Design of Biomimetic Leaf-type Hierarchical Nanostructure for Enhancing the Solar Energy Harvesting of Ultra-thin Perovskite Solar Cells

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Abstract

Ultra-thin perovskite solar cells have the advantages of low cost, high efficiency and flexibility, and have significant potential applications. However, a severe optical loss is often observed in the ultra-thin perovskite solar cell due to the insufficient light absorption. In this study, inspired by the efficient light harvesting of hierarchical structure in leaf, the idea of biomimetic leaf-type hierarchical nanostructure was introduced for designing highly efficient ultra-thin perovskite solar cells. In detail, three layers of hexagonal arrays of silica nanoparticles with different radius were used to construct the biomimetic leaf-type hierarchical structure. The biomimetic leaf-type hierarchical nanostructure was optimized by a finite-difference time-domain method combined with a particle swarm optimization algorithm to reduce the light reflection and increase the light absorption of the ultra-thin perovskite solar cells. The results indicated that the biomimetic leaf-type hierarchical nanostructure could enhance the light absorption of ultra-thin perovskite solar cells by maximum 39% at the long wavelength. The photocurrent of the perovskite solar cells with a biomimetic leaf-type hierarchical nanostructure was 8.4% higher than that of perovskite solar cells without a biomimetic leaf-type hierarchical nanostructure.

Keywords: Solar energy; Perovskite solar cell; Biomimetic; Hierarchical nanostructure; Radiative transfer; Full spectrum.

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1. Introduction

Renewable energy is the promising way to solve the energy and environmental crisis.^[1-3] One type of renewable energy is solar energy,^[4-6] which has excellent future for natural environment protection,^[7-10] greenhouse gas emission reductions^[11-13] and air pollution alleviation.^[14-17] Among photothermal, photoelectricity and photochemistry,^[18-21] photovoltaics is environmentally friendly, whose installed capacity has been increased dramatically in the past few years.^[22-24] Yet, the overheating of photovoltaics greatly reduces the efficiency and service life of the photovoltaics. For this reason, water and phase-change material (PCM) are usually used to cool the perovskite (PV) panels. Nowadays, unlike the above cooling method to decrease the temperature of PV cells, PV industry is moving towards ultra-thin, low-

cost and flexible solar cells, which are aimed at for consumer-oriented electronic products.^[25-28]

Perovskite solar cell has obtained tremendous interests in the past years due to their excellent characteristics.^[29,30] The PV solar cell is flexible due to the reduced thickness, and has a promising market applicability.^[31,32] However, the reduction of the PV absorber layer thickness can reduce the optical path length of light, which in turn leads to unsaturated light absorption of perovskite solar cell.^[33-36] Therefore, poor power conversion efficiency of ultra-thin PV solar cell is usually observed due to the serious optical loss.^[37,38]

For the above-mentioned problem of insufficient light absorption of ultra-thin PV solar cell, photon management was prospective to enhance the optical path length and light absorption.^[39,40] Several approaches had been proposed to manipulate the incident sunlight, which essentially increased the light absorption by controlling the scattering and focusing of light.^[41-44] For example, ultra-thin textures such as grating, prism arrays, micro-lens, nanopillars, nanopillars and nanoholes had been extensively investigated.^[45-51] These randomly textured surfaces and periodic photonic structures could be easily manufactured by wet etching, low-pressure

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deposition, and nanoimprint lithography techniques.^[52,53] Roozbeh *et al.*^[54] designed and analyzed the effects of ZnO nanorods and plasmonic nanoparticles on the performance of the perovskite solar cell. Halo *et al.*^[55] conducted a ray tracing analysis of inverted pyramids to investigate different light-trapping schemes in thin crystalline silicon (c-Si) for solar cells. Raphael *et al.* reported that structuring perovskite layers with textures could improve the photocurrent of perovskite solar cell by about 5%.^[56] Akshit *et al.*^[57] reported that micron lens arrays could improve the photocurrent of perovskite solar cell by about 6%. Xu *et al.*^[58] reported that a combination of order and disorder nanopillar/nanohole arrays could improve the average light absorption by about 97%. These ultra-thin textures could reduce the light reflection over broadband and improve the light absorption of PV solar cells.^[59] However, texturing would unavoidably enhance the surface area and defect density in the PV materials, which in turn enhanced the carrier recombination and eventually deteriorated the efficiency of the solar cells.^[60,61] Therefore, it was important to develop a useful photon management strategy, which could protect the integrity of the PV absorber layer and did not increase the recombination and capture of charge carriers.^[62]

