Full-Spectrum Solar Energy Utilization and Enhanced Solar Energy Harvesting via Photon Anti-Reflection and Scattering Performance Using Biomimetic Nanophotonic Structure

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Abstract

Conventional Si photovoltaic cells cannot convert full solar energy spectrum (400~2500 nm) into electricity owing to the mismatch between Si band gap and broad range of solar photon energies. Transparent silicon PV cell allows sunlight in the wavelength of 1100~2500 nm to transmit through itself and irradiate on the thermal absorber below. The traditional photon management method based on texturing silicon layer with nanostructures can enhance 400~1100 nm absorptivity and 1100~2500 nm transmittance of transparent silicon PV cell. However, an increase in charge carrier capture and a decrease in electricity generation efficiency are often observed with this. In this study, a novel spectral splitting method based on front-located wavelength-sized TiO₂ biomimetic moth-eye nanophotonic structure is put forward, which can inhibit the increase of charge carrier capture and recombination. The biomimetic moth-eye nanophotonic structure was optimized by using finite-difference time-domain (FDTD) method to achieve excellent photon anti-reflection and scattering properties. The calculation results indicated that the absorption factor and transmission factor of transparent silicon PV cell could be increased from 46% to 58% and from 11% to 14%; the relative power conversion efficiency enhancement rate and relative incident radiation power enhancement rate was 32% and 27% when the TiO₂ biomimetic moth-eye was adopted.

Keywords: full spectrum solar energy biomimetic nanophotonic structure; radiative transfer; light trapping; spectral splitting

Received: 24 March 2020; Accepted: 6 May 2020

Article type: Research article

1. Introduction

Human society is facing the challenge of energy demand,^[1,2,3] it is necessary to develop a variety of renewable energy sources. Solar energy is one of the most significant renewable energy sources.^[4,5,6] Photoelectric conversion and photothermal conversion are efficient ways to utilize the solar energy.^[7,8,9,10] Advanced photothermal conversion devices can utilize the

solar energy effectively,^[11,12,13,14] but the photoelectric conversion efficiency still needs to be improved. Louise *et.al*^[15] clarified the intrinsic loss mechanism that lead to fundamental limits in solar cell efficiency. Their valuable study^[15] indicated that the photons with energy below the bandgap restricted the current of PV cell. There is an increasing concern that photoelectric conversion cannot convert the full solar energy spectrum (400~2500 nm) into electricity due to the mismatch between the band gap of the semiconductor material and the broad range of solar photon energies.^[16,17] In traditional planar silicon photovoltaic (PV) cells, the Al electrode, which is used to collect charges, prevents the forward propagation of solar radiation with wavelengths between 400~2500 nm. As illustrated in Fig. 1(a), Si PV cells can only absorb and convert sunlight with wavelengths of 400~1100 nm to electricity,

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while the sunlight with wavelengths between 1100~2500 nm are converted to harmful heat.^[18,19,20] This can greatly reduce the photoelectric conversion efficiency as every 1 K rise in temperature causes a ~0.5% relative efficiency decline.^[21,22] Thus, sunlight with wavelengths between 1100~2500 nm, which accounts for 20% of the total solar energy spectrum, is not unutilized,^[23,24] further negatively affects the electricity production efficiency and can even damage the PV cells.

A lot of research has been conducted with the goal of solving this mismatch problem between the band gap of semiconductor materials and the solar photon energies in order

to realize full solar spectrum utilization.^[25,26,27] The wasted heat discharged from the PV cells could be recovered by a heat exchanger which was contacted with the back side of PV cell. The recovered heat could be converted to thermal energy or electricity by different devices. Trip anagnostopoulos *et.al*^[28] successfully used water as a cooling medium to extract the heat from overheated PV cells and converted it into useful thermal energy. It was also valuably proposed that a diffuse reflector could be added to the PV/T system to increase electricity and heat output.^[28] Ji *et.al*^[29] developed a precious thermal analysis model to analyze the annual energy

Fig. 1 (a) illustration of solar spectrum utilization in traditional planar silicon PV cell; (b) illustration of solar spectrum utilization of nanofluid-based spectral splitting method; (c) illustration of solar spectrum utilization of optical splitting film-based spectral splitting method; (d) illustration of solar spectrum utilization in LW-NIR transparent planar silicon PV cell; (e) texturing the surface of silicon layer increased charge carriers capture and charge recombination; (f) LW-NIR transparent silicon PV cell using novel biomimetic TiO₂ moth-eye nanophotonic structure for spectral splitting, while protecting the silicon layer and preventing increased charge carrier capture and surface recombination.

