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Photonic enhanced thin-film solar cells with conformal nanostructure

Yupeng Tong[a], Qian Huang[a,*], Shichong An[a], Qianshang Ren[a], Li Zhang[a], Yi Ding[a], Xiaonan Lu[b], Ying Zhao[a], Xiaodan Zhang[a]

[a] Institute of Photoelectronics Thin Film Devices and Technique of Nankai University, Tianjin 300071, China
[b] Food Nutrition and Health Program, The University of British Columbia, Vancouver V6T 1Z4, Canada

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ABSTRACT

The interaction between light and photonic nanostructures is highly promising for light management applied to thin-film solar cells (TFSC). In this work, we introduce a strategy on conformal TFSCs on periodic nanostructures. A cost-effective self-assembly approach was used to fabricate monolayers SiO_2 spherical arrays of different diameters. The structural parameters were adjusted by plasma etching procedure. Obviously, far-field light trapping properties were identified in optical performance. The conformal structure was realized in the post-deposited *a*-Si:H absorber layer. Photonic enhanced guided resonances were identified through finite-difference-time-domain simulation, resulted in an enhanced absorption coefficient both theoretically and experimentally. The near-field optical performance makes 500 nm SiO_2 nanoparticles a promising choice for TFSC applications. To leverage the benefits of the photonic enhanced behavior, an *a*-Si:H solar cell with conformal nanostructure was fabricated as the first demonstration. Enhanced absorption was exhibited over the entire wavelength range. As a result, the photonic enhanced *a*-Si:H solar cell with conformal nanostructure based on ranged SiO_2 nanospheres yielded a broadband light-management promotion, and improved the overall external quantum efficiency by 20% and 2.7%, respectively in comparison to the planar and textured AZO referenced. These results provide a promising platform for future development of cost-effective photonic enhanced nanostructured optoelectronic devices with efficient broadband light management.

1. Introduction

Increasing the efficiency of thin-film solar cells (TFSCs) and reducing the cost of production has always been a goal pursued by researchers, and the use of an effective trap structure can increase the solar-cell current and thus improve efficiency. Light trapping using nanostructures has received increasing attention, and various methods for light capture are currently being studied, including photonic crystals, plasmonic nanostructures, nanowires, and dielectric gratings (Upping et al., 2011; Sheng et al., 2014; Wang et al., 2014; Huang et al., 2013; Guo et al., 2014; Xiao et al., 2015; Song et al., 2012; Naughton et al., 2010; Lee et al., 2011). The application of these mechanisms has been proven to enhance the current and efficiency of solar cells. In the design of light-trapping nanostructures, the structural geometry and choice of materials for light harvesting have a great impact. Spherical structure is the most special candidate, since its symmetry naturally allows the acceptance of a wide range of incident light and can enhance solar cells' light absorption capacity at different angles (Grandidier et al., 2012).

The application of SiO_2 spheres as light-trapping structures in solar cells has been widespread. SiO_2 has a very small absorption in the entire wavelength range and is suitable as the light-trapping structure in TFSCs. Chen et al. (2012) used a monolayer of SiO_2 nanospheres closely arrayed on a silicon wafer as a mask in the silicon surface etching nanocolumn and nanocone shape reduces the reflection of the surface of the silicon wafer. Huang et al. (2012) applied the randomly distributed submicrometer silica spheres to the front surface of amorphous silicon (*a*-Si:H) solar cells, and the efficiency of the solar cells was improved by 8.5%, demonstrating the scattering ability of the SiO_2 submicrospheres. The wavelength-scale SiO_2 dielectric spheres were embedded in the *c*-Si, and the total integrated absorption of incident photon flux across the visible AM-1.5 spectrum is on the order of 5–10% greater than the same geometry without any dielectric scatterers (Nagel and Scarpulla, 2010). Liang et al. (2014) and Ducros et al. (2016) also handled the hexagonal monolayer and closely arranged microspheres in a periodic trap electrode, and fabricating the high efficiency the *μc*-Si:H solar-cells of 8.56% (Liang et al., 2014) and enhancing the *a*-SiGe:H solar-cells current density by 10% (Ducros et al., 2016). Grandidier and co-workers

* Corresponding author.
E-mail address: carolinehq@nankai.edu.cn (Q. Huang).

