical characteristics of micromorph with the ARC are presented in Fig. 12, including the J-V and PV characteristics.

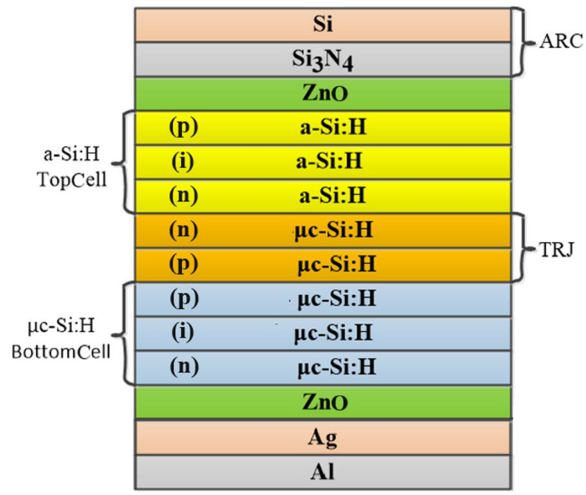

Fig. 11 Schematic structure of an a-Si:H/μc-Si:H tandem solar cell with proposed ARC

a-Si:H/μc-Si:H tandem solar cell with proposed DBR

A substantial portion of incident light, especially in the infrared region, struggles to be absorbed in the thin intrinsic layer of a-Si:H, with some being partially absorbed in the μc-Si:H bottom cell. Conventional light-trapping methods, such as using a silver-coated ZnO (ZnO/Ag) back reflector, are hindered by intrinsic losses stemming from surface plasmon modes generated at the metal–dielectric interface (Müller et al. 2004; Springer et al. 2004; Paetzold et al. 2010). Photonic crystals, on the other hand, have the potential to ideally reflect nearly 100% of light over a specific wavelength band (Krc et al. 2009).

In our approach, we replace the combination of Ag/Al with a 1D photonic crystal known as a distributed Bragg reflector (DBR). A 1D photonic crystal is a structure where two different materials with distinct thicknesses (d_1, d_2) and refractive indices (n_1, n_2) are periodically stacked in a fixed direction. By carefully selecting materials with a higher n_1/n_2 ratio, we can achieve higher reflectance around the central wavelength (λ_B). Additionally, it is essential for the reflectance bandwidth, often referred to as the forbidden gap in photonic crystals, to be sufficiently comprehensive. This characteristic enables the

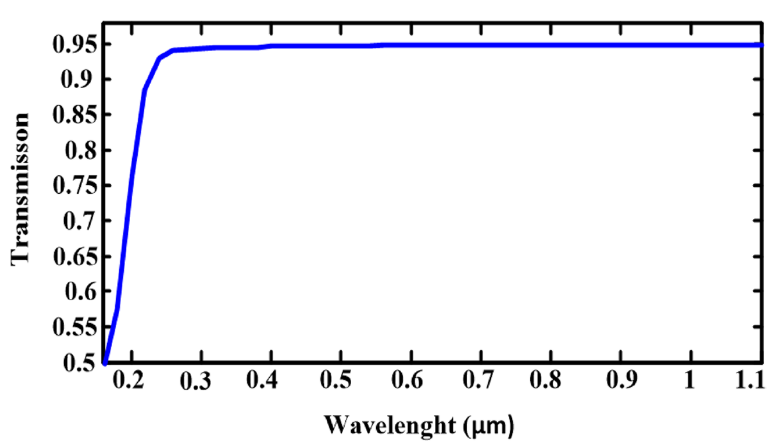

Fig. 10 Normalized transmission from the surface of the cell as a function of wavelength

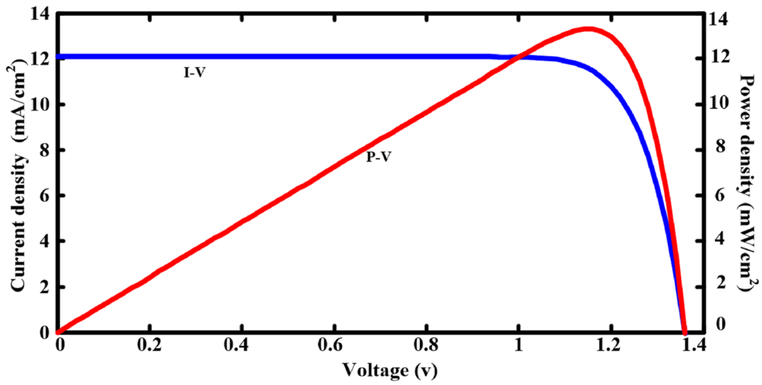

Fig. 12 J-V and P–V characteristics of an a-Si:H/μc-Si:H tandem solar cell with proposed ARC