conversion efficiency of PV/T system used in Hong Kong residences. The numerical calculation results indicated that the power generation efficiency of PV reached to 10.3% and thermal energy conversion efficiency reached to 70.3%.^[29] Recently, the thermoelectric materials have been rapidly developed.^[30] Sark^[31] successfully installed a thermoelectric device on the back of the photovoltaic cell, which can convert the heat to electrical energy. Their well-developed theoretical calculations indicated that the power conversion efficiency of photovoltaic-thermoelectric system could reach to 23%. Considering the spectral response of the PV cell, Kraemer *et.al.*^[32] innovatively used spectral splitting technology to divide sunlight into two partial bands. The photon energy higher than the band gap of the PV cell was diverted to the photovoltaic cell. The photon energy lower than the band gap of the photovoltaic cell was diverted to the thermoelectric device. The advantage of this system proposed by Kraemer *et.al.*^[32] is the spatial decoupling of PV cell and thermoelectric device. The PV cell and thermoelectric device are allowed to work at different conditions. Two main methods can spatially decouple PV cell and thermal absorber, which allows the PV cell and thermal absorber to work at different conditions;^[33,34] they are spectral splitting methods that utilize a nanofluid or an optical splitting film, which are shown in Figs. 1(b) and 1(c), respectively. In the nanofluid-based spectral splitting method, a nanofluid with selective spectral properties is used to absorb sunlight with wavelengths between 1100~2500 nm, while allowing sunlight with wavelengths of 400~1100 nm to be transmitted to the PV cells for electricity generation. The wavelengths absorbed by the nanofluid are used to heat the nanofluid, rather than the PV cells.^[35] In the case of an optical splitting film, spectral splitting is achieved by using the film to reflect desirable sunlight with wavelengths of 400~1100 nm to the PV cells for electricity generation, while sunlight with wavelengths of 1100~2500 nm is transmitted to heat a thermal absorber.^[36] Several theoretical and experimental studies have validated the use of spectral splitting methods based on nanofluids and optical splitting films to realize full solar spectrum utilization. However, their practical application is severely limited due to precise optical path requirements that, if unmet, can lead to serious light leakage.^[37] In addition, the high cost and frangibility of optical splitting film, and the instability of nanofluid also limit their application in real PV cells.

To overcome the limitations of nanofluid-based and optical splitting film-based spectral splitting methods, researchers have proposed a new mechanism to realize full solar spectrum utilization, which was made possible by the development of transparent conductive oxides (TCOs) such as indium tin oxide (ITO) and aluminum-doped zinc oxide (AZO).^[38] As shown in Fig. 1(d), the Al contact at the bottom of the polished Si wafer is replaced by a transparent conductive oxide, which enables sunlight with wavelengths of

1100~2500 nm to pass through the photovoltaic cell. This type of photovoltaic cell is known as a long-wavelength near infrared (LW-NIR) transparent planar silicon PV cell. However, some of the desirable solar energy in the wavelength range of 400~1100 nm could also pass through the TCO electrode, thus reducing the photoelectric conversion efficiency due to the short optical length of LW-NIR transparent planar silicon PV cells. Additionally, the anti-reflection coating (ARC) of LW-NIR transparent planar silicon PV cells is only effective for a limited range of wavelengths. Thus, photon management of the full solar wavelength spectrum could be further optimized to improve the absorption of 400~1100 nm sunlight, and the transmittance of 1100~2500 nm sunlight.

In order to extend the optical length and to provide excellent anti-reflection over the full sunlight spectrum, Xu *et.al.* successfully proposed the use of nanostructures, such as nanopillar and nanohole arrays,^[39] to texturize the silicon surface. This texturing method was shown to significantly improve sunlight absorption in the 400~1100 nm range and sunlight transmittance in the 1100~2500 nm wavelength range via an anti-reflection property combined with scattering effects. As illustrated in Fig. 1(e), the nanostructures on the silicon surface increase the number of defects and the surface area of the silicon layer, which increase charge carrier capture and recombination.^[40] Therefore, the major problem with this method is the loss of photoelectric conversion efficiency with the enhancement of spectral absorption and transmittance in the 400~1100 nm and 1100~2500 nm wavelength ranges, respectively. The compromise between optical gains and electrical performance deterioration must be carefully evaluated. Otherwise, no PV efficiency enhancements would be observed. Thus, in the ideal scenario, sunlight absorption in the 400~1100 nm range and sunlight transmittance in the 1100~2500 nm range would be greatly improved without increasing the surface defects and surface area of the silicon layer.^[41]

A survey of the current literature has indicated that LW-NIR transparent planar silicon PV cells can enable the transmittance of sunlight with wavelengths of 1100~2500 nm, but some desirable solar radiation in the range of 400~1100 nm is also transmitted through the PV cells, thus decreasing the energy conversion efficiency. With the sacrifice of silicon layer defect increase, traditional photon management method needs to fabricate nanostructure textures of silicon layer to enhance the absorptivity in 400~1100 nm and transmittance in 1100~2500 nm of transparent PV. In this study, a novel biomimetic nanophotonic structure for spectral splitting is proposed with the goal of realizing full solar spectrum utilization without electrical performance deterioration. As shown in Fig. 1(f), the TCO surface is covered with a TiO₂ moth-eye biomimetic nanophotonic structure at the TCO-silicon layer interface, which provides excellent antireflection and near-field forward scattering

properties while protecting the silicon layer and preventing increased charge carrier capture and surface recombination. The finite-difference time-domain (FDTD) method combined with a global optimization algorithm was used to design and optimize the novel biomimetic nanophotonic structure of the spectral splitting system to obtain maximum sunlight absorption and transmittance in the 400~1100 nm and 100~2500 nm wavelength ranges, respectively.

