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Numerical analysis of the angular insensitive photovoltaic light harvesting with the biomimetic scattering film inspired by the rose petal epidermal topography

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ABSTRACT

Understanding the angular insensitive light harvesting principle is very important to the performance prediction and the optimal design of photovoltaic devices. A biomimetic scattering film was fabricated in our previous work by replicating rose petal epidermal topography with polydimethylsiloxane. It was experimentally proved that devices coated with this scattering film showed remarkable improvement in angular insensitive light harvesting. To further explore the principle behind it, a numerical analysis method was presented in this paper to evaluate the performance of photovoltaic devices with biomimetic scattering films. The parabolic cone array with disorder geometric parameters was used to approximate the real rose petal epidermal topography. Firstly, the optical properties of the bio-texture with geometrical disorders are investigated by means of ray tracing methods. Its light scattering ability, transmission and light trapping efficiency were quantified though a specific simulation model. Then, two types of photovoltaic devices were simulated, involving thick silicon films and thin film organic solar cells. It was concluded that the light harvesting was attributed to two aspects, the light trapping efficiency of the scattering film and the device absorption rate variation under scattering light illumination. By discussing these two factors separately, it turned out that the light trapping efficiency dominated the light harvesting for an absorber with low angular sensitivity like the thick silicon film; while for the one with high angular sensitivity such as organic solar cells, the two factors both made significant contributions. Furthermore, the angular insensitive light harvesting was mainly achieved by the stable light trapping efficiency under varied incident angles. At last, the simulation developed for thin film solar cells combined ray optics and wave optics. Thus, performance with different device structures can be optimized from the calculation. All the analysis methodology in this paper can give a guide on other types of bio-textures and various applications not limited to photovoltaics.

1. Introduction

Light harvesting is always a key issue for photovoltaic devices, especially for the thin film solar cells which usually cannot achieve saturated absorption due to the nature of photovoltaic materials, such as organic or perovskite solar cells (Green et al., 2014; Heremans et al., 2010; Lunt et al., 2010; Xiao et al., 2014). The photovoltaic absorption can be improved usually by designing anti-reflection coatings, using special cell configuration of V or cone structure, introducing plasmonic or photonic nano-structure, engineering scattering texture interfaces and so on (Berginski et al., 2007; Chen et al., 2015; Dudem et al., 2016; Fan et al., 2012; Li et al., 2012a, 2012b; Park et al., 2016; Yu et al., 2014; Zhen et al., 2012, Yu et al., 2015a, 2015b). Among these methods, using scattering textures on the entrance surface of photovoltaic devices is very simple and effective. The scattering textures usually present some superior optical properties, such as anti-reflection, haze and high transmission, which can be used to enhance the photovoltaic absorption. The scattering textures can be nanostructured cellulose papers, thin film with wood composite-based film or biomimetic textures from plant epidermal topography and so on (Fang et al., 2014; Hünig et al., 2016; Huang et al., 2015; Kang et al., 2015; Zhou et al., 2014). Due to the high performance, low cost and simple fabrication process, the bio-surface textures have shown remarkable abilities for absorption enhancement and are attracting wide interest. For example,

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in the natural world, plant leaves have evolved to be very efficient at collecting light energy for living (Tsukaya, 2013; Huang et al., 2016), and flower petals have evolved to be colorful to attract pollinators for breeding (Qon et al., 1981). Thus, natural light scattering textures with high performance can be created by natural selection. Inspired by that, plant leaves surface textures were utilized in the design of a photovoltaic system and analyzed using perfectly periodic structures (Huang et al., 2016); flower petal topography was imprinted to form a scattering surface and the anti-reflection property affected by the disorders has been investigated (Fritz et al., 2017).

In our previous work, we have experimentally demonstrated that the absorption and angular insensitivity of thin film solar cells can be enhanced by using the scattering films based on rose petal topography (Zheng et al., 2017). This versatile biomimetic texture has been proven be very effective on traditional silicon solar cells, organic and perovskite thin film solar cells. However, the detailed principle of light harvesting and angular insensitivity of this biomimetic texture were not known very clearly and needed to be explored. Thus, a specific optical simulation model is established in this paper to better understand this principle, which can give better guidance for the performance prediction and the optimal design of photovoltaic devices. Based on our previous work, the optical model is improved by using the inverse concave replica of rose petal epidermal cells. In other related research, anti-reflection effects were usually used to explain the photovoltaic absorption enhancement (Fritz et al., 2017; Huang et al., 2016). It only gave the reflection of the absorber covered by scattering films, but paid little attention to device absorption rate variation under scattering light beams. In contrast, the main emphasis in this paper is placed on the light energy coupled into the absorbers and their response under scattered light, instead of the anti-reflection effects. This paper is organized as follows. Firstly, we developed a method to construct such an optical simulation model for the bio-texture. Four geometrical disorder parameters were involved to approximate the real rose petal epidermal topography and analyze their influence on the optical property. Then, the light harvesting principles were further investigated based on the test data from silicon wafer and thin film organic solar cells. Comparisons are made to show the difference between these two cases. At last, an analysis method combining the wave optics and the ray optics was applied in thin film solar cells to exploring the optimal device structures.