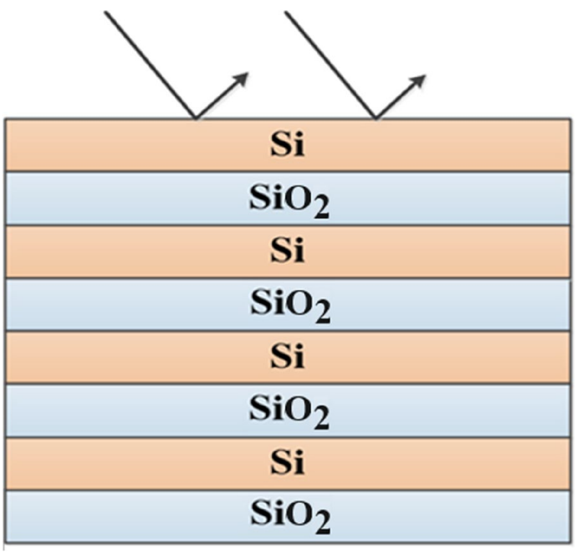

Fig. 13 Schematic structure of the proposed DBR

reflection of a broader spectrum of light within the solar spectrum back into the cell.

To attain maximum reflectance in the 700–1200-nm range for the micromorph solar cell, we opt for Si ($n_1 = 3.36$ at $\lambda = 600$ nm) and SiO_2 ($n_2 = 1.48$ at $\lambda = 600$ nm). The silicon thickness is calculated to be 47 nm at the central wavelength, λ_B, using the photonic crystal formula:

$$n_1 d_1 = n_2 d_2 = {}^{\lambda_B}/_4 \quad (1)$$

Following the optimization of the DBR structure, we propose four pairs of layers, each consisting of Si/SiO_2 with thicknesses $d_1 = 57$ nm and $d_2 = 138$ nm, as illustrated in Fig. 13. As shown in Fig. 14, increasing the number of pairs results in more than 95% of light being reflected in the wavelength range of 600–1200 nm. This longer optical path allows a significant portion of the light to be absorbed by the solar cell, especially in the