Recently, inspired by nature, such as butterflies,^[63] honeycomb^[64] and moth-eye,^[65] biomimetic nanophotonic structures have been developed to control the incident light for camouflage, antireflection and scattering.^[66,67] Leaf has the precise structure to harvest sunlight and efficiently conduct photosynthesis.^[68] Leaf usually has hierarchical structures, which manipulate the incoming sunlight to be absorbed in high efficiency.^[69] Leaf can capture and absorb incoming sunlight over broadband. Therefore, comprehending the photon management advantage of hierarchical structures observed in leaf, and imitating these hierarchical structures could offer precious instructions on designing and manufacturing nanophotonic structures for ultra-thin PV solar cells. In addition, the hierarchical nanostructure could keep the PV absorber layer from damage, which did not enhance the recombination and capture of charge carriers.

Literature survey indicated that the hierarchical structures of leaf harvest light efficiently, but the advantages of hierarchical structures are remained to be explored to improve the light absorption for ultra-thin PV solar cell. In this study, imitating the hierarchical structures observed in leaf, the idea of biomimetic leaf-type hierarchical nanostructure was introduced for designing highly efficient ultra-thin PV solar cells. The effects of the ratio, radius and filling factor of the biomimetic leaf-type hierarchical nanostructure on the light absorption and photocurrent of the PV solar cells were investigated. The particle swarm optimization algorithm was adopted to develop the full potential of the biomimetic leaf-type hierarchical nanostructure from the perspective of optics. The calculated analysis results could offer designing suggestions for enhancing light absorption and energy conversion efficiency of ultra-thin perovskite solar cells.

2. Methodology

2.1 Design of biomimetic leaf-type hierarchical nanostructure

The photon management of leaf is outstanding due to the unconventional hierarchical structures, which can provide highly efficiently light harvesting. As shown in Fig 1(a), a typical C₃ leaf has a unique hierarchical structure, and is composed of the following four-layer structures: upper epidermis layer, palisade cell layer, spongy mesophyll layer and lower epidermis layer.^[70] The epidermis layer has two unique optical properties: (1) the epidermis layer is transparent to visible light; (2) the shape of the epidermis is convex. These two optical properties enable the epidermis layer to collect the sunlight. The palisade cell layer promotes the sunlight to penetrate deep into the leaf. Leaf could manipulate and distribute the internal light to maximize the light absorption through regulating the geometry structure and packing density of the palisade cell. The spongy mesophyll layer could scatter downwards light back into the palisade cell due to the refractive index mismatch between cells and air, which could enhance the light absorption.

Based on the above photon management advantage of hierarchical structures observed in leaf, a biomimetic leaf-type hierarchical nanostructure was designed for enhancing the light absorption of ultra-thin PV solar cell. As shown in Fig. 1 (b), the biomimetic leaf-type hierarchical nanostructure was composed of three layers of hexagonal arrays of silica nanoparticles with different radius. The top layer of hexagonal arrays of silica nanoparticles with a larger radius was mimicking the epidermis layer. The middle layer of hexagonal arrays of silica nanoparticles with a smaller radius was mimicking the palisade cell layer. The bottom layer of hexagonal arrays of silica nanoparticles with a smaller radius was mimicking the spongy mesophyll layer.

