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Multi-physics analysis: The coupling effects of nanostructures on the low concentrated black silicon photovoltaic system performances

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A B S T R A C T

Black silicon (nanostructured front surface) can significantly improve the efficiency of the silicon solar cell by absorbing more solar irradiance. However, due to the band gap of the semiconductor material, most part of the absorbed solar irradiance is converted into heat to increase the temperature of solar cell. Especially under the concentrating condition, the waste heat is more. Besides, multi-physics coupling problem makes it difficult to study the effects of nanostructures on the performances of the low concentrated black silicon photovoltaic system. In this study, a multi-physics model of a low concentration photovoltaics (LCPV) that employs an all-back-contact black silicon solar cell is built. As for the multi-physics problem in LCPV, a multi-physics coupling mathematical model is developed. Its advantage is to couple near-flied optics, photoelectric conversion, and heat transfer. Furthermore, through parameter sensitivity analysis, it is proved that the coupling mathematical model is more accurate, because it takes full account of the nonlinear correlation between the output power and the temperature, and the effects of series resistance under concentrating condition. Hence, the mathematical model is used to investigate the coupling effects of nanostructures, and it is found that the nanostructure with lower reflectance may not be beneficial for the low concentrated black silicon photovoltaic due to the increased temperature. According to different circumstances, the maximum output power with the lower cost could be achieved by choosing the nanostructure with appropriate reflectance. At last, the dynamic analysis proves that the coupling effects of nanostructure lead to the result that the nanostructure with lower reflectance reduces the annual power generation per square meter of the low concentrated black silicon photovoltaic system by about 116 kW h/m^2 when the concentration ratio is 10.

1. Introduction

Due to more and more serious human related challenges to the environment, renewable energy has been gotten tremendous attention worldwide in recent years. As is well known, solar energy is one of the cleanest, most practicable, and most promising resource in all kinds of renewable energy resources nowadays, and the related researches are increasingly focused in this area [1–5]. In the field of solar energy utilization, photovoltaic devices have a broad development prospects due to high photoelectric conversion efficiency, easy installation, low maintenance, and strong adaptability. By the end of 2014, the global capacity of photovoltaics have reached over 150 GW [6].

In photovoltaic generation technology, the concentrated photovoltaics (CPV) plays an important role [7–10]. The key component of CPV is the concentrator that is mainly made of low cost optical devices, such as Fresnel lens and reflective mirrors [11]. Because the concentrator concentrates the sun light on a small sized photovoltaics, the CPV can improve the output power, and reduce the amount of semiconductor material which is the most expensive part. Compared to the high concentrated photovoltaics, the low concentrated photovoltaics (LCPV) can employ the monocrystalline silicon solar cell due to the lower operating temperature, so it has a lower cost advantage. Moreover, the low concentrator has a simpler structure, so that the LCPV is easier to install. These advantages make the LCPV get more and more researchers' attention. For example, Lamnatou and Chemisana et al. investigated the environmental profile of a dielectric-based 3D BICPV device [12]. Abu-Bakar et al. presented a novel type of LCPV concentrator known as the rotationally asymmetrical compound parabolic concentrator with a geometrical concentration ratio of 3.6675 [13]. Baig and Mallick et al. performed a case study on a 3D Cross Compound Parabolic Concentrator (3DCCPC) based low concentrating photovoltaic system, and presented the detailed optical analysis quantifying the losses based on the thickness of the encapsulant spillage [14]. Kong and Yao et al. studied the electrical and thermal outputs of a low

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concentrating photovoltaic-thermal hybrid system under different weather conditions, and find out that the electrical efficiency is 10% and the thermal efficiency is 56% on a clear day [15]. Freier and Sukki et al. analyzed the performance of a recently patented optical concentrator known as the rotationally asymmetrical dielectric totally internally reflective concentrator (RADTIRC) under direct and diffuse light conditions [16]. Yousef et al. performed a comparative performance analysis between a conventional photovoltaic system and a low-concentration photovoltaic system [17].

As previously described studies, LCPV has receives lots of attention. However, most of previous studies were focused on concentrators, where the front surface of the photovoltaics is assumed to be black body or with a specific absorptivity. In this case, the other important factor affecting the LCPV is ignored, namely, the nanostructured front surface. For LCPV, the concentration ratio is typically 2–10, therefore the nanostructured front surface is a significant way to improve the output power of the LCPV by increasing the absorbed irradiance. Especially for low concentrated black silicon photovoltaics, black silicon (nanostructured front surface) not only have the advantage of excellent antireflection for a wide range of wavelengths, but can also reduce the manufacturing costs because it is not necessary to deposit the antireflection layer. Therefore, it is necessary to also include the effects of nanostructures on the performance of the low concentrated black silicon photovoltaic system.

In general, the more absorbed irradiances mean that the photovoltaics can generate more power at room temperature. Therefore, the lower average reflectance is usually beneficial for the photovoltaics, so that most of studies about nanostructures were focused on the lower reflectance. For example, Zhong and Shen et al. made the average reflectance of the silicon nanostructure samples with different filling ratios and nanostructure lengths be less than 1% [18]; Ortega et al. exhibited the nanostructures with a very low reflectance, which is below 0.7% in the 300–1000 nm wavelength range [19]; Kuang and Lin et al. presented a teepee-like PC structure achieved by the high SF6/CHF3 ratio etching, and its average absorption can reach near 98.5% [20]; Jeong and Cui et al. etched the cone nanostructures on the front surface, which made the EQE of the ultra-thin device be larger than 80% in the spectrum of 400–800 nm wavelengths [21]. However, due to the bandgap of the semiconductor, only the part of the absorbed solar irradiance can generate the electron-hole pairs, and the rest is converted into heat to increase the temperature of photovoltaics. Therefore, the nanostructures with lower reflectance leads to not only the more electron-hole pairs, but also the more heat. Especially under the concentrating condition, the heat is more. Hence, the coupling effects of the nanostructure on performances of the low concentrated black silicon photovoltaic system should be investigated.

