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Electrical and optical properties of thin film silicon solar cells with sub-wavelength surface structure and TiO_2 passivation

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ABSTRACT

This study presents the electrical and optical properties of a thin-film p-on-n silicon solar cell with a sub-wavelength nanoporous surface structure etched into the emitter layer using metal-assisted chemical etching (MACE) before being coated with a dielectric passivation layer. The application of MACE etching for more than 5 s significantly enhanced light trapping efficiency. Surface recombination in the roughening emitter layer was suppressed by the application of a TiO_2 passivation film deposited by e-beam evaporation at a low deposition rate in conjunction with substrate rotation. A thin film silicon solar cell that underwent MACE for 10 s with a 15 nm TiO_2 passivation layer produced an impressive 51% improvement in conversion efficiency (from 6.27% to 9.62%), compared to reference solar cells fabricated without MACE processing or dielectric passivation.

1. Introduction

Numerous studies have demonstrated the effectiveness of sub-wavelength nanostructures [1–3] in reducing reflectivity and enhancing light trapping efficiency in silicon solar cells [4–8]. Light trapping increases the probability of light absorption by causing weakly absorbed incident light to undergo multiple reflections within the cell using sub-wavelength nanostructures [9–11]. However, fabricating sub-wavelength nanostructure in thin-film silicon solar cells remains a challenge [12–20]. The primary goal is to obtain a suitable balance between the optical properties of the light trapping structure and the electrical properties of carrier surface recombination in order to optimize conversion efficiency.

This study used metal-assisted chemical etching (MACE) with different etching times to fabricate nanopores on the emitter layer, which were then coated with a thin TiO_2 passivation layer. The mechanisms involved in light trapping and the prevention of carrier recombination were identified using measurements of optical reflectivity, dark and photovoltaic current–voltage (I–V), and external quantum efficiency (EQE).

2. Experiment

In this study, the epitaxial layer of the thin-film Si solar cells comprised a 5.0 μm-thick n^--Si base layer with a 0.87 μm-thick p^+-Si emitter layer grown on an n^+-Si (100) wafer using chemical vapor deposition. Doping concentrations of the base and emitter layers were approximately 2.6×10^{13} cm^{-3} and 4.3×10^{17} cm^{-3}, respectively. Following RCA cleaning, a 20 nm-thick silver (Ag) film was deposited directly onto the emitter layer using e-beam evaporation, and subsequently placed in a rapid thermal annealing (RTA) chamber at 300 °C for 10 min under an N_2 atmosphere to facilitate the formation of Ag nanoparticles. The Ag film was evaporated under a pressure of 2.67×10^{-6} mbar with an emission current of 20 mA at a deposition rate of 0.8 Å/sec. The samples then underwent MACE processing by being soaked in an $HF:H_2O_2:H_2O$ (5:1:10) solution for 1, 5, 10, 15, and 30 s to produce a sub-wavelength nanoporous structure on the surface of the emitter layer. Following MACE processing, an HNO_3 etching solution was applied to remove residual Ag particles. A 300 nm-thick Al film was deposited on the front surface using photolithograph photoresister patterns, and a 15 nm Ti/300-nm Al film was deposited on the rear surface using e-beam evaporation. These films were subsequently annealed in an RTA chamber at 450 °C for 10 min in N_2 atmosphere to fabricate a bare-type thin-film silicon solar cell

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with sufficient ohmic contact between the metal and semiconductor. In order to suppress surface recombination on the nanoporous structure, a TiO_2 film was deposited on the emitter surface by e-beam evaporation at a low deposition rate with sample rotation and then annealed at 300 °C for 10 min in H_2 atmosphere. The surface state densities of silicon can be reduced by diffusing hydrogen into the silicon/TiO_2-dielectric interface to replace the dangling bond defects during annealing processing.

