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Omnidirectional antireflective Indium-Tin-Oxide Nanorods on trapezoid-cone nanostructures for crystalline silicon photovoltaics

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1. Introduction

Over the past few years, researches of enhancing the power conversion efficiency of crystalline silicon (c-Si) solar cell have been spotlighted. The light management by reducing surface reflection is important for all photovoltaic devices to boost the efficiency. Moreover, to achieve high efficiency for the entire day, an angular antireflective property is required for a perfect omnidirectional antireflective structure, which has been a subject of intensive research in solar cell applications.

Recently, sub-wavelength grating (SWG) nanostructures have demonstrated improved light harvesting in the silicon-base photovoltaic by minimizing the Fresnel reflection at the air/silicon interface in the range of the entire solar spectrum. Sharp-tapered SWG nanostructures exhibited excellent antireflective properties at normal incidence [1-2]. However, Sharp-tapered SWG nanostructures are not suitable for solar cell devices owing to increasing challenges of making the ohmic contact. Therefore, in this work, we demonstrated the angular-reflective properties of flat-top nanocone SWG nanostructures, known as trapezoid-cone nanostructures (FTN), with random ITO nanorods on the top. The random ITO nanorods were employed to further minimize the angular-reflectivity of trapezoid-corns. Measurements of angular-reflective spectra were achieved by using a broadband Xeon lamp and a customized integration sphere, which collected all the scattered reflected photons.

2. Experiment and Discussion

In the fabrication process, the 600nm-diameter polystyrene (PS) spheres were first spread on a p-type c-Si substrate as sacrificial masks by spin coating technique [3]. Next, reactive ion etcher (RIE) was employed to fabricate the FTN with Cl_2:O_2 =10:1 gas injection and etching time 200 seconds, which resulted in the FTN with a height of 550nm and a button tilt angle of 79°. After the removal of left-over PS spheres, the ITO nanorods were deposited on the top of FTN using the electron-beam evaporation. The detailed fabrication process was illustrated in Figure 1.

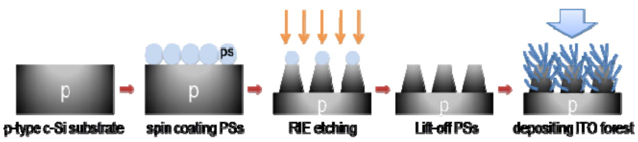

Fig.1 Schematic illustration of the fabrication process of FTN on a p-type c-Si substrate.

The top and side views of scanning electron microscopic (SEM) images of FTN before ITO nanorods deposition were shown in Figure 2 (a)-(b), respectively. The top and side views of SEM images of the FTN with 17 minutes ITO nanorods deposition time were revealed in Figure 2 (c)-(d).

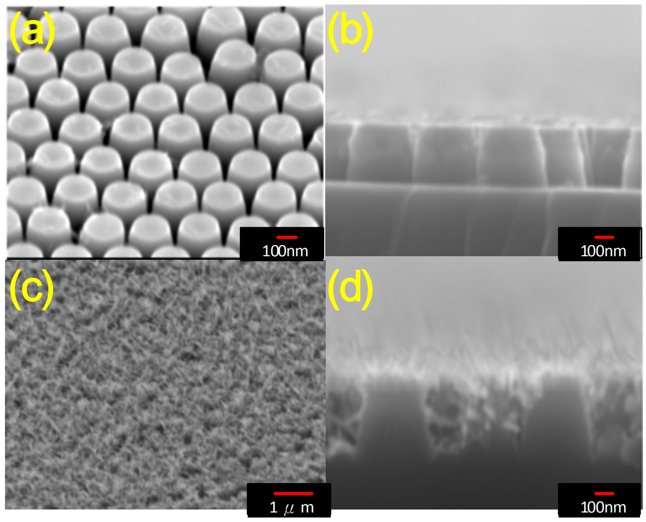

Fig. 2 (a) Top and (b) side views of SEM images of FTN before ITO nanorods deposition. (c) Top view and (d) side views of SEM images of FTN after ITO nanorods deposition.

The measured reflectance spectra at normal incidence of a flat c-Si substrate, bare FTN and FTN with three different ITO deposition time: 13, 17, and 20 minutes, were shown in Figure 3. The longer deposition time usually results in higher density and longer ITO nanorods [4]. The reflectance spectrum of bare FTN revealed inhibited reflectivity compared to that of flat silicon. The FTN with 17 minutes ITO nanorods deposition time showed the lowest reflectivity for the entire spectrum (R~4%). Interestingly, the higher density and longer ITO nanorods do not appear smaller reflectivity. The FTN with 20 minutes ITO nanorods deposition time showed higher reflectivity than that with 17 minutes deposition time, which could result from excessively high density ITO nanorods that conjugated together on the surface. The conjugated ITO nanorods formed a layer-like structure that has higher surface reflection.

