Solar Energy Materials & Solar Cells 164 (2017) 40–46

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Efficient nanostructured quasi-single crystalline silicon solar cells by metal-catalyzed chemical etching

Qiang Wang[a,b], Chengfeng Pan[a], Kexun Chen[a], Shuai Zou[a], Mingrong Shen[a], Xiaodong Su[a,c,*]

[a] College of Physics, Optoelectronics and Energy, Collaborative Innovation Center of Suzhou Nano Science and Technology, and Jiangsu Key Laboratory of Thin Films, Soochow University, 1 Shizi Street, Suzhou 215006, China
[b] School of Electronic and Information, Nantong University, Nantong 226019, China
[c] State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Keywords:
Quasi-single crystalline silicon solar cells
Metal-catalyzed chemical etching
Nano-texture
Parallel sub-cell model
Power conversion efficiency

ABSTRACT

Seed-assisted cast quasi-single crystalline silicon (Qsc-Si) technique allows the production of efficient, low-cost solar cells. However, most of the Qsc-Si wafers still consist of single- and multi-crystalline silicon grains, which lead to difficulties when attempting to achieve high efficiency by using conventional acid or alkali texture processes. This paper highlights the fact that nano-textured Qsc-Si solar cells can reach efficiencies ranging from 18.4% to 18.9% by using the same metal-catalyzed chemical etching technique, along with a depressed color difference. A parallel sub-cell model is proposed to explain how to enhance the performance of Qsc-Si cells.

1. Introduction

In recent years, crystalline silicon, including cast multi-crystalline (mc-Si), and Czochralski (CZ) single crystal (sc-Si), have dominated approximately 90% of the photovoltaic (PV) market [1–4]. From the viewpoint of the total cost of production, both sc-Si and mc-Si have advantages and disadvantages: costly sc-Si solar cells are efficient due to nearly perfect material quality, but suffer from serious light-induced degradation (LID) of efficiency due to B-O bonding; cost-effective mc-Si solar cells have 1–2% lower efficiencies than those of sc-Si cells because of more crystallographic defects and higher light loss [5–7].

The seed-assisted cast quasi-single crystalline silicon (Qsc-Si) technique was recently developed by carefully controlling the growth condition to grow <100> oriented sc-Si grains in most vertical and horizontal areas of an ingot [8–11]. Qsc-Si solar cells are expected to have efficiency close to that of sc-Si cells, due to high minority carrier lifetimes, lower grain boundaries and dislocations, while keeping the low cost and LID of mc-Si cells. It was reported that the efficiency of Qsc-Si solar cells has wide distribution, from 17.1% to 18.2%, as the ratio of sc-Si grains in the wafers varies from 50% to 100% [12–14]. However, Qsc-Si is still unpopular in the PV industry, due to two main factors: first, although it is higher in efficiency, the cost of Qsc-Si is higher than that of mc-Si. Second, most Qsc-Si wafers consist of both sc- and mc-Si grains, thus making it difficult to obtain proper texture for light trapping, and thus it reaches high efficiencies by using either conventional alkali or acid texture processes [15]. Therefore, the need to find an effective texturing technique for the efficient Qsc-Si cell is urgent.

The nanostructured black silicon with extremely low reflectivity has attracted attention due to its potential application in silicon-based solar cells [16,17]. Theoretically, the nano-texture can be treated as a density-graded or refraction-graded layer, which can smoothly connect the air and Si substrate, thus allowing it to suppress light reflection exponentially as the grade depth increases [18]. Several techniques, such as laser texturing, reactive ion etching (RIE), and metal-catalyzed chemical etching (MCCE), are attractive because various nanostructures can be formed on the surface regardless of grain orientations of Si wafers [19–24]. MCCE has been verified as a universal nano-texture technique for sc-Si and mc-Si wafers, and it is much more suitable for the current industry product line due to its low cost and stability. However, it is still a challenge to obtain a proper texture for both sc- and mc-Si grains in a Qsc-Si wafer, in an aim to achieve good cell performance, i.e., excellent light trapping ability, less color difference, and high efficiency.

In this work, the Qsc-Si solar cells with a mixture of sc- and mc-Si grains demonstrated 18.4% to 18.9% efficiencies using our well-established MCCE nano-texture process [25,26], and the results show that the cast Qsc-Si can be competitive with both CZ sc-Si and cast mc-Si.

* Corresponding author at: College of Physics, Optoelectronics and Energy, Collaborative Innovation Center of Suzhou Nano Science and Technology, and Jiangsu Key Laboratory of Thin Films, Soochow University, 1 Shizi Street, Suzhou 215006, China.
E-mail address: xdsu@suda.edu.cn (X. Su).

http://dx.doi.org/10.1016/j.solmat.2017.02.002
Received 12 November 2016; Received in revised form 23 January 2017; Accepted 1 February 2017
Available online 14 February 2017
0927-0248/

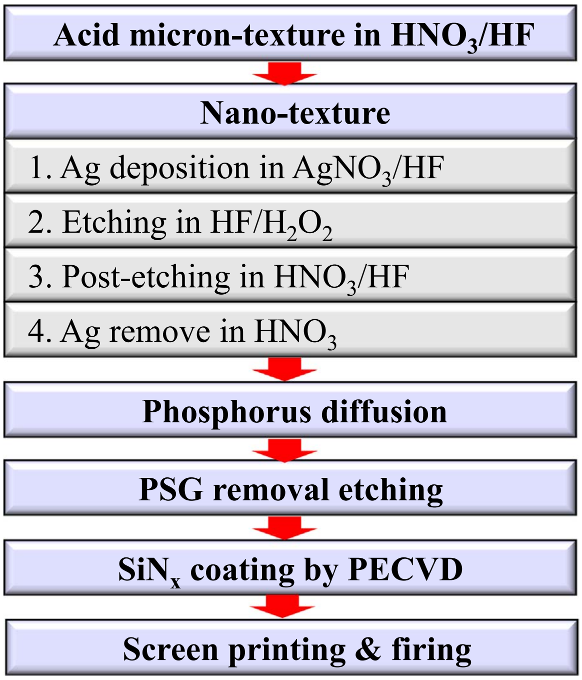

Fig. 1. Fabricating process of Qsc-Si solar cells with micron- or nano-texture.