Fig. 2(a) presents the cross-section of an ultra-thin planar PV solar cell. An ultra-thin planar PV solar cell was composed of the following five-layer structures: a transparent conductive electrode layer, an electron transport layer, a PV absorber layer, a hole transport layer, and a metal conductive electrode layer. Fig. 2(b) presents the cross-section of an ultra-thin PV solar cell with a biomimetic leaf-type hierarchical nanostructure. The radius of silica nanoparticle locating in the top layer was larger than those locating in the middle and bottom layer. The radius of silica nanoparticle locating in the middle layer was the same as that locating in the bottom layer. The ratio (R) was adopted to define the ratio between the radius of the large silica nanoparticle and the radius of the small silica nanoparticle, which was calculated by a dimensionless factor (R) as shown in Equation (1):

$$R = \frac{d_l}{d_s} \quad (1)$$

The filling factor (FF) was adopted to define the distance between the two nanoparticles, and was calculated by a dimensionless factor (FF) as shown in Equation (2):

$$FF = \frac{L}{d_l} \quad (2)$$

Fig. 1 (a) Hierarchical structure of a typical C3 leaf; and (b) schematic diagram of a perovskite solar cell with biomimetic leaf-type hierarchical nanostructure.

Fig. 2 (a) Cross-section of an ultra-thin planar perovskite solar cell; and (b) cross-section of an ultra-thin perovskite solar cell with a biomimetic leaf-type hierarchical nanostructure.

where d_l was the radius of the large silica nanoparticle locating on the top layer, d_s was the radius of the small silica nanoparticle locating on the middle and bottom layer, and L was the distance between the two nanoparticles.

Silica rarely absorbs solar energy with the wavelength range of 400–1000 nm, and is transparent to visible light.^[7] Therefore, the silica was used as the material of biomimetic leaf-type hierarchical nanostructure. Transparent conductive electrode layer should have excellent conductivity and transparency. Therefore, indium tin oxide (ITO) was adopted as the transparent conductive electrode layer. Titanium dioxide was applied into the electron transport layer. A typical

methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$) was applied into the PV absorber layer, and the thickness of the PV absorber layer was 250 nm. Spiro-OMeTAD was applied into the hole transport layer (HTM), and the thickness of the HTM was 150 nm. Ag was adopted into the back metal, and the thickness of the Ag was 80 nm. The biomimetic leaf-type hierarchical nanostructure was introduced and located on the ITO, which could be straightly incorporated onto the ITO layer by the simple colloidal spin coating technology. In addition, the biomimetic leaf-type hierarchical nanostructure would keep the PV absorber layer from damage, which did not enhance the recombination and capture of charge carriers.

Fig. 3 (a) Real part and Spiro-OMeTAD; and (b) imaginary part of refractive index for SiO₂, ITO, TiO₂, perovskite, Spiro-OMeTAD.^[78-80]

2.2 Mathematical calculation description

The Maxwell's equations can be adopted to compute the electromagnetic field distribution of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure, which can compute the optical characteristic of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure. In this study, FDTD numerical solution was adopted to compute the Maxwell's equations (3-6).^[72,73]

$$\nabla \times H = \frac{\partial D}{\partial t} \quad (3)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (4)$$

$$D = \epsilon E \quad (5)$$

$$B = \mu H \quad (6)$$

where E was the electric field, H was the magnetic field, B was the magnetic flux density, D was the electric displacement field, μ was the complex permeability, and ϵ was the complex permittivity.

After calculating the electromagnetic field distribution, the spectral absorptivity could be computed by Equation (7):^[41,60]

$$Abs(\omega) = \int P_{abs}(\omega) dV \quad (7)$$

The $P_{abs}(\omega)$ was the absorbed energy per unit volume with the normalization of the incident energy, which was expressed as Equation (8):

$$P_{abs}(\omega) = \frac{1}{2} \omega \epsilon'' |E|^2 \quad (8)$$

where ω was the angular frequency and ϵ'' was the imaginary part of the complex refractive index.

The photocurrent of the perovskite solar cell was calculated by Equation (9):

$$J_{ph} = e \int \frac{\lambda}{hc} Abs_{eff}(\lambda) I(\lambda) d\lambda \quad (9)$$

where e was the electron charge, h was Planck constant, c was the light speed, and $I(\lambda)$ was the solar spectral radiation power at AM=1.5.

