Solar Energy Materials & Solar Cells 108 (2013) 200–204

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

# Influence of the texturing structure on the properties of black silicon solar cell

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ARTICLE INFO

*Article history:*
Received 25 April 2012
Received in revised form
24 September 2012
Accepted 1 October 2012
Available online 25 October 2012

*Keywords:*
Black silicon
Texturing structure
Solar cell
Contact resistance
Conversion efficiency

ABSTRACT

An optimized textured structure is a key for high efficiency multi-crystalline silicon solar cell. In this work, black silicon wafers with various structures have been successfully produced by plasma immersion ion implantation. The surface morphology, reflectance and internal quantum efficiency have been investigated by atomic force microscope, spectrophotometer and quantum efficiency measurement system, respectively. Results show that nanohillocks with average height of 150–600 nm have been generated on black silicon surfaces by different texturing conditions, and the reflectance over the wavelength from 300 nm to 1100 nm decreases with increasing the height of nanohillocks, whereas the internal quantum efficiency worsens. The solar cell based on the optimized nanohillocks height of 300 nm yeilds efficiency of 15.99% with short circuit current of 34.0 mA/cm$^2$.



## 1. Introduction

As it is known, there can be as high as 40% reflectance on the surface of damage removed silicon due to abrupt change of refractive index on the interface between silicon and air [1]. Reducing surface reflectance to enhance light absorption is very important to improve the conversion efficiency of crystalline silicon solar cell. Generally, depositing anti-reflection coating (ARC) with intermediate refractive index (for example, $SiN_x$ [2]) is very effective to reduce surface reflectance. However, surface texturing is a more permanent and effective solution to decrease reflections. Anisotropic etching of monocrystalline silicon in alkaline solution is effective to reduce surface reflectance and widely used in industry [3]. But it doesn't work well for multi-crystalline silicon (mc-Si) wafer due to randomly orientated crystallites. Instead, isotropic etching in acid solution is widely used in industry [4]. The reflectance of acid etched mc-Si is still as high as 25%, leading to a big light reflectance loss.

To further reduce surface reflectance of mc-Si solar cell, various texturing methods have been tried and investigated. One of the most promising methods to reduce reflection is producing nanostructured surface which is often termed as "black silicon" [5]. Torres et al. have produced black silicon by femtosecond laser and demonstrated that the electrical performances were improved compared to the solar cell with non-textured surface [6]. The black multi-crystalline silicon can also be fabricated by local metal-catalyzed wet-chemical etching, and the efficiencies of the black cells can be estimated to be in the 12–14% range [7]. Reactive ion etching (RIE) is widely used to form black silicon [5,8,9]. Zaidi et al. [10] have demonstrated that the RIE textured solar cell by applying additional ion damage removal treatments can show a better short circuit current density in comparison with the solar cell by wet-chemical textured surface. And Lee showed that the conversion efficiency of multi-crystalline silicon solar cell produced by damage-free reactive ion etching can reach as high as 16.32% [11]. In our previous work [12], the black silicon has been successfully produced by plasma immersion ion implantation (PIII). The microstructure and reflectance of the black silicon have been investigated.

In the present study, the black multi-crystalline silicon has been fabricated using plasma immersion ion implantation (PIII). The influence of texturing structure on the performance of black silicon solar cell will be studied in detail.

## 2. Experimental

In this work, p-type multi-crystalline silicon wafers obtained from the same ingot with thickness of $200 \pm 20$ μm, area of 156 mm × 156 mm, and resistivity of 1–3 Ω cm were employed. First, the damage on the surface induced by wire-cutting was removed by etching in 10% NaOH solution at 80 °C. After that, the black silicon wafers fabricated by plasma immersion ion implantation process with different conditions as shown in Table 1. Then all the black silicon wafers were subjected to acid washing in 2% HCl and followed in 10% HF to remove the contamination and

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0927-0248/$ - see front matter 
http://dx.doi.org/10.1016/j.solmat.2012.10.001

oxides. The wafers were phosphorus doped using phosphorous oxychloride ($POCl_3$) as the dopant source at the temperature of 825 °C. Afterward all the wafers were subjected to edge etching and the removal of phosphosilicate glass (PSG) layer with diluted HF (10% by volume). Silicon-nitride layer with thickness of 80 nm and refractive index of 2.05 was grown by plasma enhanced chemical vapor deposition (PECVD) process. Finally, the front and back metallization of all the wafers were carried out by screen-printing technique and followed by baking and co-firing in a conveyer belt furnace. The fabrication process of acid textured solar cell was identical with that of black silicon solar cells.