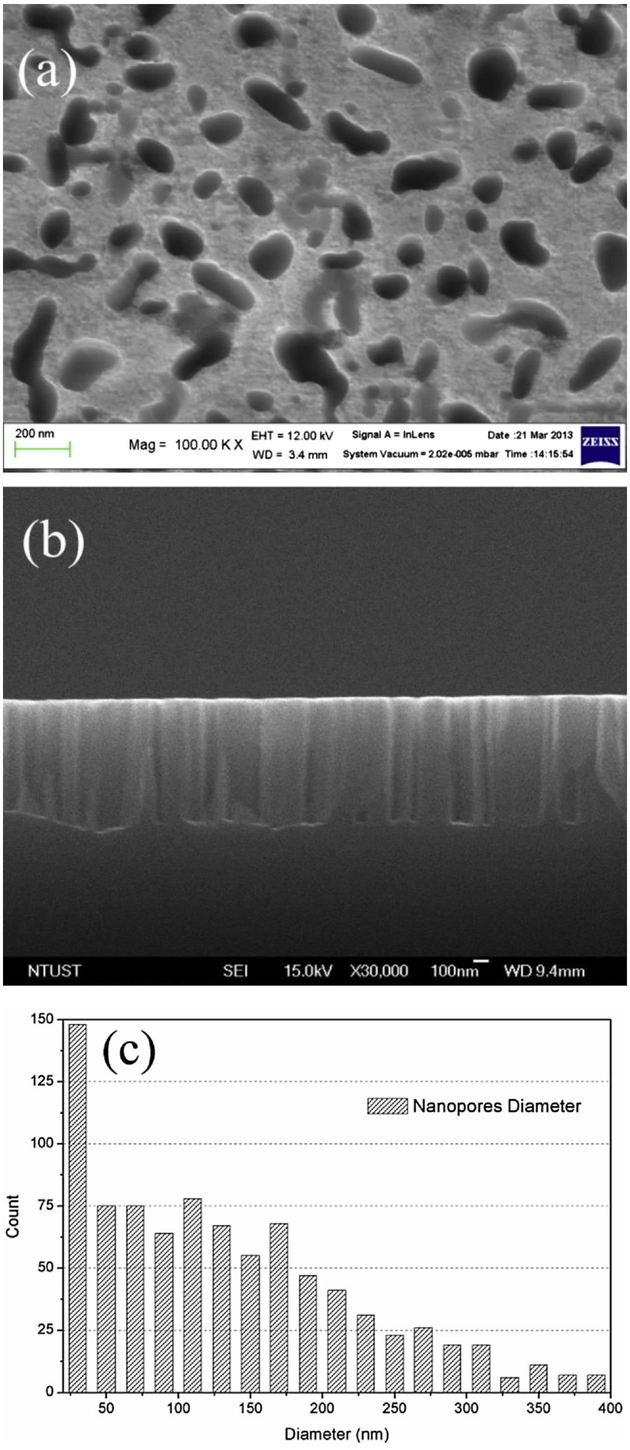

Fig. 1. (a) Top-view and (b) side-view SEM image of a sample following MACE etching for 30 s, (c) the size distribution of the etched pores obtained by analyzing the top-view SEM image using J-image software.

We examined the profile and dimensions of the pores etched using MACE for 30 s using top-view and side-view scanning electron microscopy (SEM) images, respectively. The size distribution of the etched pores was calculated by analyzing the SEM image using J-image software. The optical reflectivity of the etched samples was measured using a UV/Vis/NIR spectrophotometer (PerkinElmer Lambda 35) within a wavelength range of 350–1050 nm. Light trapped in the etched emitter layer with a nanoporous structure can generally be examined using optical reflectivity curves, in which higher light trapping efficiency is associated with lower reflectivity. The reverse saturation current (I_0) and ideality factor (n) were characterized using dark I–V measurements (Agilent/HP 4145B) in order to compare the electrical and optical properties of cells fabricated with nanoporous structures of various depths. The short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), and conversion efficiency (η) were measured using photovoltaic I–V measurements under one-sun AM 1.5G (1000 mW/cm^2) solar simulation at 25 °C. A solar simulator (XES-151S, San-Ei Electric Co., Ltd.) was calibrated using a National Renewable Energy Laboratory (NREL)-certified crystalline silicon reference cell (PVM-236) prior to device measurement. Finally, the contribution of light trapping and photocurrent generation resulting from a reduction in optical reflection and the suppression of surface recombination by applying TiO_2 passivation were examined in accordance with EQE responses (Enli Technology Co., Ltd.).

3. Results and discussion

Fig. 1(a) and (b) respectively present top-view and side-view scanning electron microscopy (SEM) images of the sample following MACE etching for 30 s, respectively. The dimensions of the etched nanopores varied between 30 nm and 400 nm, and are consistent with those of Ag nanoparticles after annealing. In addition, the size distribution of the etched pores is presented in Fig. 1(c). The side-view SEM image in Fig. 2 presents a side-view of a sample in which etching depth is a function of MACE duration. MACE for 30 s resulted in an etching depth of 786 nm, which approaches the interface of the emitter and base layers.

The spectrum of optical reflectivity in silicon solar cells with and without MACE processing is presented in Fig. 3. Reflectivity was decreased by increasing the duration of MACE etching. Extending etching time to beyond 5 s expanded the bandwidth to 350–1050 nm and resulted in low reflectivity values of <10%. Generally, solar cells with lower surface reflectivity have superior

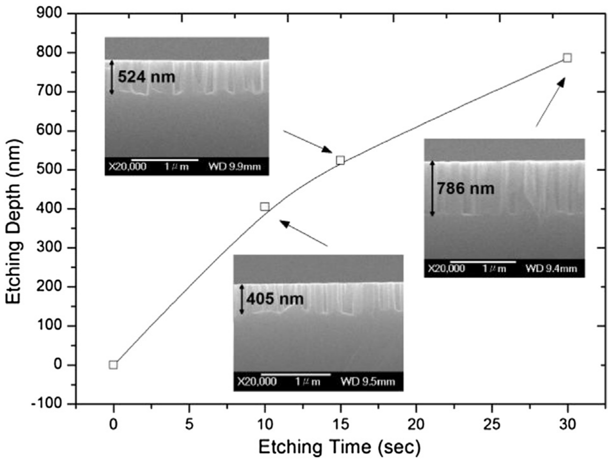

Fig. 2. Etching depth and side-view SEM image of samples, in which etching depth is a function of MACE time.