The maximum potential of Sbiomimetic leaf-type hierarchical nanostructure to improve the light absorption of

PV solar cell was investigated. The biomimetic leaf-type hierarchical nanostructure was optimized by the FDTD method combined with the particle swarm optimization algorithm. The particle swarm optimization algorithm^[74-76] was an optimization calculation method, which imitated the bird's predation.

Fig. 4 Spectral absorptivity and reflectivity calculated by FDTD and TM.

3. Model validation

For the purpose of checking numerical calculation accurateness in this study, the numerical results calculated by FDTD method were compared with those calculated by transfer-matrix (TM) method and rigorous coupled-wave analysis (RCWA) method, respectively. The model validation had two parts. Exactly, the first part was that the reflectivity and absorptivity of the planar PV absorber layer calculated by FDTD method were compared with those calculated by TM method. The second part was that the reflectivity of photovoltaic having nanostructures calculated by FDTD method was compared with those calculated by rigorous

coupled-wave analysis (RCWA) method in Ref.^[77] The complex refractive index used in the calculation was shown in Figs. 3(a) and 3(b).^[78-80]

Fig.4(a) presented the comparison of the planar PV absorber layer's spectral absorptivity computed by FDTD method and TM method, respectively. As shown in this figure, the planar PV absorber layer's spectral absorptivity computed by FDTD method matched well with that computed by TM method with the maximum absolute error ($\delta = |A_{\text{FDTD}} - A_{\text{transfer matrix}}|_{\text{max}}$) of 4%. Fig.4(b) presents the comparison of the planar perovskite absorber layer's spectral reflectivity computed by FDTD method and TM method, respectively. As shown in this figure, the planar PV absorber layer's spectral reflectivity computed by FDTD method matched well with that computed by TM method with the maximum absolute error ($\delta = |A_{\text{FDTD}} - A_{\text{transfer matrix}}|_{\text{max}}$) of 5%. In addition, the reflectivity of PV having nanostructures calculated by FDTD method was compared with those calculated by rigorous coupled-wave analysis (RCWA) method employed by University of Texas at Arlington, USA in Ref.^[77] As presented in Fig. 5, the spectral reflectivity of photovoltaic having nanostructures matched well with that obtained by University of Texas at Arlington, USA in Ref.^[77]

Fig. 5 Comparison of the reflectivity calculated by FDTD with that calculated by RCWA.^[77]

4 Results and discussions

4.1 Performance of PV solar cell with/without hierarchical nanostructure

The influence of biomimetic leaf-type hierarchical nanostructure on the light absorption and photocurrent of perovskite solar cells was investigated. Fig. 6 presents the photocurrent of PV solar cell without/with biomimetic leaf-type hierarchical nanostructure. As shown in the graph, the photocurrent of PV solar cell without a biomimetic leaf-type hierarchical nanostructure was 20.6 mA/cm², and the photocurrent of PV solar cell with biomimetic leaf-type hierarchical nanostructure was 22.3 mA/cm². The photocurrent of PV solar cell with a biomimetic leaf-type

hierarchical nanostructure was 8.4% higher than that of PV solar cell without a biomimetic leaf-type hierarchical nanostructure. This phenomenon is due to the reason that the biomimetic leaf-type hierarchical nanostructure can enhance the effective light absorption of PV solar cell in the NIR wavelength range.

Fig. 6 Photocurrent of perovskite solar cell without/with biomimetic leaf-type hierarchical nanostructure.

Fig. 7 Light absorption of perovskite solar cell with/without biomimetic leaf-type hierarchical nanostructure.

