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Short communication

Efficient light trapping nanopyramid structures for solar cells patterned using UV nanoimprint lithography

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ABSTRACT

In this paper, we demonstrate that periodic inverted nanopyramid structures can enhance the power conversion efficiency of monocrystalline silicon solar cells by minimizing reflections, improving light trapping process in addition to its self-cleaning functionality. The periodic inverted nanopyramid structures were fabricated on monocrystalline silicon solar cell surfaces using a UV nanoimprint lithography. By introducing inverted nanopyramid structures on the front side of the monocrystalline silicon solar cells, the power conversion efficiency was improved by 11.73% compared to identical solar cells without the texturing. The inverted nanopyramid coating decreased the reflectance and increased the external quantum efficiency over a broad wavelength range. Moreover, the surface of the solar cells exhibited hydrophobic properties due to increased contact angle caused by the nanostructure patterns and the self-assembled monolayer coating. The enhanced hydrophobicity provided the solar cells with an added self-cleaning functionality. These results suggest that the periodic inverted nanopyramid structures has high potential in improving the performance of silicon solar cells and may be applied to different types of solar cells.

1. Introduction

Reducing optical losses in the solar cells has always been a key challenge in enhancing the conversion efficiency. In general, efficient light management has been achieved by textured surfaces that enhance the light collection and increasing the effective optical path length of the light within the absorber layer of a solar cell [1]. Various texturing studies have been carried out, such as texturing at the back side [2] or at the front side of a solar cell [3] or pre-texturing the solar cell substrates [4,5] where a wide variety of light management schemes have been investigated to enhance the power conversion efficiency of a solar cell. The use of nanostructures for improving the light absorption and trapping in solar cells is a more promising method compared with the traditional micro-sized surface texturing [6,7].

Nanostructures can be fabricated by various techniques including electron beam lithography (EBL) [8], laser interference lithography (LIL) [9], nanoimprint lithography (NIL) [10,11], nanosphere lithography (NSL) [12] and Block copolymer lithography (BCPL) [13]. Nanoimprint lithography is one of the most promising low-cost methods for nanostructure patterning over a large area with high throughput, high resolution, and high fidelity. Various nanostructures such as nanowires [14–16], nanorods [17], nanocones [18], nanopyramids [19], nanopillars [20] and metal nanostructures such as nanogrooves [21] and nanoparticles arrays [22–24] have been extensively studied. Despite their excellent light trapping properties, texturing the active solar cell region or introducing metal nanostructures results in poor charge carrier collection due to increased surface recombination. Fang Jiao et al. [25] demonstrated that the imprinting of moth-eye-like structures on the front side of monocrystalline Si solar cell surface enhanced the conversion efficiency by 19% compared to the reference solar cell by coupling incident light into the absorber layer. This approach of surface texturing differs from other approaches such as texturing the active material or using metal nanostructures. This approach enhances solar cell performance without introducing additional surface recombination and also provides excellent solar cell self-cleaning functionality.

However, the periodic inverted nanopyramid structures have not been demonstrated on solar cells by means of UV nanoimprint lithography. The objective of this work was to determine the enhancement of monocrystalline Si solar cell performance employing periodic inverted nanopyramid structures using low cost and scalable approach.

In this work, the periodic inverted nanopyramid structures were fabricated on the front side of monocrystalline Si solar cell surface by means of UV nanoimprint lithography. The reflectance, external

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quantum efficiency, current-voltage measurements and wettability of the monocrystalline Si solar cells with and without the inverted nanopyramid structures were investigated. The monocrystalline Si solar cells with inverted nanopyramid structure show enhancement of light trapping and power conversion efficiency in addition to high hydrophobic surfaces suitable for self-cleaning purposes.

2. Material and methods

2.1. Master mold preparation

As a stamp, the periodic inverted pyramid structures were formed on Si mold and subsequently replicated to form upright nanopyramid using UV curable resist coated mold. An OrmoStamp UV curable resist (micro resist technology GmbH) was used to form nanostructures by means of UV nanoimprint lithography. The periodic inverted pyramid structure master Si mold was fabricated by laser interference lithography and subsequent pattern transfer by combined reactive ion etching and KOH wet etching. Additional details on the fabrication process of master mold can be found in the reference [6]. A (1H, 1H, 2H, 2H-Perfluorooctyl) trichlorosilane also known as F_{13}-TCS solution from Sigma-Aldrich was used as an anti-sticking layer placed on molds and imprint resists sides respectively.

