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Cost-effective hollow honeycomb textured back reflector for flexible thin film solar cells

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ABSTRACT

We demonstrate an effective light trapping back reflector (BR) for flexible thin-film solar cells (TFSCs) that is composed of self-ordered flexible nanoporous anodic aluminum oxide (np-AAO) with hollow hexagonally-symmetric honeycomb textures (hollow-HSHT) under a cost-effective anodic oxidation approach. The dielectric nano-scatters are well compatible with nearly all types of TFSCs, including cells produced using high temperature processes. The performance of the hollow-HSHT nanostructure were investigated both experimentally and theoretically. The enhanced diffraction behavior, guided resonance and light absorption were identified through finite-difference-time-domain (FDTD) simulation. A highly conductive AZO film was deposited on the hollow-HSHT as a back electric contact for making solar cells. As a result, the flexible and periodic hollow-HSHT based BR yielded an efficiency of 8.3% for thin-film a-Si:H solar cell, which is much higher than the efficiency of 6.7% for the reference cell on the flat AZO back contact. Furthermore, the hollow-HSHT based BR provides a means of enhancing absorption in whole wavelength range, thus opening an approach for creating high-efficiency, low cost flexible TFSCs.

1. Introduction

For the further development and world-wide market growth of photovoltaic (PV) power generation, a reduction of the investment costs of the PV system is one of the major issues. To reduce the usage of materials and the production cost of modules, a substantial amount of researches have been focused on lightweight and mechanically flexible thin-film solar cells (TFSCs) [1]. Due to the significantly reduced thickness, thin film silicon solar cells and modules incorporating amorphous (a-Si:H) or/and microcrystalline (μc-Si:H) silicon as the absorber materials, light trapping, i.e. increasing the path length of incoming light, plays a critical role for device performance. Most light trapping schemes are based on texturing the interfaces of the solar cells [2–4]. The common approach is usually based on rough randomly texture substrates [5]. However, the theoretical understanding of such rough surfaces is presently still poor, where both the layer thickness and the wavelength of the light have the same order of magnitude [2]. Alternatively, applying a periodic light trapping array applies an effective method to improve the optical properties in TFSCs. A number of light trapping schemes have been proposed and demonstrated by using nanostructures [6–11], including nanobowls, nanoshells, nanocones, nanowires, nanodomes and zigzags to achieve advanced light trapping through guiding the incident light into the absorber layer and strongly light scattering for the increase of the optical path length.

Hexagonally-symmetric honeycomb textures (HSHT) have been proposed and demonstrated to achieve advanced optical performance in silicon based TFSCs [12–15]. Laboratory-fabricated cells have achieved HSHT by photolithographic patterning and wet chemical etching for μc-Si:H solar cells [13]. Despite the excellent optical performance of these surface textures, their dependency on complex and expensive photolithographic patterning processes has prevented their application in commercial production [12,13]. Sai et al. patterned honeycomb textured Al substrates fabricated by anodic oxidation and post-etching process in TFSCs with significant enhancement in spectral response and efficiency [14,15], which provide a cost-effective approach to realize effective light trapping nanostructure in TFSCs.

In this study, we put forward the application of self-ordered hollow-HSHT nanostructure for flexible TFSCs. Anodic oxidation was chose to achieve the nanoporous anodic aluminum oxide (np-AAO) on the flexible aluminum foil. Differential from the similar approach has been reported by the AIST group as cited by refs [13–15], we omitted the post-etching process in the anodic

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oxidation approach, and retained the hollow hexagonally-symmetric honeycomb nanotextures which supposed to provide additional photonic management for the flexible TFSCs.

The structural and optical properties of these hollow-HSHT light trapping nanostructure were characterized. We also numerically demonstrate this performance using full-field finite difference time-domain (FDTD) simulations. The enhanced diffraction behavior and guided resonance were identified to achieve advanced light trapping through guiding the incident light into the absorber layer and strong light scattering for the increase of the optical path length. Further, a transparent and conductive AZO covering layer was deposited by magnetron sputtering over the hollow-HSHT nanostructure, generating a composite structure with electrical conductivity and then composing a hollow-HSHT based BR for flexible TFSCs. In this case, the highly conductive AZO provides the lateral current path and minimizes the Ohmic losses. In addition, the dielectric scatters are well compatible with nearly all types of TFSCs, including cells produced using high temperature processes. Finally, we correlated the hollow-HSHT based BR properties to the *n-i-p* a-Si:H solar cell performance. Thus, the results reported here propose a promising and cost-effective candidate for flexible TFSCs.

2. Experimental methods

Np-AAO arrays with hollow-HSHT nanostructure were fabricated through a two-step anodization process [16]. All of the electrochemical experiments were conducted in a two-electrode electrochemical cell using a graphite counter electrode and a potentiostat (Hua Tai electronics co., LTD, HCP10-250) equipped with a voltage multiplier. The electrolyte temperatures were accurately controlled by a Julabo refrigerated / heating circulator (Ping Xuan scientific instrument co., LTD) and were validated with a glass thermometer before each experiment.

