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Wideband Light Scattering of Periodic Micro Textured Glass Substrates for Silicon Thin-Film Solar Cells

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A glass texturing process was developed to enhance the light scattering in the wideband wavelength range for thin-film hydrogenated amorphous silicon solar cells. Periodic honeycomb structures were patterned on glass substrates by a simple photolithography and chemical wet-etching process using HF (10%) solutions. We investigated the optical properties of the textured glasses for various etching times (i.e., the statuses of the etching steps), which were characterized using optical measurements and finite-difference time-domain simulations. We found the reproducible texturing conditions for obtaining high transmittance and haze values, and the angular distribution measurements showed that the scattered light is diffracted and trapped within the solar cell. The textured glass substrates showed a maximum transmittance of 95.5% and a haze ratio of about 61% in the wideband wavelength range, and the finite-difference time-domain simulation expected a very high short-circuit current density of ~21.9 mA/cm^2 for a single-junction thin-film hydrogenated amorphous silicon solar cell employing the honeycomb textured glass substrates, which will be useful for developing high-performance thin-film hydrogenated amorphous silicon solar cells.

Keywords: Reflectance, Haze Ratio, Light Trapping, Thin Film, Solar Cell.

1. INTRODUCTION

Light-trapping techniques are used to enhance the absorption of the incident light in thin film (TF) solar cells. It has been shown that a higher short-circuit current density (J_{SC}) can be achieved with a textured surface using experimental and computational approaches.[1–3] Hydrogenated amorphous silicon (a-Si:H) solar cells have many advantages as TF solar cells; Si is a nontoxic and abundant material; thus, TF a-Si:H solar cells can be feasibly produced on large-scale glass substrates at a low cost. The fabrication processes of a-Si:H are mature in that they have already been used to produce solar cells as well as displays and other semiconductor devices. However, the low absorption of TF a-Si:H cells needs to be improved to increase their performance. Therefore, microscale surface textures can be utilized to increase the optical path length of the photons near the band edge of the photoactive layer.[4] These micro textured surface geometries that can simultaneously reduce the surface reflection and scatter the light in the broadband wavelength region are highly desirable for high-efficiency solar cells using glass substrates.

The conventional light-trapping scheme of TF solar cells has focused on the engineering of randomly textured surfaces, which can completely scatter or diffract the absorbed photons to oblique angles and hence enhance the path length within the absorption layers.[5–7] For a superstrate-based solar-cell configuration, front-glass/transparent conductive oxide (TCO) films with a natural or post-etched TCO rough surface are mostly used to trap the incoming light. Common TCO materials such as indium tin oxide (ITO),[8] fluorine-doped tin oxide (SnO_2:F),[9] and aluminum-doped zinc oxide (ZnO:Al)[10] are employed as the front contacts of TF a-Si:H solar cells. The improvements in the optical properties due to TCO materials may be limited for a randomly textured surface.

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In this work, we developed a glass texturing process for a periodic honeycomb structure on glass substrates by using general photolithography and simple chemical wet-etching methods to improve the light-trapping properties for TF a-Si:H solar cells. The optical properties of the textured glasses were characterized with transmittance and haze measurements, which were also confirmed with optical simulation by the finite-difference time-domain (FDTD) method, and measurements of the angular distribution (AD) of the transmitted light for light trapping. In order to estimate the light-trapping effects on the TF solar cells, we calculated J_{SC} of TF a-Si:H single-junction solar cells on textured glass using an FDTD simulation.

2. EXPERIMENTAL DETAILS

Honeycomb patterns were created on thin a-Si:H mask layers (~0.2 μm) on top of glass substrates by using an ultraviolet (UV) photolithography. Circular holes (diameter of ~3 μm) were patterned on the mask layer and spatially repeated in a period of 3×3 μm, imitating the honeycomb geometry. Then, the glass substrates were textured by the chemical etching process using diluted hydrogen fluoride (HF 10%) etchant solutions for 30–120 s. After removing the residual masks with a reactive-ion etching method, the etched textures on the glass substrate were observed using focused ion-beam (FIB) spectroscopy (Model: TESCAN Lyra Dual Beam FIB FEG with energy dispersive X-ray spectroscopy (EDS)). For the optical characterization of the textured glass, the total and diffuse transmittances were measured with an integrating sphere of a quantum efficiency measurement system (QEX7, PV Measurement Inc.), and the AD of the light transmitted through the textured glass was investigated using an in-house goniometry measurement system and FDTD simulation (ExpertOLED) for the degree of etching.