**Table 1**
Conditions of fabricating black silicon wafers.

| Conditions | The ratio of $SF_6$ to $O_2$ | Voltage pulses (V) | Etching time (min) | Radio frequency power (w) |
|---|---|---|---|---|
| C1 | 2.5/1 | −500 | 5 | 900 |
| C2 | 3/1 | −500 | 3 | 900 |
| C3 | 3/1 | −500 | 5 | 900 |
| C4 | 3/1 | −1000 | 5 | 900 |
| C5 | 3/1 | −1500 | 5 | 900 |

The microstructures as well as surface areas of the black silicon wafers were investigated by atomic force microscope (AFM). The surface reflectance was examined by a UV–VIS–NIR spectrophotometer (Varian Cary 5000) equipped with an integrating sphere detector in the wavelength from 300 nm to1100 nm. The sheet resistance was studied by Four-probe sheet resistance measurement with mapping mode. Internal quantum efficiency (IQE) was measured on a Solar Cell Scan 100 quantum efficiency measurement system. The performance of the solar cells was determined by the JR-1250 Solar Cell I. V. Tester and Sorter under one sun global solar spectrum of Air Mass (AM) 1.5 at 25 °C. The cross-sectional micrographs of Ag–Si contact of the solar cells were investigated with a JEOL JSM-7001 F field emission scanning electron microscope (FESEM).

## 3. Results and discussion

The photographs of the polished wafer and textured wafers ( C1, C3, C5) are exhibited in Fig. 1. It can be demonstrated that we have successfully produced the black silicon wafers with homogeneous surfaces, and the wafers become more and more black varying with the texturing conditions from C1 to C5. The

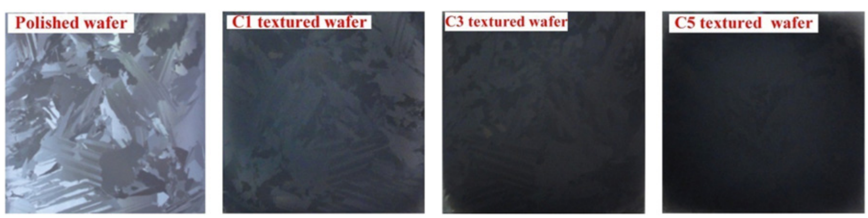


**Fig. 1.** Photographs of the polished silicon wafer and the black silicon wafers with the texturing conditions of C1, C3 and C5.

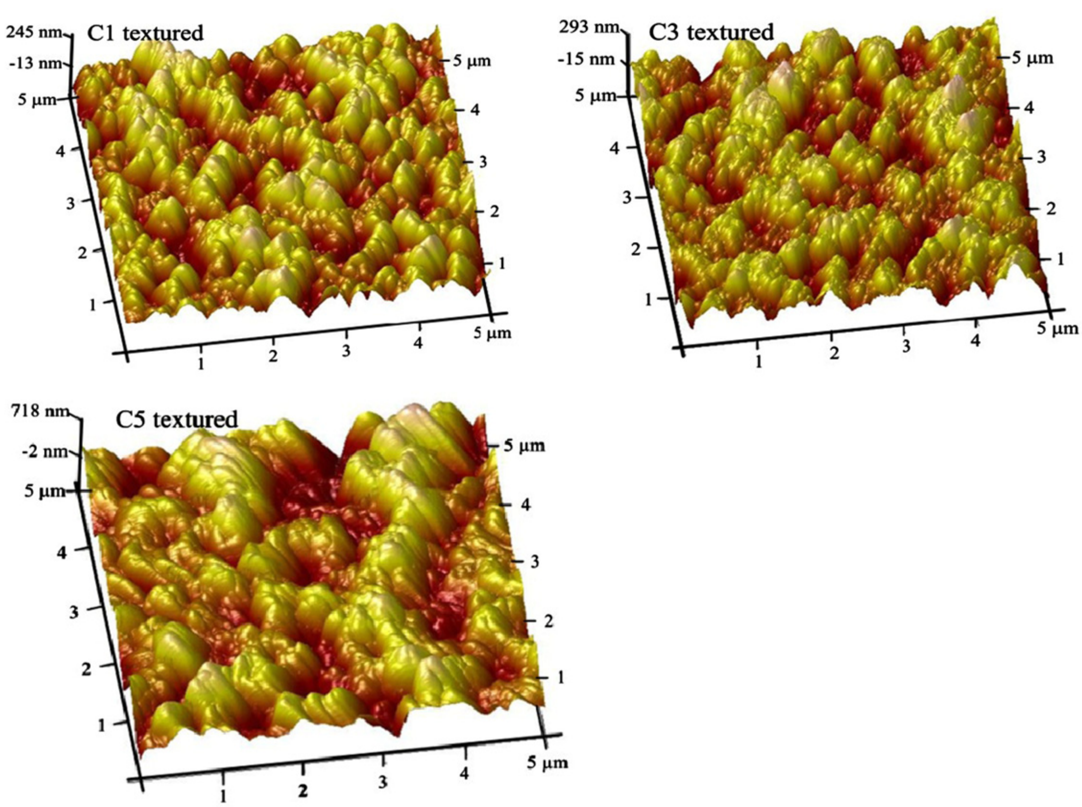


**Fig. 2.** AFM of the microstructures of the black silicon wafers with different texturing conditions. It typically shows that the black silicon surfaces are covered with dense nanohillocks, and the heights of the nanohillocks are 150 nm, 300 nm and 600 nm for the surfaces of the C1 textured, C3 textured and C5 textured, respectively.