Solar Energy Materials & Solar Cells 144 (2016) 740–747

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Black silicon laser-doped selective emitter solar cell with 18.1% efficiency

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ARTICLE INFO

Article history:
Received 10 June 2015
Received in revised form
14 October 2015
Accepted 15 October 2015
Available online 11 November 2015

Keywords:
Black silicon
Reactive ion etching
Laser doping
LDSE
Plating

ABSTRACT

We report fabrication of nanostructured, laser-doped selective emitter (LDSE) silicon solar cells with power conversion efficiency of 18.1% and a fill factor (FF) of 80.1%. The nanostructured solar cells were realized through a single step, mask-less, scalable reactive ion etch (RIE) texturing of the surface. The selective emitter was formed by means of laser doping using a continuous wave (CW) laser and subsequent contact formation using light-induced plating of Ni and Cu. The combination of RIE-texturing and a LDSE cell design has to our knowledge not been demonstrated previously. The resulting efficiency indicates a promising potential, especially considering that the cell reported in this work is the first proof-of-concept and that the fabricated cell is not fully optimized in terms of plating, emitter sheet resistance and surface passivation. Due to the scalable nature and simplicity of RIE-texturing as well as the LDSE process, we consider this specific combination a promising candidate for a cost-efficient process for future Si solar cells.

1. Introduction

Nanoscale texturing of silicon (Si) surfaces has been shown [1–7] to reduce the total weighted average optical reflectance to well below 1% over a broad range of wavelengths and incident angles. Compared to the typical front surface reflectance of ~2 and ~8%, from conventionally textured mono- [8] and multi-crystalline [9] Si solar cells, respectively, nanoscale texturing such as described in [10–12] offers a potential of improved power conversion efficiency for Si solar cells due to reduced reflectance loss.

We use black silicon [13,14,11] nanostructuring to achieve low reflectance, which can be modelled in a mean-field approximation as a graded refractive index at the Si-air interface [15]. von Gastrow et al. [16] reported excellent passivation of black Si surfaces using atomic layer deposition (ALD) of Al_2O_3. Repo et al. [17] achieved a power conversion efficiency of 18.7% on 400 µm thick float-zone Si using cryogenic deep reactive ion etching (RIE) as texturing and plasma assisted atomic layer deposition (ALD) of Al_2O_3 for a passivated emitter rear locally diffused (PERL) cell and 22.1% on an interdigitated back contact (IBC) cell with similar ALD-passivation [18]. Oh et al. [19] achieved a power conversion efficiency of 18.2% on 300 µm thick float-zone Si by combining a metal-assisted wet etching black silicon process for texturing, tetramethylammonium hydroxide (TMAH) damage removal etch and thermal SiO_2 passivation. Yoo [20] used industry grade Czochralski (Cz) Si and RIE texturing and achieved a power conversion efficiency of 16.7%. Wang et al. [21] applied black Si by metal-assisted wet etching and ALD of Al_2O_3 on industry grade Cz Si and achieved 18.2% efficiency.

The primary reason for the relatively low efficiencies reported for black Si solar cells so far is the significant emitter and surface recombination [19,2] resulting from increased surface area, defects from the texturing process and increased emitter doping through the nanostructured surface yielding increased Auger recombination. These effects usually lead to reduced short-circuit current and open-circuit voltage. Thus, a selective emitter design could improve the efficiency of black Si solar cells. In order to achieve a selective emitter without the use of multiple high-temperature process steps and photolithography, laser doping and subsequent self-aligned Ni/Cu-plating has been suggested by several groups [22–24]. The laser-doped

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http://dx.doi.org/10.1016/j.solmat.2015.10.018
0927-0248/

selective emitter (LDSE) process offers excellent sheet resistance control, self-alignment of front metal contacts to the local highly doped areas and a fast, low-temperature process scalable to industrial throughput. Hallam et al. achieved 19.3% efficiency for a LDSE solar cell on large-area Cz Si substrates using an industrial turnkey production line with the addition of laser-doping and plating [25]. The LDSE process has also been successfully applied to bifacial silicon solar cells [26]. An important feature of the LDSE cell process is the replacement of screen-printed Ag front contacts with plated Ni/Cu-contacts. Due to the economic benefits of replacing Ag by Cu in the solar industry [27] and the extensive studies of Ni/Cu-plating applied for Si solar cells [28–31] the self-aligned, high-performing Ni/Cu-plated front contacts is an important and promising feature of LDSE solar cells.