A highly conductive AZO film was deposited on the hollow-HSHT nanostructure and functional cell as a back electric contact (sheet resistance R_{sq} : $\sim 15\ \Omega \text{sq}^{-1}$, thickness: 500 nm) using RF magnetron sputtering from a ceramic ZnO:Al_2O_3 target (1 wt%) in a KJLC Lab-18 sputtering system. Note that the hollow-HSHT nanostructure is dielectric, and the back electric current transports laterally in this AZO layer and is collected by the cathode. The silicon-based thin films (n-a-Si:H, p-nc-Si:H and i-a-Si:H) were fabricated using a radio frequency plasma-enhanced chemical-vapor deposition (RF-PECVD) process. The evaporated ITO front contact with an area of 0.253 cm^2 was used to define the area of the solar cells. The final structure in the *n-i-p* a-Si:H solar cell was BR/n-a-Si:H (15 nm)/i-a-Si:H (300 nm)/p-nc-Si:H (15 nm)/ITO (80 nm). For comparison, sputtered AZO (100 nm) were deposited on Al foil to composite the flexible and flat BR.

Atom force microscope (AFM; SPA 800, SII Nanotechnology) measurements were carried out to investigate surface morphologies and cross-sectional features of the hollow-HSHT nanostructures. The scattering reflectance (R_{sca}) were evaluated using a UV–vis–NIR spectrophotometer (Carry 5000, Varian) with an integrating sphere. The calculated reflectance haze (H_R) was determined as the fraction of diffuse (scattering angels exceeding 5°) reflectance that constituted the total reflectance: $H_R = [R_{sca} - R_{spe}]/R_{sca} \times 100\%$. Current-voltage (J-V) characteristics and spectral response were measured with a Wacom solar simulator (WXS-156S-L2, AM1.5GMM) and a quantum efficiency system (QEX10, PV Measurement), respectively. The external quantum efficiency (EQE) curves of all the solar cells in this study were measured at 0 V biased 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}) values obtained from *EQE* measurement.

In this letter, the FDTD algorithm was used to calculate the scattering fraction, the electrical field intensity $|E|^2$ distribution and the external quantum efficiency of the solar cell, $EQE(\lambda)$. The optical constants as a function of wavelength for each of the materials used in the simulation were measured in our laboratory by ellipsometry WVASE32 and then fit to the FDTD data by a multi-coefficient model, which accurately accounts for broadband linear material dispersion [17,18].

3. Results and discussion

The hollow-HSHT nanostructures were primarily achieved by a classical two-step anodization process on cleaned and annealed Al foils in 0.1 M H_3PO_4 under oxidation voltage ranged from 140 to 180 V, symbolled as sample a (140 V), sample b (160 V) and sample c (180 V), respectively. The hollow-HSHT nanostructure was formed during the self-ordering anodization process, as identified in Fig. 1. The structural parameters as average pore diameter and periodicity were extracted from the cross-sectional profiles of the periodically hexagonal structures (Fig. 1d–f), as illustrated in Fig. 2. Apparently, the structural parameters increase directly proportional to the applied voltage, with the average pore diameter and the periodicity of the hollow- HSHT increase from 285 to 336 nm and 535–616 nm, respectively. This means that according to adjust the oxidation voltage, we can controllably manage the light modulating properties of the hollow-HSHT nanostructure.

Surface morphology is important for light scattering in thin film n-i-p-type solar cells. A great root-mean-square (RMS) roughness always results in an enhanced EQE in the long wavelength range, as cited by Refs. [19–21]. But the performance of the hollow hexagonally-symmetric honeycomb nanostructure in the photonic management for TFSCs has not been confirmed yet. In this paper, a theoretical study was calculated in order to facilitate the understanding of photonic modulating mechanisms of this hollow-HSHT nanostructure, which can be employed to enhance the absorption in solar cells. We depicted a flat model for both the nanostructure and the based TFSC for FDTD simulation to discuss the mechanism in photonic management and the performance in solar cell application.

Fig. 3 depicts the three-dimensional (3D) model of the conformal structures with the hollow-HSHT nanostructure investigated in our simulation. In order to analysis the major issue, we simplified three models for different simulations. The hollow-HSHT model was abstracted as periodic hollow hexagonal np-AAO configurations strictly adhered on an Al foil as described in Fig. 3a. A thin film a-Si:H absorber layer covered on the hollow-HSHT for electric field distribution simulation as described in Fig. 3b. When we want to obtain the electric field distribution in the near field vision and the scattering distribution in the far field version which were both provided by the hollow-HSHT nanostructure, we omitted the conductive AZO layer as depicted in Fig. 3a and b. When we want to obtain the whole cell performance in which the highly conductive AZO and ITO layers provides the lateral current path and minimizes the Ohmic losses, we included the transparent conductive layers in the cell model. A detailed hollow-HSHT based flexible TFSC model was illustrated in Fig. 3c.

Fig. 4 depicts the electric field distribution of Fig. 3b (Model B) with structural parameters extracted from sample c (Fig. 1c) while the thickness of a-Si:H absorber layer is set at 300 nm, keeping in consistent with the thickness used in the solar cell. The resulting two-dimensional electric field distribution map shows a large number of features for which the photonic managing is strong. The features arise from the resonant coupling of sunlight to a