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Enhanced Power Conversion Efficiency for Silicon Solar Cells Utilizing a Uniformly Distributed Indium-Tin-Oxide Nano-Whiskers

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1. Introduction

The key feature of high-efficiency photovoltaic technology is to collect light power as much as possible, independent of the spectrum response and incident angles [1-2]. The conventional anti-reflective coating (ARC) is in general realized by the deposition of multiple dielectric layers with gradient refractive indices, which restricts light harvesting to a relatively narrow spectrum response and direct incident angle [3]. Over the past few years, versatile sub-wavelength structures (SWS), such as periodic nano-pyramids, and random nano-rods, have emerged as promising candidates for AR coatings due to excellent AR properties over a broad range of incident angles and wavelengths [4]. However, the fabrication cost involving either electron beam (e-beam) lithography and/or dry etching is significant. The resulting surface recombination could also deteriorate device performance, making applications of SWS in commercial solar cells unrealistic.

In this work, we demonstrate an enhanced angular response of the power conversion efficiency (PCE) for crystalline silicon solar cells by evaporating a layer of uniformly distributed indium-tin-oxide (ITO) nano-whiskers [5]. Reflectance spectroscopy shows that the silicon cells with the nanostructured material exhibit broadband antireflective characteristics (R < 7%) for the wavelength range of 450 nm- 1050nm, better than those with the conventional SiNx ARC. The external quantum efficiency measurement also reflects the enhancement in near-infrared wavelengths. As a result, the PCE of a cell with the nano-whisker ARC achieves 17.18%, compared to 16.08% for a cell with the conventional SiNx ARC.

2. Experimental

The schematic of fabricated devices is shown in Fig. 1(a), where the cell with the nano-whisker ARC on the SiN_x layer as the inset shows. Figure 1(b) shows the tilted top view scanning electron micrographs (SEM) of the evaporated ITO nano-whiskers, where the nano-whiskers are very uniformly distributed. The inset of the Figure 1(b) is the nano-whisker structures. The device fabrication followed standard processes up to the step of electrode printing. The cells were then divided into two groups for the reference and the nano-whisker cells. The cell area is 2.5x3.5 cm^2. The ITO nano-whiskers were then deposited on SiNx-coated solar cells using an electron-beam evaporation system by introducing 1 sccm nitrogen. The pressure was controlled at 10^{-4} torr. The ITO vapor deposit on cell at

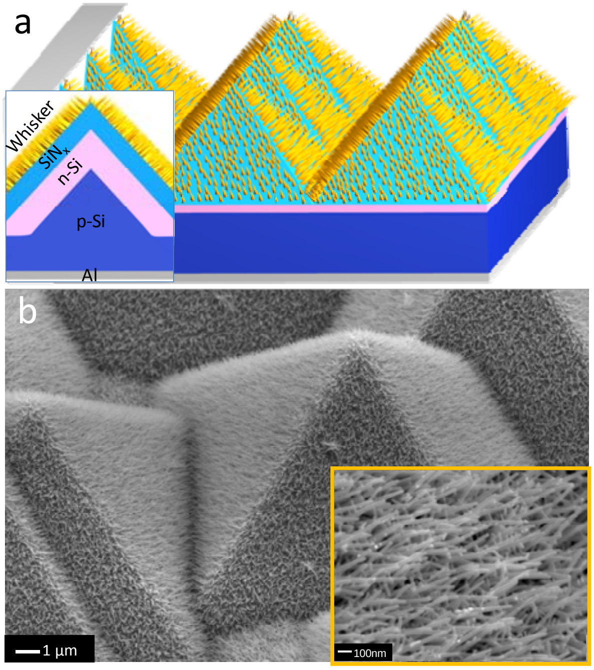

Fig. 1 (a) Schematic of a solar cell with an ITO nano-whisker antireflection coating. The inset shows device structure. (b) Scanning electron micrographs of the nano-whisker structures the on textured solar cell surface. The inset image shows the magnified whisker structure consisting of ITO trunks and branches.

normal incidence with respective to substrate. However, the pyramid textured surface has an angle of 50 degree with respective to the incident vapor flux. Presumably, the ITO nano-whisker growth is facilitated by a self-catalyst vapor-liquid-solid(VLS) mechanism. In the past, the catalyst VLS mechanism is used for grow ITO nano-columns by metal catalyst, such as Sn nano-particle or Au [6]. The catalyst induced a lower melting point near the interface causing nuclei-crystal growth. In this case, the doped Sn atoms play the role of the catalyst that decreases the melting point of In-Sn alloy [7]. The thin surface then turns into the liquid phase due to the high Sn composition. The liquid phase promotes the absorption of the ITO vapor to supply In2O3 growth [8] in various directions, resulting in the whisker structures.