2. Material and methods

2.1 Design of the nanophotonic structure for spectral splitting

Thermoelectric (TE) generator can convert the thermal energy to electricity.^[42] The TE have been extensively studied since its figure of merit is not limited by theory and thermodynamics.^[42] Scholars have developed a series of thermoelectric devices to absorb the heat of PV cells, which is called as PV-TE hybrid system.^[42,43]

Direct-coupled PV-TE hybrid system and indirect-coupled PV-TE hybrid system are two typical types. For direct-coupled PV-TE hybrid system, the PV cell and TE are directly stacked. The hot side of the TE is directly connected to the back plate of the PV cell, and the cold side of the TE is exposed to the air. The cold side of the TE also can be connected to cooling devices.^[44,45,46,47] For indirect-coupled PV-TE hybrid system, PV cell and TE are separated in space. Considering the spectral response of PV cell, the photon energy of the sunlight higher than the band gap of PV cell is utilized by PV cell, while the photon energy of the sunlight lower than the band gap of PV cell is transferred to the TE. Usually, the indirect-coupled PV-TE hybrid system has lower temperature in PV cell and higher efficiency and absolute feasibility.^[43] The indirect-coupled PV-TE hybrid system is concerned in this study.

The strategy for full-spectrum solar energy utilization using biomimetic nanophotonic structure-based spectral splitting method is illustrated in Fig. 2. As shown in Fig. 2(a), in this full-spectrum solar energy utilization system, the Si PV cell can absorb sunlight with wavelengths of 400~1100 nm for producing electricity. The AZO is chosen as base electrode for Si PV cell, which enables sunlight with wavelengths of 1100~2500 nm to pass through the photovoltaic cell and irradiate the thermoelectric (TE) device.

In actual operation, the thermal absorber existed convection, conduction, and radiation losses.^[48,49] Many studies had been reported that convection, conduction, and radiation losses limited the temperature of the thermal absorber at high temperature.^[50,51,52] The TE was enclosed in an insulating layer to inhibit conduction and convection heat losses. The transparent silica aerogel had high transmittance in solar spectrum, low emissivity in mid infrared and low thermal conductivity.^[53] The transparent silica aerogel was used to inhibit conduction, convection, and radiation heat losses of the blackbody absorber. Using transparent silica aerogel could reduce the total heat loss by more than 70% compared to not using transparent silica aerogel.^[53] Therefore, transparent aerogel was selected as the thermal insulation material on the top of the TE. The blackbody absorber was attached on the hot side of the TE to absorb the incident radiation power that transmitted from the transparent silicon PV cell. The material of the blackbody absorber was the nonselective high temperature black paint with a solar absorptance $\alpha = 0.97$.^[53] Consequently, the TE device locating on the bottom of Si PV cell can absorb and convert sunlight with wavelengths of 1100~2500 nm to heat for producing electricity. Fig. 2(b) illustrates the design of the novel TiO₂ moth-eye nanophotonic structure that can provide anti-reflection and near-field forward scattering properties to achieve spectral splitting. This novel design consists of a layer of the TiO₂ moth-eye nanophotonic

Fig. 2 (a) Illustrations of the full-spectrum solar energy utilization of LW-NIR transparent silicon PV cell with biomimetic nanophotonic structure; (b) the design of the LW-NIR transparent silicon PV cell with nanophotonic structure.

structure covered by a TCO layer. The method of designing the TiO₂ moth-eye structure on the TCO layer has the following advantages. The first advantage is that it does not require structuring the silicon layers and does not increase the charge carrier capture and recombination.^[54] The second advantage is that this novel design can achieve full solar spectrum utilization without the need for an optical splitting film or nanofluids, thus greatly simplifying the system. The third advantage is that it can enhance the super hydrophobic and self-cleaning of the silicon transparent PV cell, which greatly improves the durability of the PV cell under outdoor complex conditions.^[54]

The type of PV cell illustrated in Fig. 2(b) will be referred to as a LW-NIR transparent silicon PV cell with TiO₂ moth-eye nanophotonic structure. It is composed of a moth-eye structure, TCO layer, silicon layer, TCO layer, and an anti-reflection coating. TiO₂ was chosen for the moth-eye structure as it exhibits a low optical absorption and high real refractive index.^[55] For large-scale manufacturing, it is feasible that the TiO₂ moth-eye is designed and arranged on the TCO layer. The colloidal lithography technology can be used to combine the TiO₂ moth-eye on the TCO layer.^[54] Colloidal lithography technology is inexpensive and can design and build TiO₂ moth-eye nanostructure with high quality on the large areas of TCO layer. AZO was used for both TCO layers owing to its good transparency and low electrical resistance. Amorphous silicon with a thickness of 300 nm and TiO₂ were used for the silicon layer and the anti-reflection coating, respectively.