2.2. UV imprinting process

Prior to coating, the glass substrate was cleaned with acetone, methanol, and isopropyl alcohol (IPA) solvents in an ultrasonic bath and then rinsed with deionized water and finally dried with Nitrogen gas. Next, the substrate surface was treated using oxygen plasma to enhance optimum adhesion at the interface between the glass and the OrmoPrime08. The OrmoPrime08 from micro resist technology was used as an adhesion promoter solution based on organofunctional silanes. After that, the substrate was baked using an oven at 200 °C for 30 min and cooled down to room temperature immediately before coating. OrmoPrime08 was deposited onto the glass substrate by spin coating at a spin speed of 4000 rpm for 60 s. The spin-coated film was then baked on a hot plate at 150 °C for 5 min and cooled down to room temperature. Finally, a liquid and transparent UV curable resist was spun coated onto the OrmoPrime08 layer coated substrate at a spinning speed of 6000 rpm for 60 s and prebaked on a hot plate at 80 °C for 2 min.

To perform the imprint experiments, a vacuum operated home-built imprint tool was attached to the UV illumination source of the Karl Suss Mask Aligner (MA-6) system. This created a vacuum environment in order to reduce the air bubbles trapped in-between the mold and resist during the imprint process. The Si master mold/UV curable resist/glass plate was loaded into the imprint tool. A vacuum pressure of 4 mbar and the Mask Aligner (MA-6) system were then activated, and the resist was cured under a UV exposure for 4 min using 4.4 mW/cm^2 illumination intensity with 365 nm UV source at room temperature. Finally, a manual de-molding process was utilized by applying gradual force using a scalpel at one corner of the mold in order to delaminate between the two material surfaces. The upright nanopyramid pattern was successfully replicated from the Si mold to the glass substrate with high fidelity, which was used as a stamp in the second imprint process. After the UV nanoimprint process, F_{13}-TCS based SAM was coated onto the upright nanopyramid patterned glass substrate in order to enhance the anti-sticking property.

In order to measure the effect of the inverted nanopyramid structure for improving the photo-current conversion efficiency, the inverted nanopyramid structures were replicated onto a monocrystalline Si solar cell front surface by the same UV imprinting method using upright nanopyramid patterned glass substrate as a master stamp. Fig. 1 illustrates the schematic diagram of overall imprint process steps. In this study, the solar cells were fabricated in our lab. Details of the solar cells fabrication are given in the Supporting Information.

2.3. Characterization techniques

The nanostructures of the samples were examined by scanning electron microscope (SEM) (JEOL 7000F FE-SEM) and atomic force microscope (AFM) to determine the pattern of the master stamp was replicated uniformly on the top of the solar cell surface. The reflectance of the monocrystalline Si cell with and without the inverted nanopyramid structures was obtained using UV–visible spectrophotometer at room temperature, with an integrating sphere over the wavelength range of 300–1200 nm. The current density-voltage characteristics were measured for the solar cells using a Keithley 2400 source meter and a solar simulator (ABET Sun3000) with AM 1.5G filter under illumination of 1 sun. The external quantum efficiency (EQE) was also performed using tungsten –halogen lamp in combination with a monochromator (CS130 1/8m). In addition, for hydrophobicity evaluation, the contact angle of water droplets on Si surface with and without pattern were measured using a contact angle goniometer with Edmund Scientific Camera.

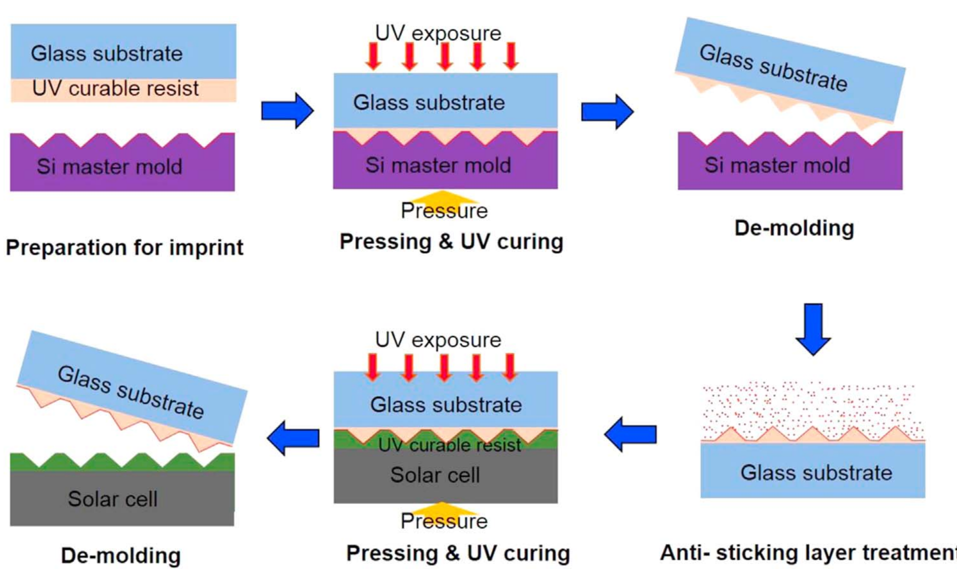

Fig. 1. The schematic diagram of the imprint process steps.