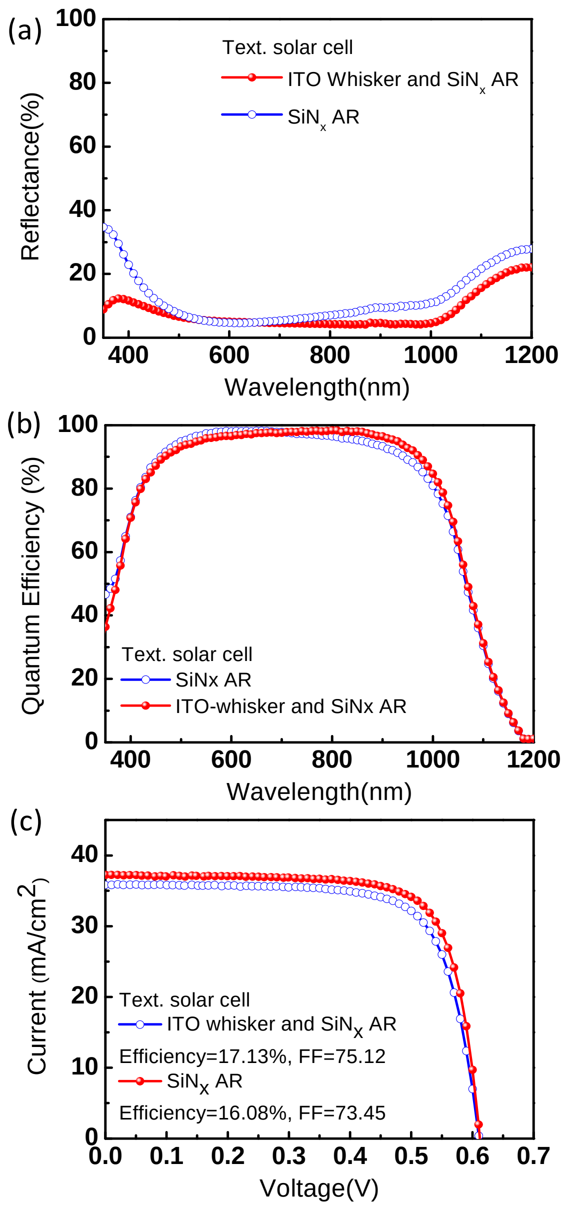

Fig. 2(a) The reflectance spectra, (b) external quantum efficiency, and (c) Current-density-voltage characteristics of solar cells with ITO nano-whiskers and a conventional SiN_x antireflection coating under a AM 1.5G standard testing condition (STC).

3. Results

The reflectance spectroscopy was conducted in a UV-VIS spectrometer for Lambda 750 (PerKinElmer corp.), including an integral sphere with a light spot diameter of $1cm^2$. As shown in Fig. 2(a), the reflectance of cells with the ITO nano-whiskers exhibit broadband anti-reflective characteristics (R < 7%) for the wavelength range of 450nm-1050nm. Compared to that of a textured Si substrate with a SiN_x ARC, ITO nano-whiskers successfully suppress the reflection in the near-infrared wavelength range from 700nm to 1100nm. The ITO nano-whisker layer functions as an optical buffer layer with low refractive indices to suppress the Fresnel reflection [9]. Detail mechanisms are still under investigation.

The external quantum efficiency (EQE) measurement of an ITO-whisker cell and a reference cell with a 80nm thick SiN_x layer. As shown in Fig. 2(b), the quantum efficiency of the cell with whisker ARC reflects the enhancement in the wavelength range of 700-1000nm due to the improved light transmission. Moreover, the corresponding current-density-voltage characteristics are shown in Fig. 2(c). The short-circuit current density (J_{sc}) of the whisker cell increases by $1.41mA/cm^2$, from $35.84mA/cm^2$ to $37.36mA/cm^2$. Overall, the PCE is also enhanced by 7% (from 16.1% to 17.2%) by using the ITO nano-whisker ARC.

4. Conclusions

In conclusion, distinctive ITO nano-whiskers, grown by electron-beam evaporation, have been employed as a cost-effective ARC for Si solar cells. Reflectance spectroscopy verifies that the nanostructure exhibits excellent anti-reflection at normal incidence for the wavelength range of 450nm~1050nm. The nanostructured ITO AR layer achieves 17.2% conversion efficiency.

Acknowledgements

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