Fig. 7 presents the effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure and the effective light absorption of PV solar cells without a biomimetic leaf-type hierarchical nanostructure. As shown in the graph, the effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure was higher than that of PV solar cells without a biomimetic leaf-type hierarchical nanostructure in the 400~800 nm wavelength band. And the biomimetic leaf-type hierarchical nanostructure mainly enhanced the light absorption of PV solar cells at the long wavelength. For example, at $\lambda=761$ nm, the effective

absorptivity of the perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was 92%, while the effective absorptivity of the perovskite solar cell without biomimetic leaf-type hierarchical nanostructure was 66%. Therefore, the effective light absorption for perovskite solar cell was improved by 39%

at 761 nm, when the biomimetic leaf-type hierarchical nanostructure was adopted. Fig. 6 shown the parasitic absorptivity of perovskite solar cell with/without biomimetic leaf-type hierarchical nanostructure as well. The parasitic absorptivity of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure was lower than 10% in the 400~800 nm wavelength band, and the parasitic absorptivity of perovskite solar cell with biomimetic leaf-type hierarchical nanostructure was lower than 10% in the 400~800 nm wavelength band as well. The biomimetic leaf-type hierarchical nanostructure did not improve the parasitic absorptivity of the PV solar cell, which did not increase the possibility to decrease the photocurrent of PV solar cells.

Fig. 8 Field of the absorption per unit volume (P_{abs}) of PV solar cell without/with a biomimetic leaf-type hierarchical nanostructure along the X-Z cross sectional plane at $\lambda=761$ nm.

In order to explain the light absorption difference between the PV solar cells without the biomimetic leaf-type hierarchical nanostructure and the PV solar cells with the

biomimetic leaf-type hierarchical nanostructure, the mechanism of biomimetic leaf-type hierarchical nanostructure to enhance the light absorption of PV solar cell at long wavelength was investigated. Fig. 8 displays the field of the absorption per unit volume (P_{abs}) of PV solar cells without the biomimetic leaf-type hierarchical nanostructure and PV solar cells with the biomimetic leaf-type hierarchical nanostructure at $\lambda=761$ nm, respectively. Fig. 8 (a) displays the field of the absorption per unit volume (P_{abs}) of PV solar cell without the biomimetic leaf-type hierarchical nanostructure at $\lambda=761$ nm. As shown in the graph, the absorption of the solar energy of 761 nm was distributed in the entire PV absorber layer along the Z axis, and the PV absorber layer mainly absorbed the solar energy of 761 nm wavelength within a depth of 100 to 150 nm from the surface. The reason for this absorption distribution was that the perovskite absorber layer could not completely absorb the incoming longer wavelength (761 nm) due to the low absorption coefficient of PV absorber layer at longer wavelength (761 nm). Therefore, the unabsorbed longer wavelength (761 nm) would reflect back and forth at the upper and lower surfaces of the PV layer, which would form Fabry Perot interference effect.

Fig. 8 (b) displays the field of the absorption per unit volume (P_{abs}) of PV solar cell with the biomimetic leaf-type hierarchical nanostructure at $\lambda=761$ nm. As shown in the graph, the absorption of the solar energy of 761 nm was scattered in different locations, when the biomimetic leaf-type hierarchical nanostructure was used. The biomimetic leaf-type hierarchical nanostructure could scatter the incident solar energy of 761 nm into distinct orientation, and the scattering light with a distinct orientation would travel in the PV absorber layer along the X and Y axis directions. Therefore, the light absorption of solar energy of 761 nm was improved.

4.2 Effects of ratio (R) on the performance of PV solar cell

The ratio (R) was adopted to define the ratio between the diameter of the large silica nanoparticle and the diameter of the small silica nanoparticle. The influences of R on the photocurrent and effective light absorption of the PV solar cells with a biomimetic leaf-type hierarchical nanostructure are presented in Figs. 9 and 10, respectively. The photocurrent of PV solar cells with a biomimetic leaf-type hierarchical nanostructure and PV solar cells with a biomimetic leaf-type hierarchical nanostructure with the different R is displayed in Fig. 9. As shown in the graph, the photocurrents of PV solar cells without a biomimetic leaf-type hierarchical nanostructure were 19.9, 20.5, 20.4, 20.6, 20.6 and 20.8 mA/cm^2 . The photocurrents of PV solar cells with a biomimetic leaf-type hierarchical nanostructure were 20, 22.1, 21.5, 22.4, 21.9 and 22.1 mA/cm^2 with the R of 1:1, 1:2, 1:3, 1:4, 1:5 and 1:6, respectively. The photocurrent of PV solar cells with a biomimetic leaf-type hierarchical nanostructure was 0.5%, 7.8%, 5.4%, 8.7%, 6.3% and 6.3% higher than those of PV solar cells without a biomimetic leaf-type hierarchical nanostructure. Therefore, biomimetic leaf-type hierarchical nanostructure with different R could improve the photocurrent of PV solar cells with different improvement.

