Materials Science in Semiconductor Processing 25 (2014) 2–17

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

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

Review

Fabrication and characteristics of black silicon for solar cell applications: An overview

Chih-Hung Hsu [a], Jia-Ren Wu [a], Yen-Tien Lu [b], Dennis J. Flood [c], Andrew R. Barron [d,e,f], Lung-Chien Chen [a,*]

[a] *Department of Electro-optical Engineering, National Taipei University of Technology, 1, section3, Chung-Hsiao E. Rd., Taipei 106, Taiwan*
[b] *Department of Chemical and Biomolecular Engineering, Rice University, Houston, TX 77005, USA*
[c] *Natcore Technology, Inc., 87 Maple Avenue, Red Bank, NJ 07701, USA*
[d] *Department of Chemistry, Rice University, Houston, TX 77005, USA*
[e] *Department of Materials Science and Nanoengineering, Rice University, Houston, TX 77005, USA*
[f] *College of Engineering, Swansea University, Singleton Park, Swansea SA2 8 PP, Wales, UK*

A R T I C L E   I N F O

Available online 20 February 2014

Keywords:
Black silicon
Solar cell
Reflectivity
Refractive index
Nano

A B S T R A C T

Anti-reflective (AR) coatings are a critical component of a commercially viable solar cell because by lowering reflection from the surface of the cell they enable more light to be absorbed and hence improve the power conversion efficiency of the cell. Silicon solar cells represent >80% of present commercial cells and the most common AR coating is PECVD silicon nitride; however, recently, black silicon (b-Si) surfaces have been proposed as an alternative. Black silicon is a surface modification of silicon in which a nanoscale surface structure is formed through etching. Due to the continuous change of the refractive index of this structure surfaces with very low reflectivities are observed (~1%). This review summarizes the recent and substantial developments of black silicon for use in solar cells and discusses the advantages and disadvantages of the different methods of fabrication.

Contents

1. Introduction . . . 3
2. Methods of fabricating black silicon (b-Si) . . . 4
   2.1. Dry etching . . . 4
   2.2. Wet chemical etching . . . 8
3. Fabrication of solar cells . . . 11
   3.1. Metal-assisted chemical etching . . . 11
   3.2. Plasma immersion ion implantation (PIII) . . . 13
4. Comparison of synthetic methods for b-Si and solar cell efficiency . . . 14
5. Contact formation on black silicon solar cells . . . 14
6. Theoretical basis for the low reflectance of black silicon . . . 15
7. Conclusions . . . 16
   Acknowledgments . . . 16
   References . . . 16

* Corresponding author. Tel.: +886 2 2771 2171; fax: +886 2 8773 3216.
E-mail address: ocean@ntut.edu.tw (L.-C. Chen).

http://dx.doi.org/10.1016/j.mssp.2014.02.005
1369-8001

1. Introduction

A key requirement for an efficient solar cell is a low surface reflectance to maximize the amount of incident photons absorbed by the semiconductor to convert the incident light into electrical energy. The use of an anti-reflection (AR) coating is used to suppress the reflection of the solar cell surface by forming destructive interference of incident light. For silicon solar cells AR coatings are generally silicon nitride (SiN_x) thin films produced by chemical vapor deposition (CVD). The resulting cells have a reflectance of about 6% as compared to 40% for a polished wafer. However, AR coatings are limited in use because it only reduces the reflection for a narrow range of light wavelength and incident angle since its functionality is based on a quarter-wavelength coating. As a potential replacement for the conventional AR coating, so-called "black silicon" (b-Si) was first reported by Jansen et al. [1].

Black silicon is a surface modification of silicon where a nanoscale surface structure is formed through etching. The resulting nanoscale structure (from porous surface to bulk silicon) provides an extremely low reflectivity of close to 0% [2–4]. Because the b-Si surface nano-structure exhibits high absorption over a wide spectral range (250–2500 nm) [4,5] it offers an ideal solution as an AR coating for solar cells [6–9], as well as applications in photodetectors [10], photodiodes [11], and gas sensors [12]. The nanoscale structure may be in the form of inverted nanoscale cones (i.e., with the tip of the cones pointing upward away from the silicon surface) or a series of nanoscale pores of varying depths and diameters extending into the surface. Both types of nanoscale structures are distributed randomly over the silicon surface.

