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Investigation of 3-dimensional structural morphology for enhancing light trapping with control of surface haze

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ABSTRACT

A comparative study of 3-dimensional textured glass morphologies with variable haze value and chemical texturing of the glass substrates was conducted to enhance light trapping in silicon (Si) thin film solar cells (TFSCs). The light trapping characteristics of periodic honeycomb structures show enhanced transmittance and haze ratio in numerical and experimental approaches. The periodic honeycomb structure of notched textures is better than a random or periodic carved structure. It has high transmittance of ~95%, and haze ratio of ~52.8%, and the haze property of the angular distribution function of transmittance shows wide scattering angles in the long wavelength region because of the wide spacing and aspect ratio of the texture. The numerical and experimental approaches of the 3-D texture structures in this work will be useful in developing high-performance Si TFSCs with light trapping.

1. Introduction

Light trapping in thin film solar cells is commonly achieved by incorporating a rough surface at the front transparent contact electrode layer; deposition is the first step of the fabrication process of thin film solar cells (TFSCs) [1]. For p-i-n solar cells, the transparent conductive oxide (TCO) films develop textured surfaces during their deposition or growth procedure or in subsequent etching steps after the deposition, which helps scatter the light to be trapped in thin film solar cells. High short circuit current densities (J_{SC}) have been reported with properly designed textured surfaces in many experimental and computational approaches [2–4]. Micro-scale textured surfaces can increase the optical path length of incident photons with energies within or near the band gap edge of the solar cell's absorption layers [5]. At the same time, the textured surface geometries can reduce reflection at the front surfaces. Thus, enhancing the scattering of light in the broadband wavelength region is highly desirable for improving the efficiency of thin film solar cells on a glass substrate.

Conventional light trapping schemes of silicon TFSCs focus on the engineering method of making random textured surfaces that can scatter and diffract the absorbable photons to oblique angles and hence enhance the path length in the absorption layers [6–8]. For a superstrate-based solar cell configuration, glass/TCO films with rough surfaces prepared by naturally-textured-deposition or post-deposition-etched methods are mostly used as front contact electrodes in Si TFSCs, where indium tin oxide (ITO) [9], fluorine-doped tin oxide (SnO_2:F) [10], and aluminum-doped zinc oxide (ZnO:Al) [11] are commonly used. Fig. 1 shows the trend of high J_{SC} values reported for hydrogenated amorphous silicon (a-Si:H) [12–15], hydrogenated microcrystalline silicon (μc-Si:H) [4,16–20] single junctions, and tandem solar cells [21–25] with various (random, periodic, and honeycomb) light trapping structures. In Fig. 1, most J_{SC} values were obtained with small-sized random structures, but recent values (solid marks in Fig. 1) for μc-Si:H and a-Si:H cells were obtained in periodic and honeycomb structures in micro scale; the maximum current density was 29.4 mA/cm^2 in a

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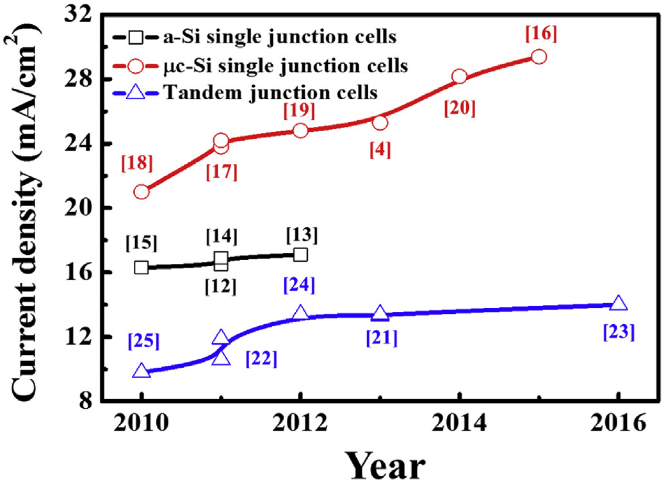

Fig. 1. Research trends in current density of amorphous, microcrystalline silicon and tandem thin film silicon solar cells, respectively.