Fig. 9 Effect of ratio (R) on the photocurrent of perovskite solar cell.

Fig. 10 Effects of the ratio (R) of biomimetic leaf-type hierarchical nanostructure on the effective spectral absorptivity of perovskite solar cells.

The effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with the different R is displayed in Fig. 10. As shown in the graph, the light absorption of the biomimetic leaf-type hierarchical nanostructure with the R of 1:1 was lower than that of the biomimetic leaf-type hierarchical nanostructure with the other R . Little difference in the light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with the ratio of 1:2, 1:3, 1:4, 1:5 and 1:6 was observed in the short wavelength of 400~700 nm. However, the obvious difference in the light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with the ratio of 1:2, 1:3, 1:4, 1:5 and 1:6 was observed in the long wavelength range of 700~800 nm. The light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with the ratio of 1:3 and 1:6 did not have obvious absorption peaks in the long wavelength range of 700~800 nm, while the light absorption of PV solar cells with a biomimetic leaf-type

hierarchical nanostructure with the ratio of 1:2, 1:4 and 1:5 had absorption peaks in the long wavelength range of 700~800 nm. Therefore, the biomimetic leaf-type hierarchical nanostructure could enhance the light absorption of PV solar cells in the long wavelength range of 700~800 nm.

4.3 Effects of radius on the performance of PV solar cell

(a) Different radii of nanostructure

(b) Effects of radius on photocurrent

Fig. 11 Effect of radius of biomimetic leaf-type hierarchical nanostructure on the photocurrent of perovskite solar cells.

In this section, the R between the radius of large silica nanoparticle and the radius of small silica nanoparticle was set to 1:4. The influence of the radius of the top layer of large nanoparticle on the photocurrent and effective light absorption of the perovskite solar cell with a biomimetic leaf-type hierarchical nanostructure is displayed in Figs. 11 and 12, respectively. The photocurrent of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with different radius is displayed in Fig. 11. As shown in the graph, the photocurrents of PV solar cells with a biomimetic leaf-type hierarchical nanostructure were 20.3, 21.6, 22.5, 21.4 and 21 mA/cm², while the radii of top layer of large nanoparticle were 0.104, 0.204, 0.304, 0.404, and 0.504 μm , respectively. The photocurrents of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with radius of 0.304 μm were 10.8%, 4.2%, 5.1%, and 7.1% higher than those with radii of 0.104, 0.204, 0.404, and 0.504 μm , respectively. This phenomenon was induced due to the reason that a biomimetic leaf-type hierarchical nanostructure with different radii had different enhancement capabilities for effective spectral absorptivity of PV solar cells.

Fig. 12 Effect of radius of biomimetic leaf-type hierarchical nanostructure on the effective light absorption of PV solar cells.

The effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with different radius of the top layer of large nanoparticle is displayed in Fig. 12. As shown in the graph, the trend of effective spectral absorptivity with a biomimetic leaf-type hierarchical nanostructure varied with the change of the radii. The trend of the effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure was the same in the 400~675 nm band with radii of 0.104, 0.204, 0.304, 0.404 and 0.504 μm . However, the trend of the effective light absorption of perovskite solar cells with a biomimetic leaf-type hierarchical nanostructure was different in the 675~800 nm band with the radii of 0.104, 0.204, 0.304, 0.404 and 0.504 μm . The obvious difference was that the PV solar cells with a biomimetic leaf-type hierarchical nanostructure with radius of

0.304 μm had an effective light absorption peak at the $\lambda=761$ nm, while the PV solar cells with a biomimetic leaf-type hierarchical nanostructure with radii of 0.104, 0.204, 0.404 and 0.504 μm did not have obvious effective light absorption peaks in the wavelength range of 675~800 nm.