Furthermore, the working process of the low concentrated black silicon photovoltaic system mainly includes the propagation of sunlight on the nanostructured front surface, photoelectric conversion, and heat transfer, which are mutually coupled with each other. However, most of current studies just coupled the electricity and temperature, and did not consider the near-field optical characteristics. In addition, their way of coupling the electricity and temperature was to build the correlation equation of the temperature and the efficiency of photovoltaics, and which was then used as internal heat source for the heat transfer. This method has two flaws: (1) The correlation equation is assumed to be linear; (2) The concentration ratio is used as a constant coefficient of the correlation equation to calculate the efficiency at the corresponding temperature and concentration ratio.

In this paper, a LCPV model that employs an all-back-contact black silicon solar cell is built. A multi-physics coupling mathematical model is developed to deal with the complicated interactions among the near-field optics of nanostructure, the electrical characteristics of photovoltaics, and the heat transfer of low concentrated black silicon photovoltaic system. Meanwhile, this coupling mathematical model takes full account of the nonlinear correlation of the output power and temperature, and the effects of series resistance on solar cell under concentrating condition. At last, under the ideal conditions and the actual dynamic conditions, the coupling effects of nanostructures on the performances of the low concentrated black silicon photovoltaic system are analyzed respectively.

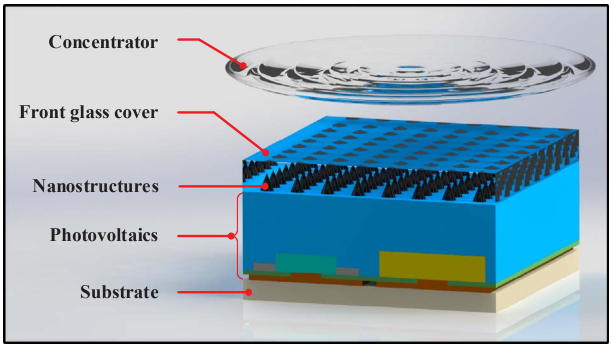

Fig. 1. Schematic of the low concentrated black silicon photovoltaic system.

2. Physical model

In this study, the low concentrated black silicon photovoltaic system mainly consists of the concentrator, front glass cover, photovoltaics, and substrate as shown in Fig. 1. Due to the simple preparation process and good anti-reflection, the cone nanostructures are chosen to be etched on the front surface of photovoltaics, and its dimension is determined by height H, base diameter D, and the space between two adjacent cone nanostructures L. In order to eliminate the influence of front contact electrode on the absorption of solar irradiance, the photovoltaics is chosen to be the all-back-contact black silicon solar cell.

Fig. 2 shows the 2D computational domain of all-back-contact silicon solar cell defined at the x-z plane. The standard AM1.5 solar light is vertically incident upon the solar cells. The cone nanostructures are etched on 2.2 Ω cm N-type crystal silicon substrate with a width of W_{sub} 250 μm and a thickness of T_{sub} 280 μm. On the back surface, the width of the contacts is W_{c} 30 μm, and the passivation layer is applied which results in a locally contacted structure. The n++ phosphorus high-doped (7.010^{19} cm^{-3}), n+ phosphorus low-doped (1.010^{19} cm^{-3}), and p+ boron low-doped (1.010^{19} cm^{-3}) are widths of $W_{\mathrm{n++}}$ 60 μm, $W_{\mathrm{n+}}$ 45 μm, and $W_{\mathrm{p+}}$ 105 μm. The n++, n+, and p+ regions with unique doping are thicknesses of $T_{\mathrm{n++}}$ 2.5 μm, $T_{\mathrm{n+}}$ 1.4 μm, and $T_{\mathrm{p+}}$ 5 μm, respectively. The series resistance is 0.5 Ω cm^2, and the shunt resistance is ignored because it is typically due to manufacturing defects. The surface recombination velocities at the contacts ($S_{\mathrm{n++,e}}$ and $S_{\mathrm{p++,e}}$) are 5.010^{6} cm/s. The surface recombination velocities at the non-contacted regions, $S_{\mathrm{n++,p}}$, $S_{\mathrm{n+,p}}$, and $S_{\mathrm{p+,p}}$, are 7.010^{3} cm/s, 1.010^{3} cm/s,

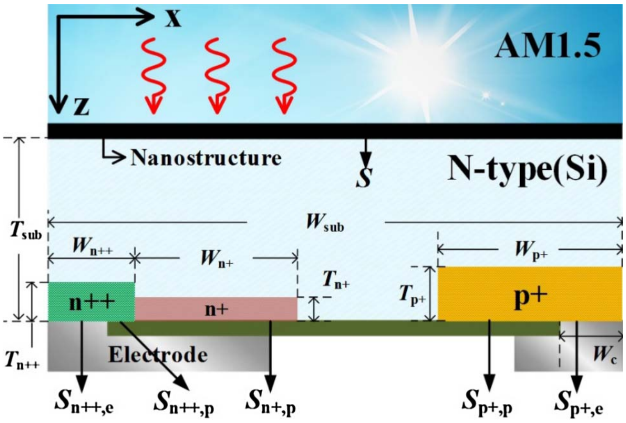

Fig. 2. Schematic of the all-back-contact black silicon solar cell.