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reported the a series of work on adding SiO_2 nanospherical arrays directly to existing thin-film solar cells (Grandidier et al., 2011, 2012; Grandidier and Atwater, 2012; Grandidier et al., 2013), in which the resonance mode of whispering gallery modes (WGMs) was excited by SiO_2 nanospheres thus to improve the light absorption of solar cells. These studies focused on the addition of a layer of nanospherical structure to a flat cell. In the simulation calculation, the conformal structure of the absorption layer and the spherical substrate was designed, and the absorption efficiency and absorption ability with different spheres were studied, while the theoretical analysis needs to be further verified by experiments (Yang et al., 2015). Aforementioned examples demonstrate the efficacy of the application of SiO_2 dielectric spheres in TFSCs, but the limits of the approach have yet to be investigated. In particular, the scattering layers have not been benchmarked against best-in-class control samples, such as solar cells with the same texture defined in the absorber, and their effects on the front-surface reflection and parasitic absorption have not been parsed.

In present study, we explore these limits by approaching the photonic enhanced absorber with conformal nanostructures. A cost-effective self-assembly approach was used to fabricate a hexagonal monolayer SiO_2 spheres with different diameters (d = 1500, 1000 and 500 nm), and the duty cycle was adjusted by plasma etching procedure. The optical properties of the SiO_2 spheres were studied in detail, then the *a*-Si:H absorption layer was deposited directly to investigate the light-trapping ability. The physical mechanism of the effect of SiO_2 spheres was investigated by simulation. To leverage the benefits of the conformal nanostructure, an *a*-Si:H solar cell was fabricated as the first demonstration. Although *a*-Si:H was used as the model material in this work, the developed conformal solar cells in the framework of the two-dimensional (2D) periodic SiO_2 nanospheres can also be used for other types of thin-film PV devices, such as organic solar cells and emerging high-performance perovskite solar cells.

2. Experimental methods

The fabrication procedure of the *a*-Si:H solar cell with conformal nanostructure on ranged SiO_2 spheres is schematically illustrated in Fig. 1. The hexagonal monolayer and closely arranged SiO_2 micro/nano spheres were fabricated using the "Langmuir-Blodgett" (LB) self-assembly technique (Wu et al., 2013; Retsch et al., 2009). The glass substrate used in the experiment was immersed in a H_2SO_4/H_2O_2 (2:1) piranha solution for 24 h to improve the hydrophilicity of the glass surface (Ho et al., 2011), followed by triple rinsing in deionized water. Silica spheres of different diameters (d = 1500, 1000 and 500 nm) were synthesized according to Stober's processing method (Stöber et al., 1968). The purified silica spheres were dispersed in an ethanol solution, and the final volume fraction was set to approximately 10%. An emulsion solution of SiO_2 spheres was then injected into the water to form a LB film in a hexagonal monolayer configuration at the air/water interface (Gao et al., 2015). Slowly pulling up the glass substrate that had been previously immersed in water vertically, the LB film was transferred to the glass substrate, and then dried at room temperature.

To make the SiO_2 spheres suitable for the front surface of the TFSCs' application, a plasma dry-etching process using CF_4 as the reaction gas was performed to adjust the spacing and duty cycle of the SiO_2 micro/nanospheres. In the fluorocarbon plasma, a series of reactions (*e.g.*, ionization, decomposition, and adsorption) will produce CF_x particles and polymers and provide better selectivity for etching the silica (Guo and Sawin, 2010).