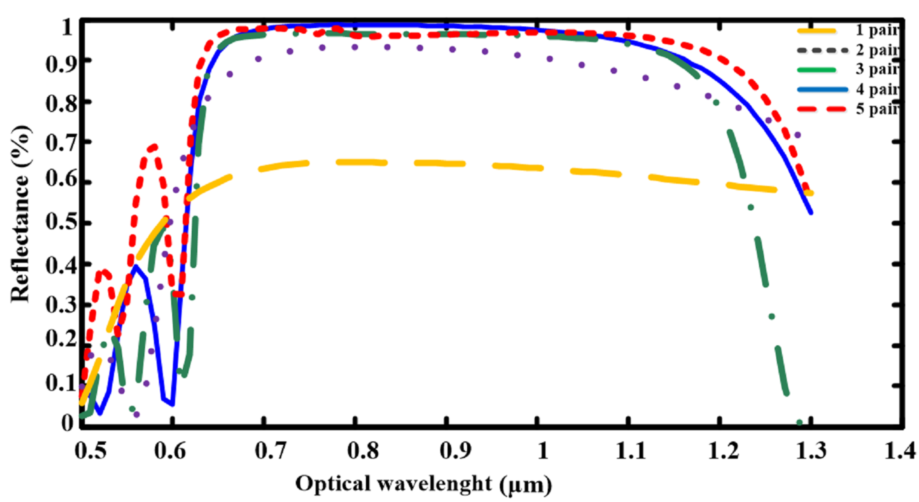

Fig. 14 Normalized reflection of the proposed DBR as a function of wavelength

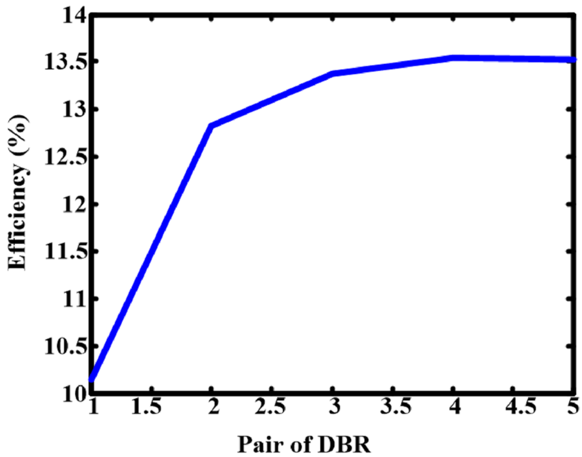

Fig. 15 Efficiency for various numbers of pairs of DBR

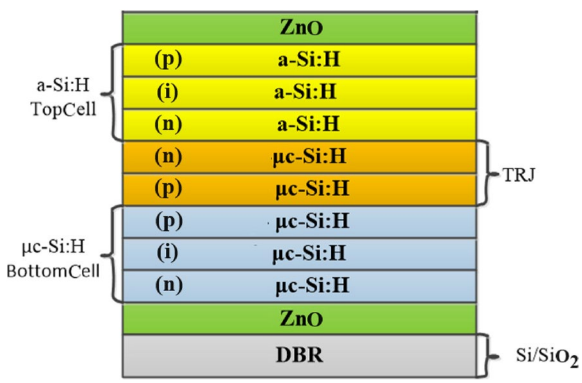

Fig. 16 Schematic structure of an a-Si:H/μc-Si:H tandem solar cell with proposed DBR

bottom sub-cell. While a single pair of DBR provides a broader wavelength range, the normalized reflectance remains below 60%. In the design of DBR as a back reflector, the primary objective is to enhance absorption in the long wavelength region around 1200 nm, which is satisfactorily achieved with four pairs.

Figure 15 showcases the efficiency of the micromorph solar cell using various numbers of DBR pairs. As expected, the utilization of a single pair results in an efficiency of approximately 10.29%, while the calculated efficiency rises to around 13.68% with the incorporation of a four-pair layer at the back of the solar cell, as depicted in Fig. 16. Current density and power density characteristics of the a-Si:H/μc-Si:H tandem solar cell with the proposed DBR are illustrated in Fig. 17.

Compared to the ZnO/Ag/Al back reflector, the use of ZnO/DBR enhances the current density to 12.27 mA/cm^2, with the V_{OC} and FF reaching 1.36 and 82.15%, respectively.

Modification of doping in proposed micromorph

In this section, by incorporating all components, including the TRJ, SiO_2/Si_3N_4, and the 1D photonic crystal, into the micromorph solar cell, the efficiency of the final configuration is significantly enhanced. As depicted in Fig. 18, we present the proposed a-Si:H/μc-Si:H tandem solar cell. Our simulations indicate that the efficacy of the final solar cell reaches 13.71% after implementing advanced light-trapping techniques.

To further improve conversion efficiency, we have introduced a uniform impurity concentration to both the p-a-Si:H and n-layers of the TRJ. This modification results in a 14% conversion efficiency. The impurity levels for the p-a-Si:H and n-layers of the TRJ are selected as 4×10^{20} cm^{-3} and 2×10^{20} cm^{-3}, respectively. The

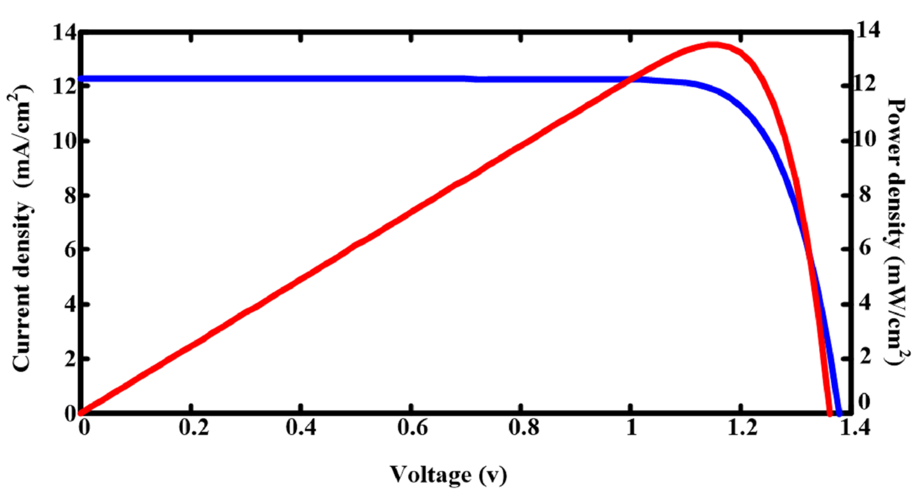

Fig. 17 J-V and P–V characteristics of an a-Si:H/μc-Si:H tandem solar cell with proposed DBR