2.2 Theoretical calculations

As illustrated in Fig. 2(b), the sunlight absorption and transmittance of the biomimetic moth-eye nanophotonic structure and the anti-reflection coating are mainly influenced by six physical parameters; they are the height (R_z), radius (R), and spacing (P) of the moth-eye nanophotonic structure, the thickness of the top (t_{top}) and base (t_{base}) AZO layers, and the thickness of the anti-reflection coating (t_{ARC}). The size of the moth eye was on the order of the illuminating wavelength, which would result in the phenomena of interference and diffraction. The interaction between light and matter was complex. The exact solution of Maxwell's equations was required to determine the distribution of electric field and light absorption field. The FDTD method had been proved to be an effective full-wave analysis method and could be used to accurately solve extensive electromagnetic problems.^[39,54,56] Therefore, the FDTD solver was used to calculate the distribution of electric field for the 3D model built by the authors. The interference, diffraction, reflection, absorption and scattering were all considered in the calculation.

The arrangement of the biomimetic moth-eye nanophotonic structure is periodic. Therefore, only one period of a square array of the moth-eye nanophotonic structure was modeled during the FDTD calculations. Symmetric and anti-

symmetric boundary conditions were applied at the x and y boundaries, which allowed simulation model to be reduced to a quarter of one period. The application of symmetric and anti-symmetric boundary conditions can reduce the calculation time and effectively saved memory. The boundary condition of perfectly matched layers (PML) was used for the upper and lower boundaries to absorb all outgoing light along the z-axis. A monitor was set below the PV cell to record the spectral transmittance $\tau(\lambda)$ in the wavelength range of 1100~2500 nm. For wavelengths of 400~1100 nm, the electric field distribution in each element of the simulated area was recorded in the FDTD calculations. The corresponding power absorbed by the PV cell per unit volume, $P_{abs}(m^{-3})$, could be calculated based on the divergence of the Poynting vector:^[54]

$$P_{abs} = -0.5\text{real}\left(\vec{\nabla} \cdot \vec{P}\right) \quad (1)$$

To avoid the divergence, a more numerically stable form was adopted:^[54]

$$P_{abs} = 0.5\omega\epsilon''|E|^2 \quad (2)$$

where ω was the angular frequency, ϵ'' was the imaginary part of the permittivity, and E was the electric field intensity.

The quantum efficiency of a solar cell, $QE(\lambda)$, was defined as:^[54]

$$QE(\lambda) = \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} \quad (3)$$

where $P_{in}(\lambda)$ and $P_{abs}(\lambda)$ were the powers of the incident and absorbed light, respectively, within their corresponding material at the wavelength λ .

All the photons were absorbed by the Si layer, where the charge carriers were generated. Thus, all electron-hole pairs generated could contribute to the photocurrent, J_{sc} , which was calculated by incorporating the sunlight spectrum, $I_{AM=1.5}$, as follows:^[54]

$$J_{sc} = e \int \frac{\lambda}{hc} QE(\lambda) I_{AM=1.5}(\lambda) d\lambda \quad (4)$$

where e was the charge on an electron, h was the Planck constant, and c was the speed of light in free space. The calculated J_{sc} was used to evaluate the silicon layer absorption within the 400~1100 nm wavelength range. It should be noted that only photons absorbed by the silicon layer could generate electron-hole pairs. Any photon absorption by TiO₂ and AZO was considered as parasitic absorption without any electricity generation.

The absorption factor $A^{[57]}$ of the transparent silicon PV cell was calculated through averaging the spectral absorption over the sunlight spectrum $I_{AM=1.5}$:

$$A = \frac{\int_{400\text{ nm}}^{1100\text{ nm}} A(\lambda) I_{AM=1.5}(\lambda) d\lambda}{\int_{400\text{ nm}}^{2500\text{ nm}} I_{AM=1.5}(\lambda) d\lambda} \quad (5)$$

Similarly, the transmission factor τ was calculated as:

$$\tau = \frac{\int_{1100 \text{ nm}}^{2500 \text{ nm}} \tau(\lambda) I_{AM=1.5}(\lambda) d\lambda}{\int_{400 \text{ nm}}^{2500 \text{ nm}} I_{AM=1.5}(\lambda) d\lambda} \quad (6)$$