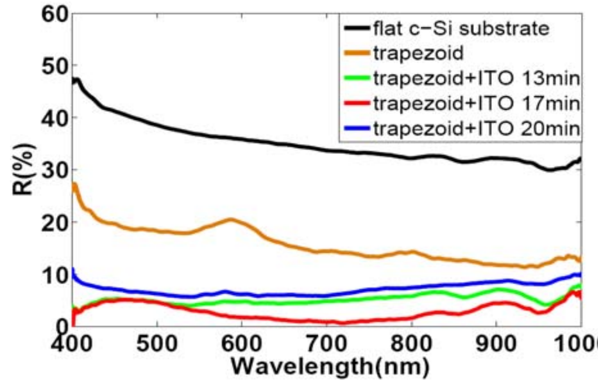

Fig. 3 Flat c-Si, bare FTN, and FTN with different deposition times were measured reflectivity spectrometer by integration sphere system.

For sufficient light harvesting in the entire day, angular-antireflective characteristics of solar cells are important. Measurements of angular-reflective spectra were achieved by using a broadband Xeon lamp and a custom-built 15cm-diameter integration sphere. The collected photons were analyzed by a spectrometer. The measured angular-reflective spectra of bare FTN and FTN with ITO nanorods deposition time of 13, 17, and 20 minutes were illustrated in Figure 4(a)-(d), respectively. The FTN with 17 minutes ITO nanorods deposition time showed the most inhibited reflectivity over the entire spectrum and the angles of incidence (AOI) up to 60°.

To further investigate the capability of solar power harvesting for the entire day, the AM1.5G weighted reflectance was defined in the following:

$$< R >= \frac{\int_{400nm}^{1000nm} R(\lambda) I_{AM1.5}(\lambda) d\lambda}{\int_{400nm}^{1000nm} I_{AM1.5}(\lambda) d\lambda}$$

Where $R(\lambda)$ is the measured reflectivity and $I_{AM1.5}$ is the intensity of standard solar spectrum. The weighted reflectance of FTN with three different ITO deposition time: 13, 17, and 20 minutes and bare FTN is shown in Figure 5. The weighted reflectance showed less than 10% with respect to all AOI for the FTN with ITO nanorods. The optimal omnidirectional antireflective property appeared when the FTN with 17 minutes ITO nanorods deposition time. The weighted reflectance showed only ~5% at all AOI for the FTN with ITO nanorods with 17 minutes deposition time, which is 13% smaller than the bare FTN. The result guaranteed excellent solar power harvest from normal to 60° AOI.

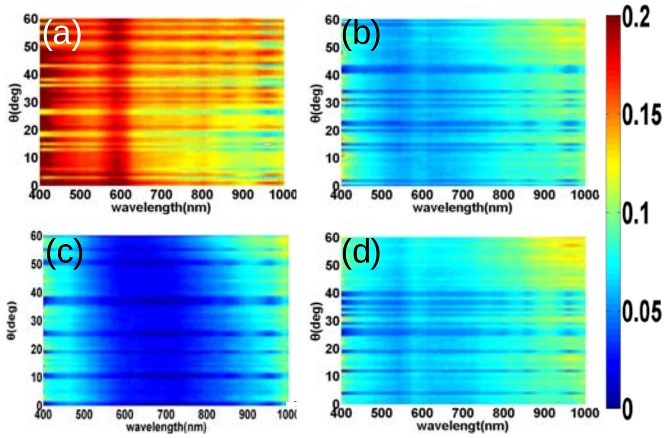

Fig. 4 Measurement of angular-reflective spectra of (a) bare FTN, the FTN with (b) 13 minutes, (c) 17 minutes, and (d) 20 minutes ITO nanorods deposition times.

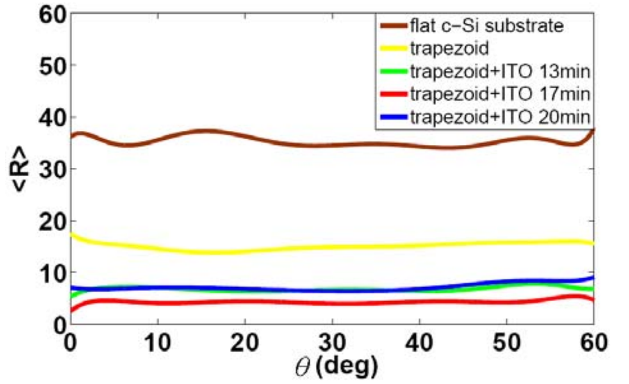

Fig. 5 The AM1.5G weighed reflectance of flat c-Si substrate, bare FTN, and FTN with 13 minutes, 17 minutes, and 20 minutes.

3. Conclusions

In summary, we investigated the angular antireflective properties of trapezoid-cone nanostructures with ITO nanorods on the top. The FTN with 17 minutes ITO nanorods deposition time showed the minimal reflectivity, as low as 4%, at normal incidence. The angular-reflective spectroscopy of the FTN with ITO nanorods showed inhibited reflectance compared to the bare FTN. The AM1.5G weighted reflectance showed the optimal angular-antireflective properties of the FTN with 17 minutes ITO nanorods deposition time.

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