3. RESULTS AND DISCUSSION

Figure 1 shows the cross-sectional views of the textured glass samples for various etching times: (a) Etch-1 (early-etching step): 30 s, (b) Etch-2 (high-texture-etching step): 90 s, and (c) Etch-3 (over-etching step): 120 s. The isotropic etching of the HF solutions increases the circle size and the etching depth of the textured glass substrates as the etching time increases; the diameters of the circles for Etch-1 and Etch-2 are ~3.27 and ~4.73 μm, respectively, in Figures 1(a) and (b). As the chemical etching progresses from the early-etching step to the high-texture-etching step, the textured circles become closer and meet adjacent circles, and the etching depth becomes higher. If the etching process progresses to the over-etching step, the texturing appears as a rounded hexagonal shape, and the etching depth gradually decreases as the etching time increases; Figure 1(c) shows the sample taken from the over-etching step, and its average etching depth is ~1.1 μm, which is smaller than the depth of 1.74 μm for Etch-2 in Figure 1(b).

Figure 2 shows the simulated and measured total transmittances ((a) simulation, (b) experiment) and haze ratios ((c) simulation, (d) experiment) of the textured glass substrates. In Figure 2, the transmittance behaviors of the samples show similar trends in both the simulated and measured results. The textured surfaces changed the optical transmittance behaviors of the etched samples. Note that the average transmittance of Etch-1 in the wavelength range of 400–1100 nm is ~92.7%, which is similar to the transmittance of bare glass substrates (Corning glass), but the transmittances of Etch-2 and Etch-3 are 95.4% and 95.5% respectively, which are slightly higher than that of bare glass. This is because the textured surfaces reduce the reflectance and enhance the total transmittance. The haze ratio of Etch-1 is ~5%-slightly higher than 1% for bare glass, but the haze ratios of Etch-2 and Etch-3 are a high value of ~61.7%.

To further investigate the light scattering at the micro sized textured surface of glass, we measured the AD of the light transmitted through the textured glass substrates, which are shown in Figures 3(a) and (b). For this measurement, we used two lasers with different lasing wavelengths of 405 and 975 nm as incident light sources in order to compare the light-trapping properties at short (405 nm) and long (975 nm) wavelengths. In Figures 3(a) and (b), the scattered light generally decreases exponentially as the scattering angle increases, and the shorter-wavelength light scattered more than the longer-wavelength light. The Etch-1 sample exhibited a similar transmittance to the

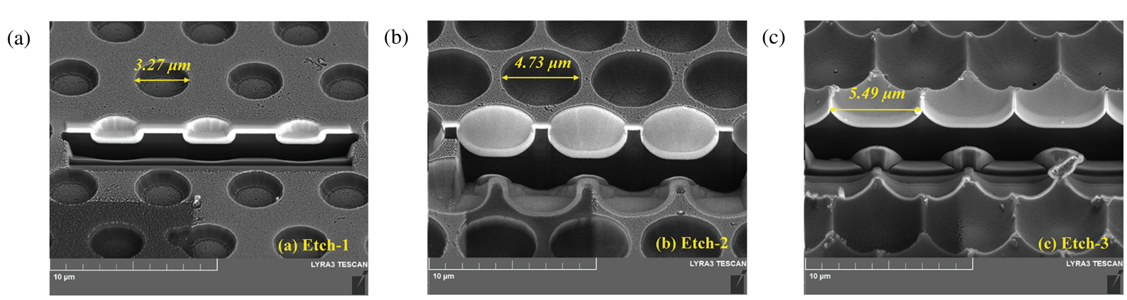

Figure 1. FIB cross-sectional views of textured glass surface morphologies: (a) Etch-1, (b) Etch-2, and (c) Etch-3 as a function of time at fixed 10% HF etching solution.