The relative power conversion efficiency enhancement rate for transparent silicon PV cell was calculated as:

$$\delta_{PCE} = \frac{|J_{sc,1} - J_{sc,2}|}{J_{sc,1}} \quad (7)$$

The relative incident radiation power enhancement rate for thermal absorber was calculated as:

$$\delta_{IRP} = \frac{|P_1 - P_2|}{P_1} \quad (8)$$

Where incident radiation power (P) was calculated as:

$$P = \int_{1100 \text{ nm}}^{2500 \text{ nm}} \tau(\lambda) I_{AM=1.5}(\lambda) d\lambda \quad (9)$$

Different silicon semiconductor materials would exhibit different below-bandgap absorption. In the 1100 nm~1700 nm band, the absorption coefficient (α) of n-type c-Si materials that was used by Santergen *et.al* in the Ref. [57] mentioned by the reviewer was in the order of 10^4 . However, the studies in the Ref. [58,59] indicated that, the absorption coefficient (α) and absorptivity of n-type amorphous silicon materials which was used in this study, were in the order of 10^0 and 10^{-3} . Therefore, the below-bandgap absorption was not taken into consideration.

The particle swarm optimization (PSO) algorithm was used to determine the optimal physical parameters. PSO is a population-based algorithm inspired by the swarming of flocks of birds or insects. This algorithm had been widely used for photon management, since it iteratively regulates the physical parameters of the nanophotonic structure to maximize absorption factor A and the transmission factor τ .

3. Model validation

To validate the model results in this study, the calculated spectral absorptivity and reflectivity were compared with the results obtained by transfer-matrix method and rigorous coupled-wave analysis (RCWA) method. The authors used the absolute error to evaluate the reliability of model results. Four validation study cases were conducted to assess the accuracy of the FDTD numerical calculations used in this work. The real (n) and imaginary (k) parts of the optical constants of TiO_2 , amorphous silicon, and AZO used in the FDTD calculations were taken from Ref. [55,60,61], and they are shown in Fig. 3. Three cases of absorption by a transparent planar silicon PV cell were calculated using both the FDTD method and the transfer-matrix method. As shown in Figs. 4(a), 4(b), and 4(c), the numerical results calculated using the FDTD method match well with those calculated using the transfer-matrix method for different incident angles ($0^\circ \sim 60^\circ$) and polarizations (transverse-magnetic (TM) and transverse-electric (TE)). The maximum absolute error between the two

methods ($\delta_{\max} = |A_{\text{FDTD}} - A_{\text{transfermatrix}}|$) was less than 2%. For further model validation, the reflectivity of a silicon PV cell with moth-eye structures was calculated using FDTD and the results were compared to reflectivity calculated using the rigorous coupled-wave analysis (RCWA) method from Ref. [62]. As shown in Fig. 4(d), the reflectivity of the silicon PV cell calculated using the FDTD method is in good agreement with the results obtained by the University of Texas at Arlington, USA, [62] which were calculated by RCWA method. The maximum absolute error between the two methods ($\delta_{\max} = |R_{\text{FDTD}} - R_{\text{RCWA}}|$) was less than 1%. Based on the above four validation cases, it can be concluded that the FDTD method used in this work can achieve reliable numerical calculations.

Fig. 3 The real (blue) and imaginary (red) refractive index as a function of wavelength for amorphous Si, TiO_2 , and AZO (from top to bottom) Ref. [58,59,60].

4. Results

Section 4.1 details the optimization and comparison of traditional and LW-NIR transparent planar silicon PV cell structures. Low absorption factor A and the transmission factor τ were observed for the LW-NIR transparent planar silicon PV cell, which prompted the design of the novel nanophotonic structure to address these issues. In section 4.2, with the goal of addressing the drawbacks of LW-NIR transparent planar silicon PV cells, a novel spectral splitting method based on a TiO_2 biomimetic moth-eye nanophotonic structure is proposed. The structure of the LW-NIR transparent silicon PV cell with a biomimetic moth-eye nanophotonic structure was optimized to enhance the absorption factor A and the transmission factor τ .

4.1 Comparison of traditional and LW-NIR transparent PV cells

In this section, the optimization of traditional and LW-NIR transparent planar silicon PV cells is presented. The thicknesses of the top (t_{top}) and base (t_{base}) AZO layers of both types of planar silicon PV cells were optimized using the

Fig. 4 Results of the four model validation studies conducted. Comparison of the absorption by a transparent planar silicon PV cell calculated using the FDTD method and the transfer-matrix method at incident angles of (a) 0°, (b) 30°, and (c) 60°. (d) Comparison of the reflectivity calculated by FDTD with that calculated by RCWA method in Ref. [62].

FDTD method. For the traditional planar silicon PV cell, as shown by the labelled point 1 in Fig. 5(a), the photocurrent (J_{sc}) reached a maximum value of 249.7 A/m² when the t_{top} and t_{base} were 69 nm and 66 nm, respectively. For the LW-NIR transparent planar silicon PV cell, as shown by the labelled point 1 in Fig. 5(b), the J_{sc} reached a maximum value of 228.4 A/m² when t_{top} and t_{base} were 69 nm and 20 nm, respectively. The optimized physical parameters for both the traditional and LW-NIR transparent planar silicon PV cells are listed in Table 1.