4.4 Effects of filling factor (FF) on performance of PV solar cell

In this section, the influence of the filling factor (FF) of the top layer of large nanoparticle on the photocurrent and effective light absorption of the PV solar cell with a biomimetic leaf-type hierarchical nanostructure is displayed in Figs. 13 and 14, respectively. The R was set to 1:4. The radius of the top layer of large nanoparticle was set to 0.304 μm . The photocurrent of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with different filling factor (FF) is displayed in Fig. 13. As shown in the graph, the photocurrents of PV solar cells with a biomimetic leaf-type hierarchical nanostructure are 21.4, 21.7, 22.5, 21.5 and 20.9 mA/cm², while the FF of top layer of large nanoparticle is 1, 1.05, 1.15, 1.25 and 1.35, respectively. The photocurrent of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with a FF of 1.15 was 5.1%, 3.7%, 4.7%, and 7.7% higher than those with a FF of 1, 1.05, 1.25, and 1.35, respectively. This phenomenon was induced due to the reason that the biomimetic leaf-type hierarchical nanostructure with different FF had different enhancement capabilities for the effective light absorption of perovskite solar cells.

The effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with different FF of the top layer of large nanoparticle was displayed in Fig. 14. As shown in the graph, the light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure decreased with increasing FF within the wavelength range of 400~686 nm. In the wavelength range of 686~800 nm, the trend of the effective light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with a FF of 1 was different from those with a FF of 1.05, 1.15, 1.25 and 1.35. The obvious difference was that the PV solar cells with a biomimetic leaf-type hierarchical nanostructure with a FF of 1 had no effective light absorption peak, while the PV solar cells with a biomimetic leaf-type hierarchical nanostructure with a FF of 1.05, 1.15, 1.25 and 1.35 had obvious effective light absorption peaks in the wavelength range of 686~800 nm. The light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with a FF of 1.15 was higher than those with a FF of 1.25 and 1.35 within the wavelength range of 400~686 nm. In addition, the light absorption of PV solar cells with a biomimetic leaf-type hierarchical nanostructure with a FF of 1.15 was higher than those with a FF of 1, 1.05, 1.25 and 1.35 within the wavelength range of 686~800 nm. Therefore, the biomimetic leaf-type hierarchical nanostructure with a FF of 1.15 could enhance the light absorption and photocurrent greatly.

Fig. 13 Effects of the filling factor (FF) of top layer of large nanoparticle on the photocurrent of perovskite solar cells with biomimetic leaf-type hierarchical nanostructure.

Fig. 14 Effects of the filling factor (FF) of top layer of large nanoparticles on the effective spectral absorptivity of PV solar cells with a biomimetic leaf-type hierarchical nanostructure.

5. Conclusions

A serious optical loss was often observed in the ultra-thin planar perovskite solar cells. In this study, the idea of biomimetic leaf-type hierarchical nanostructure was introduced for reducing the optical loss and enhancing the light absorption. The geometrical parameters (ratio, radius and filling factor) of the biomimetic leaf-type hierarchical nanostructure was crucial to enhance the light absorption of perovskite solar cell. The particle swarm optimization algorithm was adopted to develop the full potential of biomimetic leaf-type hierarchical nanostructure from the perspective of optics. The following conclusions could be drawn:

- The biomimetic leaf-type hierarchical nanostructure could scatter the incident light with a long wavelength into a distinct orientation and enhance their optical path

length in the perovskite absorber layer to enhance the light absorption of the perovskite solar cell;

- The biomimetic leaf-type hierarchical nanostructure could enhance the light absorption of ultra-thin perovskite solar cell by maximum 39% at the long wavelength;
- The photocurrent of the perovskite solar cell with a biomimetic leaf-type hierarchical nanostructure was 8.4% higher than that of perovskite solar cell without biomimetic leaf-type hierarchical nanostructure;
- The ratio, radius and filling factor of the biomimetic leaf-type hierarchical nanostructure mainly influenced the effective light absorption of the perovskite solar cell in the long wavelength band.

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Supporting Information

Not applicable

Conflict of interest

There are no conflicts to declare.

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