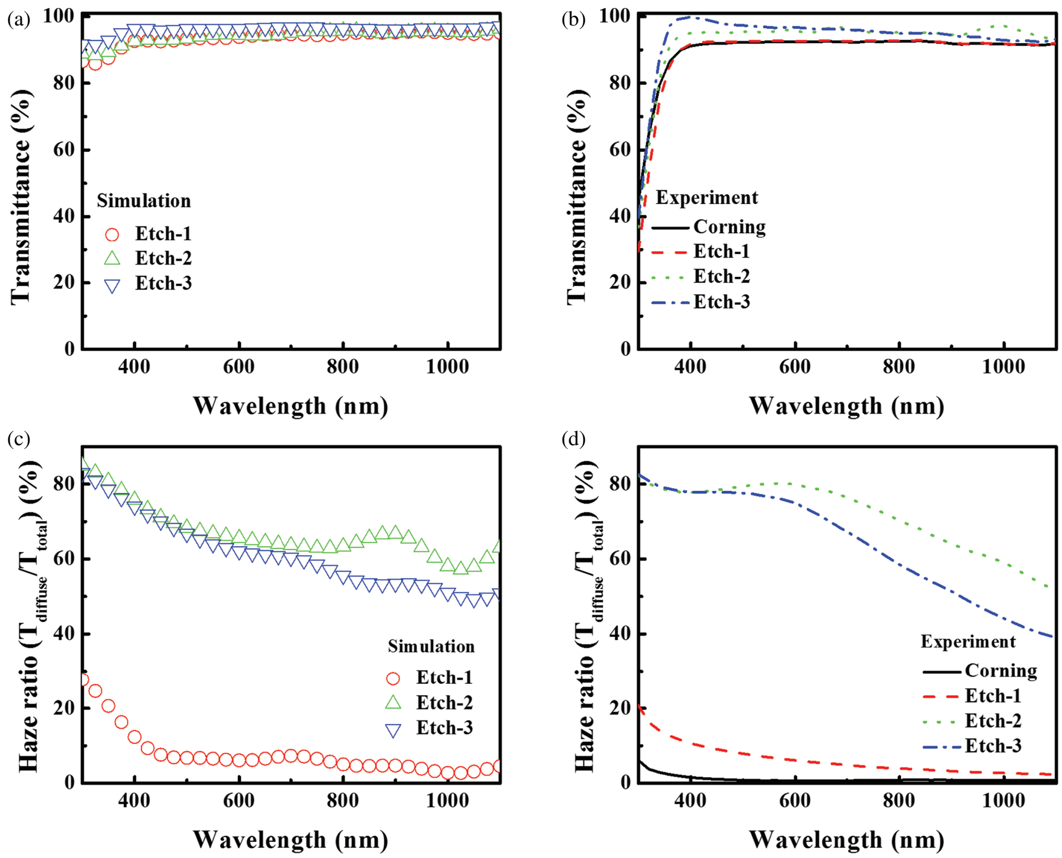

Figure 2. Simulation and experimental results of the optical properties of different textured glass surface morphologies. Transmittance: (a) Simulation and (b) experiment. Haze ratio: (c) Simulation and (d) experiment.

bare glass substrate but still has a small amount of scattered transmitted light and exhibits the AD in Figures 3(a) and (b). In Figures 3(a) and (b), Etch-2 and Etch-3 exhibit periodic peaks in the AD of the transmitted light; the period for the 405-nm wavelength is smaller than that of the 975-nm wavelength. The intensity level of the AD curve of Etch-2 is similar to that of Etch-3 for the 405-nm wavelength (Fig. 3(a)), but the intensity level of the AD curve of Etch-2 is higher than that of Etch-3 for the 975-nm wavelength (Fig. 3(b)). From the haze results in Figures 2(c) and (d), the haze ratios of Etch-2 are almost the same as those of Etch-3 in the short-wavelength region, but the haze ratios of Etch-2 become higher than those of Etch-3 in the long-wavelength region.

