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Light trapping mechanism of hemisphere cone arrays for silicon solar cells

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ABSTRACT

Hemisphere cone arrays (HCAs) is a popular light trapping structure in silicon solar cells. However, the light trapping mechanism research of that in solar cells is lacking. In this paper, the light trapping mechanism of the HCAs in silicon solar cells is studied by combination of numerical analysis and geometrical optics simulation. The results show that the HCAs structure can reduce surface reflectance by ~60% compared with flat structure by multiple injections of the incident light. At the same time, the HCAs can make ~43% unabsorbed light return to the absorbing layer of solar cells again. To verify the theoretical calculation results, a flat and a square hemispherical cone arrays PDMS thin films are prepared by a micro/nano-processing method, and the reflectivities of a silicon wafer covered the flat and the HCAs PDMS thin films were measured. The experimental measured results are basically consistent with the theoretical calculation results. The numerical calculation results also show that the total optical path length of the thin film Si solar cell covered with the HCAs structure increases from 2ω to 4ω.

1. Introduction

With increasing power demands, solar radiation is playing a more and more important role as a clean and inexhaustible energy source. By the end of 2015, the milestone of 200 GW of installed photovoltaic capacity was achieved, with an annual growth rate of ~40% from 2010 to 2015. The International Energy Agency (IEA) even predicted that, by the end of 2050, the 4600 GW of installed photovoltaic capacity will be achieved, and the photovoltaic generated energy will account for ~16% of global generated energy. However, the relatively high cost of manufacture and low photoelectric conversion efficiency (PCE), still impede the broad use of solar cells. To improve the PCE, many light trapping structures, such as nano/micro-pyramids (Mavrokefalos et al., 2012; Liu et al., 2014), nanowires (Xu et al., 2017; Anttu et al., 2017; Yan et al., 2017), nanocones (Xing et al., 2017; Jeong et al., 2013; Zhang et al., 2015) nanodomes (Zhu et al., 2010; Wu et al., 2013) and nanosphere (Wang et al., 2016; Jeong et al., 2010; Chen et al., 2015a, 2015b), were taken as an effective technique in different solar cells, especially thin-film Si solar cells. They have been proved that the light trapping structures have the capability of broadband light capturing, which can dramatically reduce the front-surface reflectivity and increase the effective optical path length in active layer, but many of them have been prepared with costly and/or destructive methods, such as lithographic, wet/dry etching (Chen et al., 2016; Hu et al., 2012). These light trapping structures not only increase the production cost, but also easily destroy the original structure which lead to the decrease of lifetime or the destruction of devices, because they are always fabricated inside the cells. Thus, the large scale applications of the inside light trapping structures are limited in the industrialization field.

To avoid the destruction of the light trapping structures, people turn their attention to surface light trapping technologies, which have the distinct advantages of non-disruption, and high reliability. The most common example of the surface light trapping or anti-reflection (AR) technologies is quarter-wavelength AR coatings, which have been widely used on the front surface of photovoltaic devices/modules (Tsui et al., 2014; Fan and Lin, 2014). However, their effectiveness has wavelength and incident-angle dependencies, and high-efficiency multilayer AR coatings rely on chemical or physical process, such as sol-gel (Lee and Yoon, 2014; Bae et al., 2011) or magnetron sputtering (Kim et al., 2014; Das and Ray, 2012), which increase the production cost. Another example is a low-cost, flexible, and 3D nanocone anti-reflection polydimethylsiloxane (PDMS, a low cost, environmental friendly, and highly transparent material) thin film, which was attached to the front surface of solar cells without any adhesive. But the light absorption in the PDMS layer and the middle air layer between solar cell and PDMS led to waste of the trapped light (Tsui et al., 2014). Qingkang

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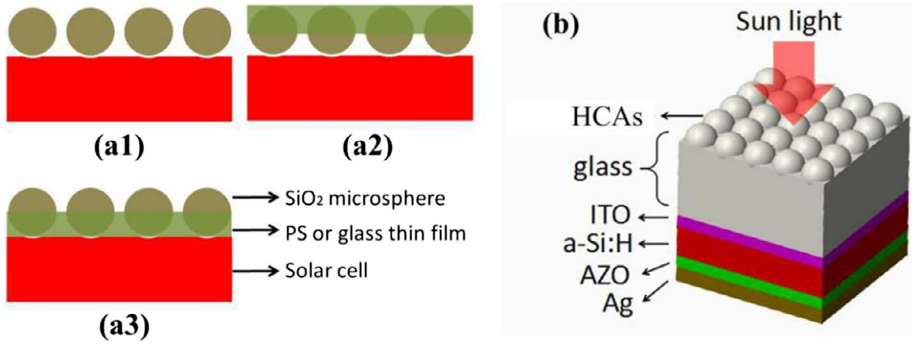

Fig. 1. (a) Schematic of the assembly process of the SiO_2 hemisphere texture surfaces. (a1) Deposition of close-packed monolayer silica microspheres via self-assembly method, (a2) deposition/spin-on polystyrene (PS)/glass thin film, and (a3) deposition of the PS /glass thin film to planar layer via heat treatment. (b) Schematic structure of the thin film Si solar cell with hemisphere cone arrays on the top surface.

Wang et al. have reported an efficient light-coupling scheme with a periodic micro-structured surface to enhance the performance of thin film solar cells, but the high fabricated cost of the periodic micro-structured surface impedes its broad use (Shen et al., 2015; Chen et al., 2015a, 2015b).