2. Optical simulation

2.1. Model construction

The scanning electron microscope (SEM) images of rose petal epidermal cells are given in Fig. 1(a) and (b). Based on these SEM images, the simulation models can be constructed. Smooth parabolic cones shown in blue in Fig. 1(c) are used here to represent the epidermal cells without taking the buckling on the cell cuticle into account. The cells are convex downward and are arrayed on a flat substrate. The neighboring cells are closely packed and overlap each other to cover the substrate as shown in Fig. 1(c). To clearly show the structure of the cells, the convex surfaces of the cells shown in red are also given in Fig. 1(c).

For the disorder-free models (Fig. 1(c)), the cones are arranged hexagonally and stand perpendicularly to the substrate plane. To imitate the real epidermis structure and explore the effects of disorders upon the optical properties, four geometrical disorder parameters of the parabolic cones are introduced, which are the position (p) with a standard deviation of σ_p, the orientation (the tilt angles (a) with a standard deviation of σ_a), and the size (heights (h) with a standard deviation of $\sigma_h(0.3r)$ and the bottom radii (r) with a standard deviation of $\sigma_r(0.3r)$). All these four parameters obey the Gaussian distribution and the standard deviations (σ) are used to evaluate the randomness. According to the SEM images, the values of these variables are set as $\sigma_p(0.5r)$, $\sigma_a(10^\circ)$, $\sigma_h(0.3r)$, and $\sigma_r(0.3r)$ respectively. For the position disorder, the location of each cell departs from its original position by a random distance with a standard deviation of 0.5r. As illustrated in Fig. 1(d), this topography is quite similar to the one observed from the samples shown in the SEM images in Fig. 1(a) and (b). For the orientation disorder, each parabolic cone tilts by a random elevation angle φ with a standard deviation of 10° following Gaussian distribution, and the tilting azimuth angles θ are distributed uniformly (Fig. 1(e)). For the size disorder, the parabolic cone has two independent geometrical parameters, heights (h) and bottom radii (r). Fig. 1(a) shows the mean value ($\bar{r}$) of the bottom radii of the cells is approximately equal to 15 µm. In the disorder situation, r of each cone will deviate from $\bar{r}$ by a random distance with a standard deviation of 0.3r (Fig. 1(g)). Similarly, the cone heights have a mean value of $\bar{h}$. When considering the disorders, the heights are also randomly assigned with a standard deviation of 0.3r (Fig. 1(f)).

2.2. Simulation details

Since the characteristic dimensions of each cell are much larger than the wavelength of light (350–800 nm), the ray optics is valid to describe the optical properties. Thus, we use a ray tracing method based on geometrical optics to evaluate the optical performance of the established model. According to the experimental data from our previous work, the replica from the rose epidermal cells was formed on a PDMS (polydimethylsiloxane) film. This material is considered as optically isotropic without chromatic dispersion and absorption and the refractive index is 1.42 in the simulation.

To achieve the optical properties of a random structure with high reliability and a desired calculation convergence, the optical incident area should be large enough to cover a large number of cells. In the calculation, the illuminated cell number is assumed to be greater than 300 and at least 3 times more cells are required outside the incident area to ensure that the energy received by the side boundaries is less than 0.5% of the total power of the light source. Through this way, a fast and stable convergence can be achieved. An unpolarized and parallel light beam is used here to approximate the sun light. Due to the nature of non-sequential ray tracing (Monte Carlo ray tracing), the number of rays traced is set to be 10^7 so as to reduce statistic noise and get reasonable results. It should be mentioned that the propagation of a light ray will be terminated in the optical simulation process once the energy of the light ray decreases to 0.1% of its original energy. This approximation is acceptable, and the computation speed can be significantly improved.

3. Results and discussion

The purpose of this work is to figure out how the scattering film (SF) can improve the absorption and the angular insensitivity of photovoltaic devices. Thus, we mainly focus on energy transfer from the light source to the absorption interface between SF and photovoltaic materials and its angular power distribution coupled into absorbers through the SF.

3.1. Scattering film optical properties

As mentioned above, it is assumed that cells are arranged hexagonally in the disorder-free model as shown in Fig. 1(c). Since other models with disorders are all based on this disorder-free model, we start with the calculation on disorder-free models. The height of the cell model will vary from 0.5r to 3r. Two parameters are defined to quantify the energy transfer. One is the ratio of the transmitted power through the SF to the incident, namely the total transmittance coefficient (t); the other is the ratio of the power of the rays hitting the exiting interface to the incident power, which is denoted by η. For different heights, the transmittance listed in Table.1 varies only in 1%, which is almost as