2. Experimental

Qsc-Si wafers (p-type, 156×156×0.2 mm^3, resistivity of 1–3 Ω.cm) were provided by Zongyi New Materials Inc., China. The fabrication process of nano-textured Qsc-Si solar cell is presented in Fig. 1. First, all as-cut Qsc-Si wafers underwent nitric acid/hydrofluoric acid (HNO_3/HF) etching to remove sawn-damage layers and form proper micron-texture on the surface. Then, pre-textured Qsc-Si wafers were applied to the metal-catalyzed chemical etching (MCCE) process, as detailed elsewhere [26,27]. In brief, the above micron-textured wafers were first deposited with silver (Ag) nanoparticles, and were then etched in hydrofluoric acid/hydrogen peroxide/water (HF/H_2O_2/H_2O) solution to form a number of nano-pores on the surface. The wafers had a post-etch in HNO_3/HF solution to convert nano-pores into final nano-texture, which was immediately dipped in a 69% HNO_3 solution to remove remaining Ag nanoparticles. Finally, all nano-texture Qsc-Si wafers were assembled into cells using a standard process, including phosphorus diffusion, removal of the edge, and back *p–n* junctions, the plasma-enhanced-chemical-vapor-deposition of the SiN_x antireflection layer, and the metallization of both front and rear contacts.

PL image of Qsc-Si ingot were measured by PLI-200 (Semilab PLI-200, Hungary). The surface and cross-sectional morphologies of the silicon wafers with different textures were observed by a scanning electron microscope (SEM, Hitachi, S4800, Japan). The optical reflectance spectra were detected using a spectrophotometer with an integrating sphere (Radiation Technology D8, China). The external and internal quantum efficiencies (EQE/IQE) were measured by a quantum efficiency measuring system (QEX7, USA). The electrical performances of solar cells were characterized by IV measurement system (Berger PSL-SCD, Germany), WT2000 (Semilab WT2000, Hungary).

Table 1
Description of Qsc-Si wafers of different percentages of sc-Si grains.

Qsc-Si	sc-Si grains (%)	Lifetime (μs)	Wafer numbers
A	> 90	≦1. 5	18
B	60–90	2.45–9.32	151
C	30–60	9.32–8.35	151
D	< 30	8.35–4.00	151

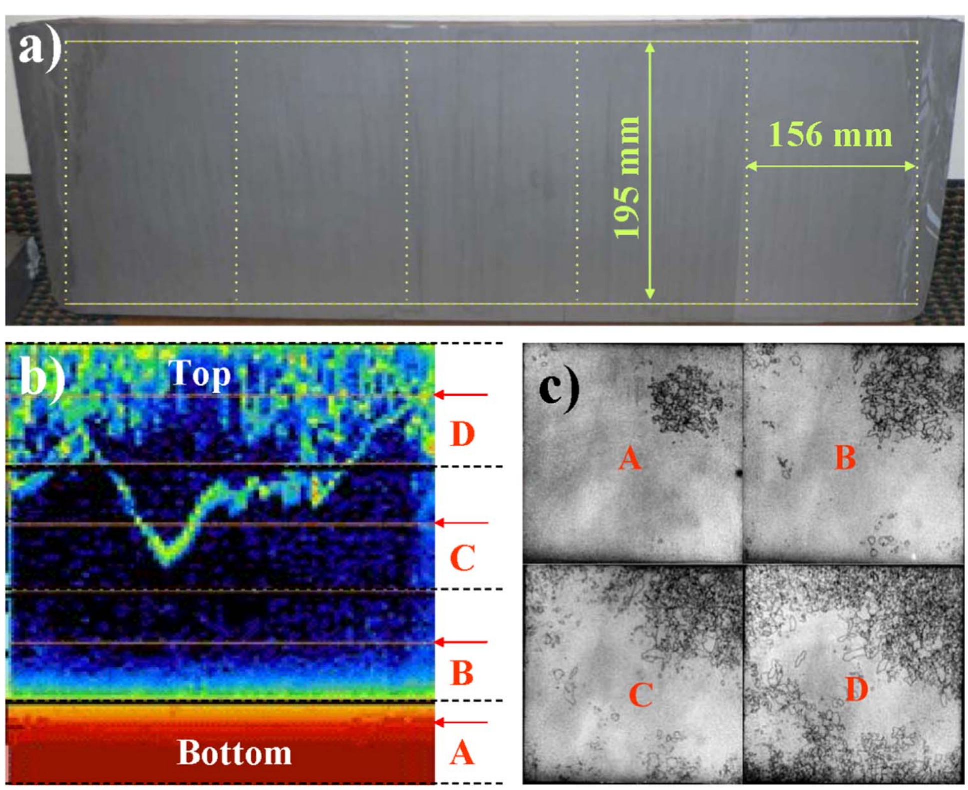

Fig. 2. a) Sectional-plane photo of an as-grown Qsc-Si ingot with a size of 800×800×248 mm^3.b) Sectional-plane PL image of a typical Qsc-Si brick with a size of 156×156×195 mm^3, cut from the center of an as-grown Qsc-Si brick. c) PL images of A, B, C, and D wafers, consisting of different proportions of sc- and mc-Si grains.