The spectral absorption in the wavelength range of 400~1100 nm for the optimized traditional and transparent planar silicon PV cells is presented in Fig. 6(a). For $\lambda < 560$ nm, the spectral absorption of the traditional planar silicon PV cell was consistent with that of the LW-NIR transparent planar silicon PV cell. For $560 \text{ nm} < \lambda < 850$ nm, the spectral absorption of the traditional silicon PV cell was higher than that of the transparent PV cell. This lower spectral absorption in the 560~850 nm range led to an 8.5% lower photocurrent in the transparent PV cell compared to the traditional PV cell, as shown in Table 1. This low spectral absorption in the 560~850 nm wavelength range is due to the weaker 1D Fabry-Perot effect in transparent planar silicon PV cells than in traditional PV cells,^[63] as can be seen in absorption density profiles in

Fig. 6(b) and 6(c). For $\lambda > 793$ nm, the spectral absorption dropped sharply for both the traditional and LW-NIR transparent planar silicon PV cells. This phenomenon is due to the sharp decrease in the imaginary (k) component of the complex refractive index of Si. At $\lambda = 850$ nm, the spectral absorptions of the traditional and LW-NIR transparent planar silicon PV cells have decreased to the same value. For $850 \text{ nm} < \lambda < 1100$ nm, the traditional and LW-NIR transparent planar silicon PV cells exhibit similar spectral absorption behavior. The parasitic absorption at wavelengths of 400~1100 nm of the traditional and LW-NIR transparent planar silicon PV cells are also presented in Fig. 6(a). They are shown by the shaded blue and red regions in the figure, and they are clearly negligible for wavelengths of 400~1100 nm. The parasitic absorption is any absorption that occurs outside of the Si layer, which cannot produce photocurrent.

As shown in Fig. 6(a), the spectral transmittance in the wavelength range of 1100~2500 nm was much higher in the LW-NIR transparent planar silicon PV cell than in the traditional PV cell, where there is no transmittance. This high transmittance was possible due to the removal of the Al contact in the LW-NIR transparent planar silicon PV cell, which allowed the forward propagation of radiation with wavelengths of 1100~2500 nm. However, the spectral

Fig. 5 Results of the top and base AZO thickness optimization using the FDTD method for (a) traditional planar silicon PV cells, and (b) LW-NIR transparent planar silicon PV cells.

Table 1. Summary of the photocurrent (J_{sc}) and transmission factor as a function of the optimal physical parameters for the three distinct PV cells.

Structure	Optimal parameters (nm)	J_{sc} (A/m ²)	τ
traditional	$t_{top} = 69$	249.7	0
	$t_{base} = 66$		
transparent	$t_{top} = 69$	228.4	11
	$t_{base} = 20$		
	$t_{top} = 38$		
	$t_{base} = 9$		
moth-eye	$R = 711$	301	14
	$R_z = 633$		
	$P = 725$		
	$t_{ARC} = 250$		

transmittance of the LW-NIR transparent planar silicon PV cell fluctuated drastically with wavelength, particularly in the wavelength range of 1200~1900 nm, and the transmittance decreased remarkably at wavelengths longer than 1140 nm. For example, the transmittance of the LW-NIR transparent planar silicon PV cell was 95% at $\lambda = 1135$ nm, and it decreased to 31% at $\lambda = 1470$ nm. Therefore, transmission factor τ of the LW-NIR transparent planar silicon PV cell was only 11%, as listed in Table 1.

Based on the above analysis of the transparent planar silicon PV cell, the low photocurrent (J_{sc}) obtained is due to the low spectral absorption in the 560~850 nm range, and the low transmission factor is due to the low spectral transmittance of 1200~2500 nm radiation. It should be noted that the spectral absorption of the LW-NIR transparent planar silicon PV cell in the 560~649 nm wavelength range was greater than 90%. The focus of the research presented in the following section is to improve the spectral absorption of the LW-NIR transparent planar silicon PV cell in the wavelength ranges of 400~490 nm and 649~850 nm, which were lower than 90%, and to improve the spectral transmittance in the

wavelength range of 1200~2500 nm.

4.2 LW-NIR transparent silicon PV with novel moth-eye nanophotonic structure

Based on the analysis presented in section 4.1, it is clear that improvements to the spectral absorption in the wavelength ranges of 400~490 nm and 649~850 nm, and the spectral transmittance in the range of 1200~2500 nm of the LW-NIR transparent planar silicon PV cell are needed. In this section, a novel spectral splitting method based on a moth-eye nanophotonic structure is presented to address the shortfalls of current LW-NIR transparent PV cells. The six physical parameters (t_{top} , t_{base} , R , R_z , P and t_{ARC}) of the nanophotonic structure are optimized using the FDTD method combined with the PSO algorithm method.