It should be noted that for Etch-2 and Etch-3, the haze ratios improved considerably for the entire wavelength region after the etching process, and wide scattering angles are present even at long wavelengths, which implies that the incident light that normally enters the glass substrates can be effectively scattered and trapped inside the TF solar cells. In periodic structures, the multiple functional components (multiple diffraction and dispersion) result in enhancements in the scattered and diffused light. This phenomenon is related to the textured geometrical structure of glass—the etching depth and the period of the textured honeycombs (i.e., the size of the etched circles).[11,12] The longitudinal depth (the period of the textured honeycombs) is related to an increase in the extent of light scattering in the long-wavelength region.[11] In this work, we used a spatial period of 6 μm in the honeycomb structure, which is sufficiently long to support the scattering in the long-wavelength region. The etching height is related to the variation in the phase ($\varnothing_d$) of the incident light as[11,12]

$$\varnothing_d = \frac{4\pi \cdot n_{\text{air}} d}{\lambda} \tag{1}$$

where n_{air} is the refractive index of air, d is the etching depth, and λ is the wavelength of the incoming light.

For Etch-2, and Etch-3, the phase variations are over 17π and 11π for the 405-nm wavelength, which are sufficiently high to fully scatter and diffract the incoming light. For the 975-nm wavelength, the phase variation of Etch-2 is 7π, which is higher than 5π of Etch-3; thus, the haze ratios of Etch-2 are slightly higher than those of Etch-3 in the long-wavelength region.

The scattered light can be trapped within TF solar cells and enhance the absorbed photocurrent. We simulated the photocurrent of TF a-Si:H solar cells on textured glass substrates using an FDTD method. In this simulation, we assumed that the front Al-doped ZnO TCO

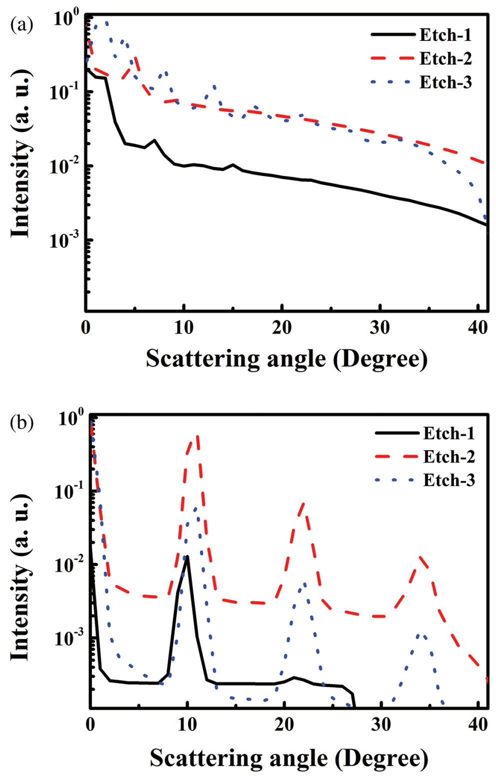

Figure 3. Angular distribution function intensities of textured glass surface morphologies obtained with laser beams having wavelengths of (a) 405 nm and (b) 975 nm for the wideband light-scattering mechanism study.