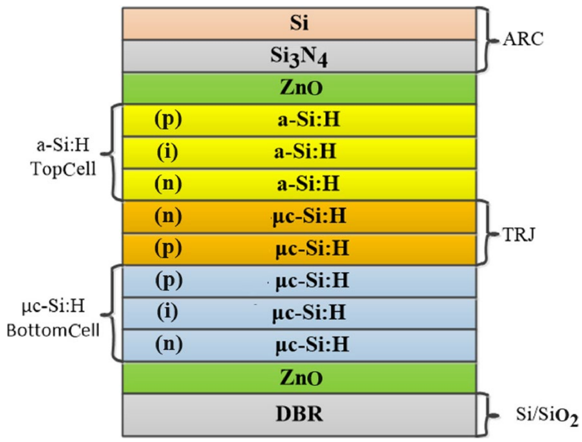

Fig. 18 Schematic structure of the proposed a-Si:H/μc-Si:H tandem solar cell

simulated values for the electrical characteristics are as follows: $J_{SC}=12.51$ mA/cm^2, $V_{OC}=1.38$ V, $FF=80.82\%$, and $\eta=14\%$. The J-V and P–V characteristics of the proposed a-Si:H/μc-Si:H tandem solar cell are presented in Fig. 19.

Figures 20 and 21 provide a comparative analysis of the electrical and optical characteristics of the micromorph solar cell with the various structures individually incorporated. These figures demonstrate a significant improvement in quantum efficiency, particularly in the bottom cell, and this enhancement is prominently depicted in both the J-V and P–V curves. Using advanced light management techniques results in an improved current density, while the open-circuit voltage remains consistent.

Table 2 offers a comparison between the proposed structure and works reported in recent years. It is evident

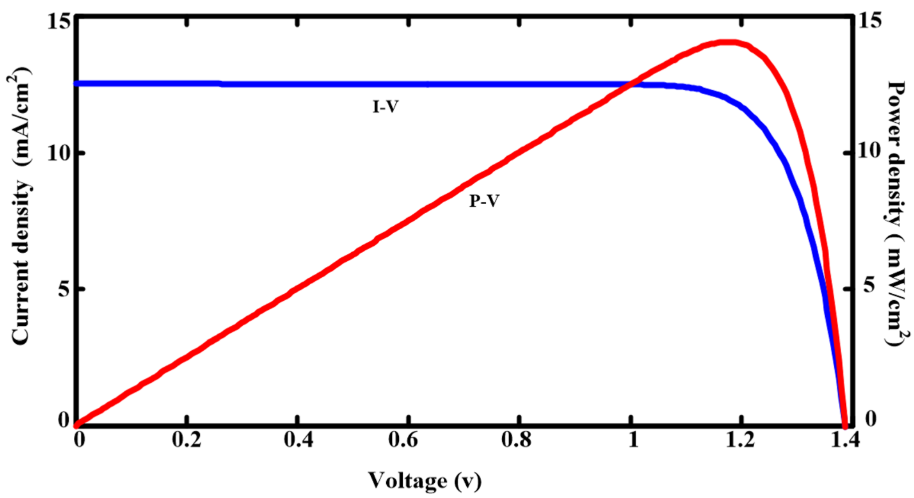

Fig. 19 J-V and P–V characteristics of the proposed a-Si:H/μc-Si:H tandem solar cell