The absorption spectra of the optimized LW-NIR transparent silicon PV cells with (green line) and without (blue line) the biomimetic nanophotonic structure are presented in Fig. 7(a). For sunlight with wavelengths of 400~490 nm, the spectral absorption of the LW-NIR transparent silicon PV cells with and without the novel moth-eye nanophotonic structure was between 87~92% and 60~90%, respectively. In the range of 649~874 nm, the spectral absorption of the LW-NIR transparent silicon PV cells with and without the novel moth-eye nanophotonic structure was between 70~94% and 10~90%, respectively. It is clear that the spectral absorption in both these wavelength ranges was significantly improved with the addition of the novel moth-eye nanophotonic structure, which resulted in an increase in the average absorption from 61 to 77% for wavelengths of 400~1100 nm and an increase in the photocurrent (J_{sc}) from 228.4 to 301 A/m². The spectral absorption enhancement in wavelengths of 400~490 nm was due to the anti-reflection and near-field forward-scattering properties provided by the moth-eye nanophotonic structure. The anti-reflection effect is caused by the gradual change in the refractive index of the moth-eye

Fig. 6 (a) The spectral absorption (left) and transmittance (right) at wavelength ranges of 400~1 100 nm and 1 100~2 500 nm, respectively, for the optimized traditional and transparent planar silicon PV cells, the wavelength was log10-scale distribution; and the absorption density profiles of (b) tradition and (c) transparent planar silicon PV cells at different wavelengths

structure from the top to bottom, which suppresses reflection and promotes absorption by causing more incident light to couple into the silicon layer.^[63] The near-field forward-scattering effect is due to the TiO₂ moth-eye nanophotonic structure serving as a convex lens that concentrates the incoming light to form an intense absorption field.^[63] The high absorption density with the semi-ellipsoid pattern caused by the moth-eye nanophotonic structure is shown in Fig. 7(b). Spectral absorption enhancement in the wavelength range of 649~874 nm was due to the longer optical length in the silicon

layer caused by the far-field scattering effect of the novel moth-eye nanophotonic structure. The far-field scattering effect occurs because the moth-eye nanophotonic structure can scatter normal incident light into different directions, and it acts as a 2D grating to excite waveguide resonance modes, which allows the scattered light to reflect multiple times between the upper and lower surfaces of the silicon layer.^[63] As a result, the optical length of the LW-NIR transparent silicon PV cell with the novel moth-eye nanophotonic structure was enhanced for wavelengths of 649~874 nm. The high

Fig. 7 (a) The spectral absorption (right) and transmittance (left) at wavelength ranges of 400~1 100 nm and 1 100~2 500 nm, respectively, for the optimized LW-NIR transparent planar silicon PV cells with and without the novel moth-eye nanophotonic structure, the wavelength was log₁₀-scale distribution. The absorption density profiles of the transparent silicon PV cell with the novel moth-eye photonic structure at **(b)** $\lambda = 400$ and 490 nm, and **(c)** $\lambda = 649$ and 874 nm

absorption density, shown in Fig. 7(c), provides evidence that the novel moth-eye nanophotonic structure causes a far-field scattering effect that enhances the spectral absorption at

wavelengths of 649~874 nm.

The parasitic absorption of the LW-NIR transparent silicon PV cell with the novel biomimetic moth-eye

nanophotonic structure is shown as the shaded green regions in Fig. 7(a). The parasitic absorption was found to be less than 10% for wavelengths of 400–500 nm, and it is basically negligible for wavelengths of 500–1100 nm. Thus, the spectral splitting method based on the novel moth-eye nanophotonic structure does not induce significant parasitic absorption for wavelengths of 400–1100 nm.

The transmittance spectra of the optimized LW-NIR transparent silicon PV cells with (green line) and without (blue line) the novel moth-eye nanophotonic structure are presented on the right of Fig. 7(a). The green and blue regions indicate when the spectral transmittance of the LW-NIR transparent planar silicon PV cell with the novel moth-eye nanophotonic structure was higher or lower than that of the LW-NIR transparent silicon PV cell, respectively. For most of the wavelength bands, the spectral transmittance of the PV cell with the novel moth-eye nanophotonic structure was higher than the transmittance of the PV cell without the nanophotonic structure. However, in the wavelength ranges of 1350–1420 nm and 1850–1890 nm, the spectral transmittance of the PV cell with the novel biomimetic moth-eye nanophotonic structure was slightly lower than that of the LW-NIR transparent planar silicon PV cell. Fortunately, the transmittance in these wavelength ranges would not influence the transmission factor τ of the PV cell with the moth-eye structure as the solar irradiance intensity in the wavelength ranges of 1350–1420 nm and 1850–1890 nm is close to zero. In addition, there is a region within the 1100–1230 nm wavelength range where the transmittance of the LW-NIR transparent silicon PV cell with the novel moth-eye nanophotonic structure was lower than that of the PV cell without the nanophotonic structure. However, this reduced transmittance for wavelengths of 1100–1230 nm can be offset by the transmittance gains in the 1230–2500 nm wavelength region. As a result, the transmission factor τ of the LW-NIR transparent silicon PV cell with the novel moth-eye nanophotonic structure was increased from 11 to 14%.