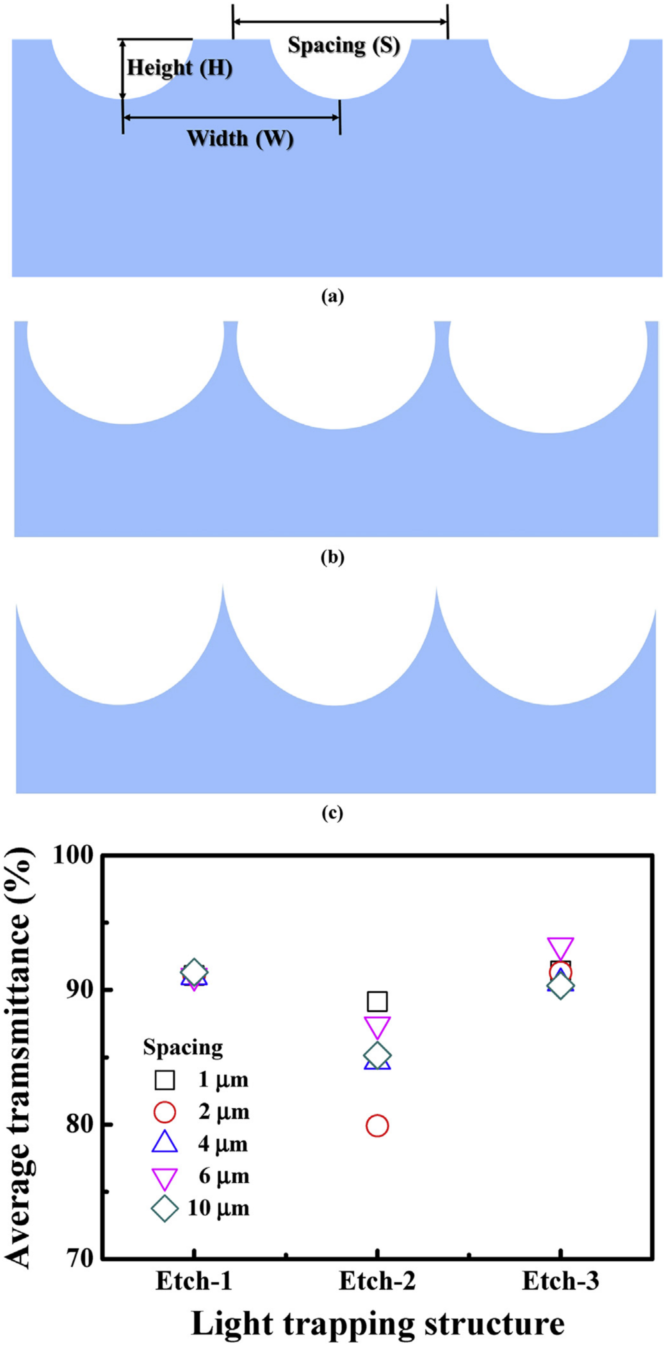

Fig. 2. Etching steps of (a) Etch-1, (b) Etch-2, (c) Etch-3 as the glass etching proceeds, and (d) optical average transmittance as function of spacing in etching step using FDTD simulation.

microcrystalline silicon single junction cell with a periodic honeycomb textured surface structure [16]. Thus, more studies using periodic structures are expected to produce higher J_{SC} for various Si TFSCs in future.

For light trapping, geometric parameters such as size and root mean square (RMS) roughness of texture shapes and spacing, and aspect ratio of periodic structures are important. In this work, we investigate the geometric parameters of micro-scale texturing on glass substrates to improve the optical properties for TFSCs. Fabrication methods of periodic textured glass structure are presented along with the experiments on the micro-scale patterns and etching of glass substrates. We show an improvement in transmittance and haze ratio of the honeycomb textured glass morphology with numerical simulation for a-Si:H/μc-Si:H tandem solar cells. Finite difference time-domain (FDTD) simulations are used to explain the light trapping mechanism and optimization of the light trapping structures. Three different structures: random, periodic (positive carved pattern), and honeycomb surfaces—commonly used in Si TFSCs—are compared with simulation and experimental results.

2. Experimental

To design and analyze the light trapping structure type, we performed finite difference time-domain (FDTD) simulations using spacing and aspect ratio (A/R, the ratio of height to spacing in Fig. 2(a)) as the geometric parameters. Based on the simulation results, we fabricated light trapping structures on Corning Eagle XG glass substrates. Honeycomb texture structures were patterned on glass substrates by wet chemical etching with a hard mask of photoresist/hexamethyldisilazane (PR/HMDS). The hard mask honeycomb patterns were formed by a general photolithography process. An HMDS layer was coated using a spin coater with sequential rotation steps (1st step: 1000 rpm, 5 s, 2nd step: 2000 rpm, 40 s, and final step: 1000 rpm, 5 s) and then baked for 3 min at 150 °C to harden HMDS between the glass and the PR mask layer. Similarly, the PR (AZ GXR-601-46 cps) was also stacked by the spin coater (1st step: 1000 rpm, 5 s, 2nd step: 5000 rpm, 20 s, and final step: 1000 rpm, 5 s) and baked in a dry oven (110 °C, 10 min). The honeycomb pattern was transferred onto the PR/HDMS by ultraviolet photolithography and finally baked for 15 min at 140 °C. Circular holes (3 μm) were opened in a 6 μm period on the glass substrates, which were selected from the FDTD simulations. An optical microscope system was used to confirm that all the observed holes were of size ~3 μm (±0.2 μm); we regularly monitored more than 5 points in each sample (5 cm × 5 cm).

The chemical etching for the glass texturing was performed in a circulating wet etching system where the etching temperature (room temperature) was kept stable during the process. The glass substrates with the PR/HMDS masks were etched in dilute hydrogen fluoride (HF) etchant (HF 0.5%) solutions; the HF etchant solutions were carefully selected in our preliminary experiments to control the etched surfaces [26]. To compare light trapping