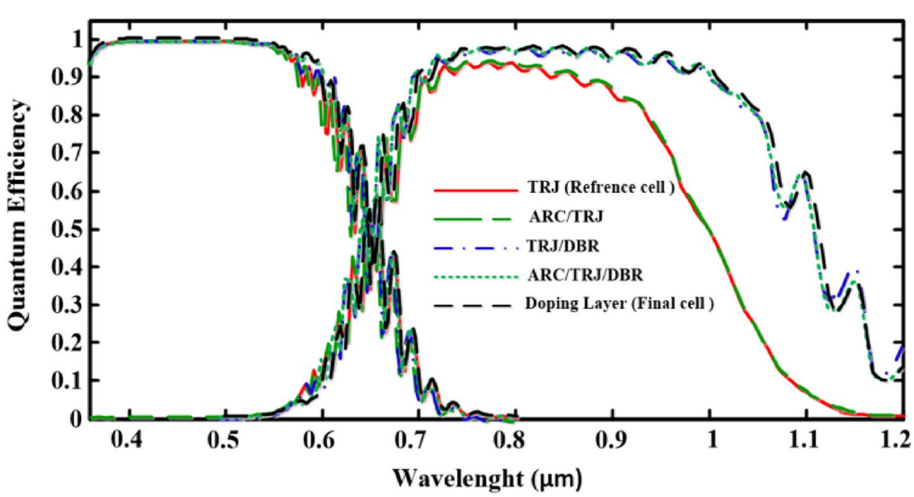

Fig. 20 Quantum efficiency for various structures of an a-Si:H/μc-Si:H tandem solar cell

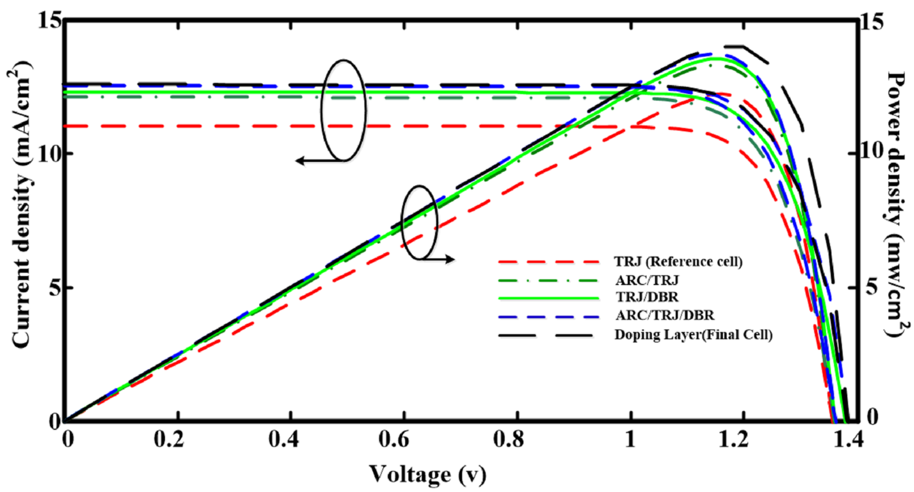

Fig. 21 J-V and P–V curves for various structures of an a-Si:H/μc-Si:H tandem solar cell

Table 2 Electrical parameters of the proposed structure

Work	J_{SC} (mA/cm^2)	V_{OC} (v)	FF (%)	Eff. (%)
Ref. (Cao et al. 2020)	8.03	1.97	74.6	11.35
Ref. (Kumar et al. 2023)	8.39	1.99	72	12.02
Ref. (Liu et al. 2018)	13.45	1.342	70.2	12.29–13
Ref. (Das et al. 2019b)	10.79	1.42	69.58	10.65
Ref. (Li et al. 2019)	12.45	1.33	72	11.92
Ref. (Zhou D, Biswas R 2008)	11.74	1.38	67.21	12.6
This work	12.51	1.38	80.82	14

that the simulation results for the proposed structure are quite promising, closely aligning with experimental results.

Conclusion

In this study, we have explored three distinct approaches to enhance photon absorption in both the top and bottom cells of the micromorph solar cell. The incorporation of the TRJ proves to be an effective method for improving the recombination rate at the interface of the sub-cells. Applying an ARC on the top cell results in an approximately 9% increase in current density. As a result, the conversion efficiency reaches 13.29%. Additionally, integrating a DBR on the backside of the micromorph cell leads to a 12.27 mA/cm^2 increase in current.

The combination of doping modifications and the implementation of all the proposed light-trapping methods in the micromorph solar cell yield a significant improvement compared to reference cell. Under global AM 1.5G conditions, the proposed cell structure achieves an open-circuit voltage of 1.38 V, a short-circuit current density of 12.51 mA/cm^2, and a fill factor of 80.82%, resulting in a total area conversion efficiency of 14%.

Code availability
Not applicable.

Authors' contributions
All the work in this paper, including the study conception and design, material preparation, data collection, and analysis, was carried out collaboratively by RE, SK, and AS. All authors have read and approved the final manuscript.

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Availability of data and materials
The data and material are available within the manuscript.

Declarations

Ethics approval consent to participate
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
All authors voluntarily agree to participate in this research study.

Consent for publication
All authors have endorsed the publication of this research.

Competing interests
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