Based on the above analyses, the absorption factor A of the LW-NIR transparent silicon PV cell with the novel moth-eye nanophotonic structure was increased from 46 to 58%, which resulted in an increase in the photocurrent (J_{sc}) from 228.4 to 301 A/m². The transmission factor τ of the LW-NIR transparent silicon PV cell with the novel moth-eye nanophotonic structure was increased from 11 to 14%, as shown in Table 1.

5. Discussion

With the goal of achieving full solar energy spectrum utilization without increasing charge carriers capture and charge recombination, the LW-NIR transparent silicon PV cell with the novel biomimetic moth-eye nanophotonic structure was proposed. Using this biomimetic nanophotonic structure on the AZO layer, the Si layer was protected while enhancements to the 400–1100 nm sunlight absorption and

1100–2500 nm sunlight transmittance was achieved.

The traditional photon management method based on texturing the silicon layer with nanostructures can enhance 400–1100 nm absorptivity and 1100–2500 nm transmittance of transparent silicon PV cell. However, this traditional method increases the number of defects and the surface area of the silicon layer, which increases charge carrier capture and recombination. Usually, the increase of charge carrier capture and recombination can be inhibited by surface doping and passivation technologies. In this study, the authors reported an optical strategy to solve the contradiction between optical benefits and electrical deterioration. The spectral splitting method based on the front-located wavelength-sized TiO₂ moth-eye nanophotonic structure was proposed. The spectral splitting method proposed by the authors did not require structuring the silicon layers, avoided the increase in the number of defects and surface area of the silicon layer. Therefore, the spectral splitting method based on the front-located wavelength-sized TiO₂ moth-eye nanophotonic structure did not increase the charge carrier capture and recombination. In this way, the relative efficiency enhancement rate of the transparent silicon PV with the TiO₂ moth-eye was similar to the relative enhancement rate of J_{sc} . As presented in Fig. 8, compared with the transparent silicon PV, the relative power conversion efficiency enhancement rate of the transparent silicon PV with TiO₂ moth-eye was 32% under the same boundary conditions. Fig. 8 also presented that the relative incident radiation power enhancement rate for thermal absorber could be increased by 27% when the TiO₂ moth-eye was applied to the transparent silicon PV. The PV-TE hybrid system with the TiO₂ moth-eye could obtain more thermal energy than the PV-TE hybrid system without the TiO₂ moth-eye under the same boundary conditions.

Fig. 8 The relative power conversion efficiency enhancement rate for transparent silicon PV with TiO₂ moth-eye, and the relative incident radiation power enhancement rate for thermal absorber.

6. Conclusions

To enhance full solar energy spectrum utilization without increasing charge carriers capture and charge recombination, a LW-NIR transparent silicon PV cell with a novel biomimetic

moth-eye nanophotonic structure providing excellent photon anti-reflection and scattering properties was proposed. The LW-NIR transparent silicon PV cell with the novel biomimetic moth-eye nanophotonic structure was optimized using the FDTD method combined with the PSO algorithm. The following conclusions can be drawn:

(1) The absorption factor of the LW-NIR transparent silicon PV cell with the novel biomimetic moth-eye nanophotonic structure was 58%, which was 8% and 12% higher than those of traditional and LW-NIR transparent planar silicon PV cells, respectively.

(2) The transmission factor of the LW-NIR transparent silicon PV cell with the novel biomimetic moth-eye nanophotonic structure was 14%, which was 14% and 3% higher than those of traditional and LW-NIR transparent planar silicon PV cells, respectively.

(3) The photocurrent of the LW-NIR transparent silicon PV cell with the novel biomimetic moth-eye nanophotonic structure was 301 A/m², which was 51.3 A/m² and 72.6 A/m² higher than the those of traditional and LW-NIR transparent planar silicon PV cells, respectively.

(4) The relative power conversion efficiency enhancement rate of the transparent silicon PV with TiO₂ biomimetic moth-eye nanophotonic structure was 32%.

(5) The relative incident radiation power enhancement rate for thermal absorber was 27%, when the TiO₂ biomimetic moth-eye nanophotonic structure was applied to the transparent silicon PV.

Acknowledgments

This work was supported by the China National Key Research and Development Plan Project (No. 2018YFA0702300), and the Natural Science Foundation of China (Grant No. 51676061) and the Taishan Scholars of Shandong Province (tsqn201812105).

Supporting information

Not applicable

Conflict of interest

There are no conflicts to declare.

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