A highly conductive AZO film was deposited on the surface of SiO_2 spheres as a front electric contact layer (sheet resistance $R_{sq} \sim 5\ \Omega sq^{-1}$; thickness, 1.0 μm) with the substrate area of 5 × 5 cm. AZO was deposited in a KJLC Lab-18 sputtering system using radiofrequency (RF) power and ceramic $ZnO:Al_2O_3$ target (1 wt.%). The deposition of the *a*-Si:H *p-i-n* cells was performed under plasma-enhanced chemical vapor deposition (PECVD) at a frequency of 13.56 MHz and temperature of ~200 °C. The intrinsic *a*-Si:H(*i*) layers were deposited using a SiH_4:H_2 mixture of 20:250 sccm at 1.9 Torr. For doping of the *p* and *n* layers, B_2H_6 and PH_3, respectively, were added. The thickness of the *p*, *n*-type doped layer and intrinsic absorption *I* layer was fixed at 10, 30 and 70 nm, respectively, which represented a compromise between absorption and stability against light-induced degradation (Benagli et al., 2009). The areas of a-Si:H solar cells fabricated in our experiments are 5 × 5 cm^2. A silver back-contact (thickness 100 nm) was deposited on top of the *p-i-n* structure by thermal evaporation through a shadow mask to define an area of 0.253 cm^2 for IV and EQE test.

A SUPRA 55VP scanning electronic nanoscope (SEM) (Carl Zeiss AG, Jena, Germany) was employed to characterize the surface morphology and cross-sectional features. The scattering transmittance (T_{sca}) was evaluated using a UV–Vis-near-infrared (NIR) spectrophotometer (Carry 5000, Varian) with an integrating sphere. Current-voltage (*J-V*) characteristics and spectral response were determined using a Wacom solar simulator (WXS-156S-L2, AM 1.5G MM) and a quantum efficiency system (QEX10, PV measurement), respectively. The external quantum efficiency (EQE) curves of all the solar cells in this study were determined at 0-V bias voltage. From the measured *J-V* curves, the open-circuit voltage (V_{oc}) and fill factor (FF) were obtained, and the current densities were normalized with the short-circuit current-density (J_{sc})

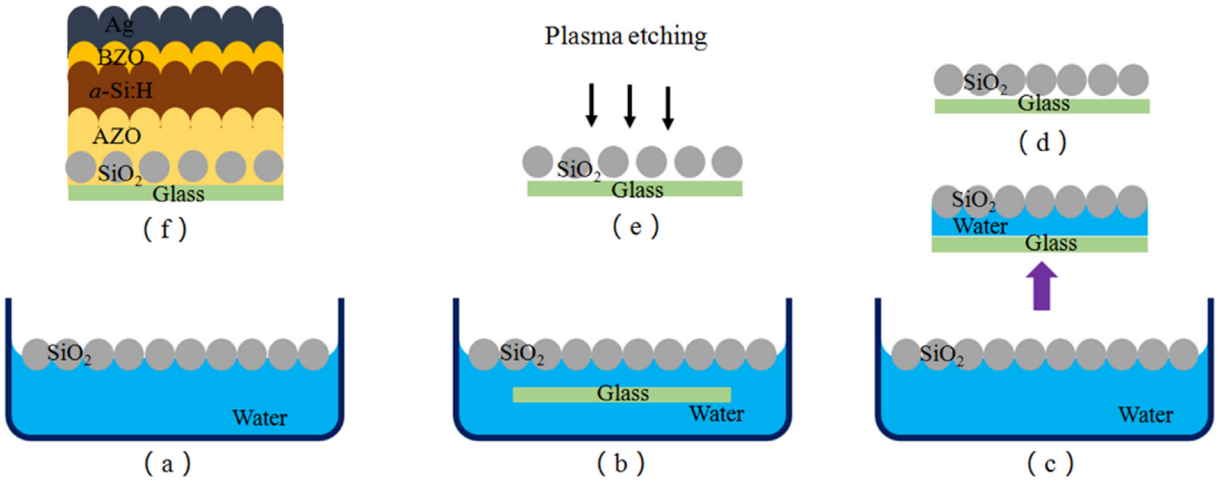

Fig. 1. Schematic procedure for fabricating *a*-Si:H solar cell with conformal nanostructures on ranged SiO_2 spheres (a–d) The hexagonal monolayer and closely arranged SiO_2 spheres were fabricated using the "Langmuir-Blodgett" (LB) self-assembly procedure (e) Adjusting the spacing and duty cycle by plasma etching method (f) Structure of photonic enhanced thin-film solar cells with conformal nanostructured interfaces.