Although originally prepared as a side effect of reactive ion etching [1], b-Si can be prepared by laser irradiation

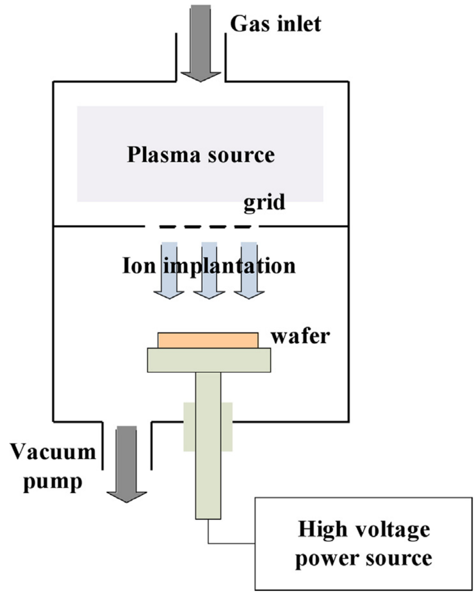

Fig. 2. Schematic illustration of a DC-plasma immersion ion implantation (DC-PIII) apparatus.

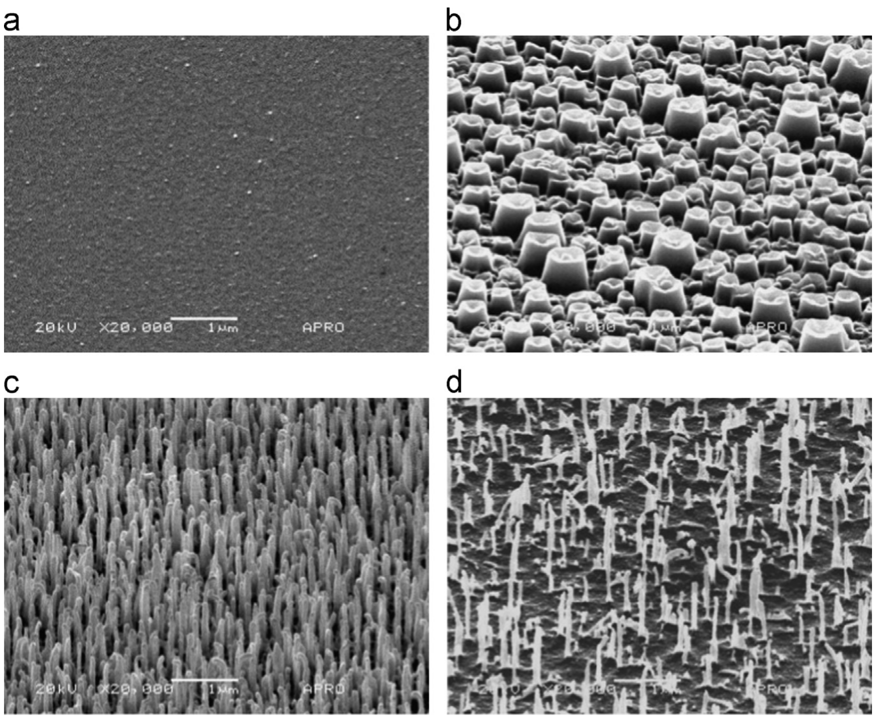

Fig. 1. SEM images of silicon surface structures formed by RIE processing with different SF_6/O_2 gas flow ratios: (a) 0.5, (b) 1.5, (c) 2.8, and (d) 4.3. RF power = 100 W and pressure = 143–302 mT. Reprinted from J. Yoo, G. Yu, J. Yi, Mater. Sci. Eng. B – Adv. 2009; 159–160: 333. Copyright (2009), with permission from Elsevier.