SiO_2 particles with unique photonic properties get the people's attention. It can effectively increase the PCE of solar cells through a suitable combination process on the top surface of the devices. The perfect function and prospect of the SiO_2 hemisphere texture surface is showed from the test and application in high-efficiency photovolatic field. Such as Jonathan Grandidier et al. have experimentally and theoretically demonstrated that the PCE of Si solar cell with a top SiO_2 layer was significantly higher than that of a flat device (Grandidier et al., 2011, 2013). Yuehui Wang et al. have experimentally proved that the monolayer of SiO2 hemisphere structure texture can serve as an omnidirectional AR structure in solar cells (Wang et al., 2009). The above researches have demonstrated that the surface SiO_2 microsphere arrays can effectively enhance the light absorption of solar cells. Fig. 1(a) shows a typical assembly process of the SiO_2 hemisphere texture surface (Ee et al., 2009; Chen et al., 2011).

Whether the 3D nanocone anti-reflection PDMS thin film or the SiO_2 hemisphere structure texture, in the end, their arrays belong to the hemisphere/similar-hemisphere cone arrays (HCAs for short). The HCAs show good light trapping properties in solar cells which have been widely proved by experiment. However, the theoretical research on the HCAs used in Si solar cells is not enough, especially on the light trapping mechanism. The light trapping mechanism research of the HCAs is not only conducive to further understand the nature of the light trapping, but also helpful for designing and optimizing the high efficient surface light trapping structure for photovoltaic. Fig. 1(b) shows the schematic structure of a thin film Si solar cell with the HCAs on the top surface.

Therefore, in this work, the numerical analysis and geometrical optics simulation approaches are used to study the light trapping mechanism of the HCAs in Si solar cell, including anti-reflection properties, total reflectivity, and total optical path length. In addition, to verify the theoretical calculation results, a flat and a square HCAs PDMS thin film are fabricated by a micro/nano-processing method. The reflectivity of a Si wafer covered a flat/HCAs PDMS thin film was theoretical calculated and then compared with experiment measured. At last, the increase of optical path length of the HCAs is discussed.

2. Experimental

2.1. Fabrication of the HCAs structure and characterization

The HCAs structure was fabricated on a PDMS thin film, so a structure glass with hemisphere pit arrays (HPAs) was fabricated firstly, and then the HCAs structure was copied by the HPAs glass. Fig. 2 shows the schematic of the key fabrication process. Firstly, a 3 inch glass wafer was cleaned by acetone and alcohol, and then boiled in a mixture of concentrated sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) with the volume ratio of 3:1 at 180 °C, to remove all kinds of organic residues. Secondly, the hemisphere pit arrays was fabricated on the glass substrate via a serious of micro/nano processing technologies, including the sputtering of metal seed mask, UV photolithography, ion beam etching, HF etching, and so on. Thirdly, the premixed PDMS (Sylgard 184, Dow Corning 10:1 ratio with the curing agent) was poured onto the HPAs glass followed by a degas and curing process. Finally, the PDMS HCAs film was obtained by directly peeling off the PDMS from the HPAs glass substrate. The period (the width of the pit) and depth of the pit arrays can be optimized by varying the mask size and the isotropic etching time in the buffered hydrofluoric acid solution (Chen et al., 2015a, 2015b). In this study, a mask with a period of 10 μm and a diameter of 2.5 μm was used, since structures with feature sizes of 10 μm are required in accordance with the spectral range of solar interest and the greater aspect ratio of the pit arrays is obtained.

It is worth mentioning that, the aspect ratio (depth to width) is less than 0.5 due to the isotropic property of the glass material, so the final HCAs obtained by the above method is the similar hemishpere cone array. But if a combined method of dry etching (reactive-ion etching, RIE) and wet etching (hydrofluoric acid etching, HF etching) is taken, we can obtain different aspect ratio pit arrays in the glass surface, and finally obtain different structure PDMS film, including hemisphere structure. More details for this will be published in the future by us.

The morphology of the HPAs glass and HCAs PDMS samples were observed by a field emission scanning electron microscope (FE-SEM, Carl Zeiss Ultra 55, Germany) operating at 3 kV. The UV–vis-NIR reflectivity and transmission spectra were carried out using a UV–vis-NIR spectrophotometer with an integrating sphere (Lambda 950, PerkinElmer, USA).

2.2. Simulation

In simulation, the particle tracking module of COMSOL Multiphysics was used to study the light trapping characteristics of the HCAs structure in solar cells. For the convenience of research on the light traveling in solar cells, the refractive indies of air, glass and silicon were selected as 0, 1.5 and 3.5, respectively. The imaginary parts of refractive index of them were neglected, and the wavelength of incident light was set to 650 nm. In order to visually view the traveling process, a model of hemispherical pit with the radius of 1(dimensionless) was built to simulate the light traveling in the HCAs. In addition, the method of Visual Basic (VB) programming was used to calculate the light reflectance, transmission, scattering and light path length.

3. Results and discussion

3.1. Optics characteristics

Based on the principle of ray optics, the light trapping properties of the HCAs can be simulated by the software of COMSOL Multiphysics. The HCAs can realize partially recycling of the incident light by a total internal reflectivity in the cone arrays. As shown in Fig. 3, the light