layer (ZnO:Al, 800 nm), *p–i–n* a-Si:H layers, rear ZnO:Al TCO layer (100 nm), and back-side Ag reflector (200 nm) are conformably deposited (a-Si:H single-junction solar cells) on the textured glass substrates in the order shown in Figure 4(a) and that the reference cell has the same layer structure on bare glass substrates. We calculated the amount of absorption in the *i*-a-Si:H layer for various thicknesses to estimate J_{SC}. Figure 4(b) shows J_{SC} of TF a-Si:H solar cells as a function of the *i*-a-Si:H layer thickness for the textured glass substrates (Etch-1, Etch-2, and Etch-3 samples). J_{SC} increases as the *i*-a-Si:H layer thickness increases for all structures. Because the textured structures help to trap the incoming light within the absorption layer, the values of J_{SC} of Etch-1 to Etch-2 are higher than that of the reference, and J_{SC} of the Etch-2 sample is further improved by ~27.6% compared to the reference cell with a 400 nm-thick *i*-a-Si:H layer. The value of J_{SC} of 21.9 mA/cm^2 is very high, which can potentially obtain an initial efficiency over 14% with a-Si:H single-junction solar cells having an open-circuit voltage (V_{OC}) of ~0.9 V and a fill factor (FF) of 70%. The behaviors of J_{SC} are in accordance with those of the haze ratios and the AD of the transmitted light, as shown in Figures 2 and 3. Although Etch-2 could have the best texture, we note that the high-texture structure might cause unwanted defects during the deposition of *p–i–n*

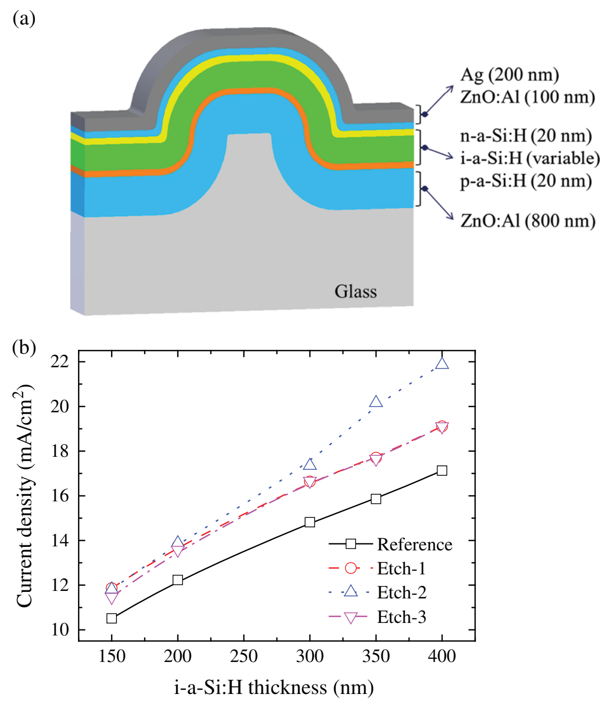

Figure 4. Wideband light scattering of periodic microtextured glass substrates for silicon thin-film solar cells.

a-Si:H solar cells, which may result in the losses for FF and V_{OC}.[14,15] Future research will investigate the optical effects for variable periods of the honeycomb structure and include the fabrication of TF a-Si:H solar cells with variable absorption thicknesses for the experimental FF and V_{OC} values in the near future. However, Etch-2 and Etch-3 clearly exhibit good light scattering over a wide band of incoming light, and the etching times for Etch-2 and Etch-3 are tolerable to control; therefore, the etching process for these wideband light-scattering textures are reproducible to obtain periodic honeycomb glass texturing with a high aspect ratio.

4. CONCLUSION

We developed a glass texturing process to obtain a honeycomb structure that provides wideband scattering of the incoming light for TF a-Si:H solar cells. The honeycomb pattern is obtained by simple photolithography and chemical etching with HF (10%) solutions on glass substrates. We investigated the optical properties of the textured glasses for various etching times (the statuses of etching steps), which were characterized using optical measurements and FDTD simulations. Glass texturing progresses with the etching status as the etching time increases: from early etching through high-texture etching to over-etching. The textured glass substrates with a honeycomb structure exhibited a maximum transmittance of 95.5% and a haze ratio of about 61% in the wideband wavelength range the visible to near-infrared wavelength region. Using the textured glass substrate, a very high value of J_{SC} of ~21.9 mA/cm^2 was expected for a single-junction a-Si:H solar cell using the FDTD simulation tool. Therefore, microscale periodic textured honeycomb glass substrates can be employed for future high-efficiency TF a-Si:H solar cells.

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