This work presents LDSE black Si solar cells fabricated on *p*-type Cz Si substrates textured by a single step, maskless RIE process. To our knowledge this combination has not been previously reported and the resulting cell is thus considered a first proof-of-concept. The emitter diffusion and surface passivation were not fully optimized, since the main goal of this study was the combination of LDSE and RIE-texturing. The primary objective of this work is to investigate how laser doping and plating processes are affected by the RIE-textured surface and vice versa. It is not obvious how a differently textured surface affects e.g. electrical properties of the laser doped regions and subsequent plating. The surface topology may alter the interaction between the laser beam and the material. Thus a different emitter profile may change the defect generation and risk of Schottky contact formation. Besides laser doping and plating, several process steps could be affected by changing from conventional to RIE-texturing: emitter diffusion could change with effective surface area and deposition of anti-reflective coating may not yield the expected layer thickness and uniformity due to the nanostructured front surface. Such effects could then further affect the subsequent laser doping and plating processes. An example hereof is spurious plating on the surface in case of pinholes in the dielectric coating resulting from a different surface topology.

For these reasons there is a need for an investigation of such RIE-textured LDSE solar cells.

2. Approach

The maskless RIE process presented in this work is applied as the texturing step in the following solar cell fabrication process:

- Saw damage removal by etching in 30% KOH at 75 °C for 2 min and subsequent cleaning in 20% HCl at room temperature for 5 min and rinsing in deionized water.
- Texturing using maskless RIE at room temperature in a O_2 and SF_6 plasma with a gas flow ratio of O_2:SF_6 = 1:1, chamber pressure of 24 mTorr, 13.56 MHz radio-frequency platen power of 100 W using a SPTS RIE system.
- Emitter formation using a tube furnace from Tempress Systems with liquid $POCl_3$ as dopant source at a temperature of 840 °C and atmospheric pressure for 50 min in O_2 and N_2 ambient, followed by removal of phosphor-silicate glass (PSG) in 5% hydrofluoric acid (HF).
- Plasma enhanced chemical vapour deposition (PECVD) of 75 nm hydrogenated amorphous silicon nitride (SiN_x:H) anti-reflective coating at 400 °C using a Roth & Rau MAiA tool.
- Screen-printing of Al rear contact with standard Al paste, which was fired using a Sierra Therm infra-red fast-firing furnace, with a peak temperature set point of 835 °C and a belt speed of 4500 mm/min.

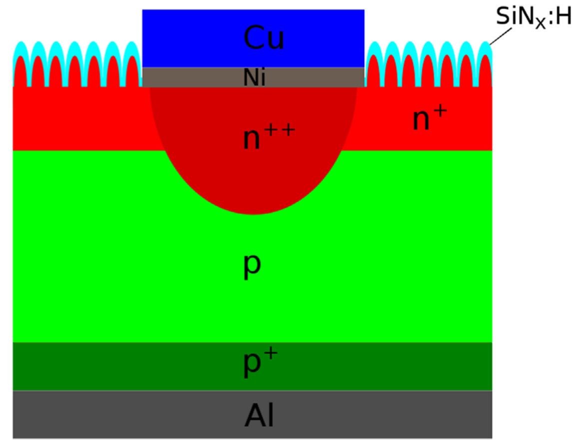

Fig. 1. Sketch of the black Si LDSE solar cell structure. The cells are textured in a single-step, maskless RIE process. The highly doped regions of the selective emitter is formed by means of local laser doping using phosphoric acid dopant and a continuous wave laser. The rear contact is screen-printed and fired Al and the front contacts are plated Ni/Cu. The dimensions of the different layers are not to scale.

- Laser doping of the front surface using spin-on of 85% phosphoric acid as doping source followed by laser doping using a continuous wave laser at a wavelength of 532 nm, 20 W laser power and 2–4 m/s laser scan speed.
- Light-induced plating of Ni acting as seed and barrier layer for the subsequent Cu plating.
- Ni sintering using rapid thermal processing (RTP) in N_2 ambient at 350 °C for 2 min.
- Light-induced plating of Cu onto the Ni seed layer.
- Edge isolation by laser ablation using a 20 W Nd:YAG Lee laser tool.

The starting substrates were 25 × 25 mm^2 *p*-type, CZ mono-crystalline Si with a thickness of 200 μm and a resistivity of 1–3 Ω cm.

Fig. 1 shows a schematic cross-section of the fabricated solar cell.

3. Characterization

J–V curves and photovoltaic performance including short-circuit current density, J_{SC}, open-circuit voltage, V_{OC}, fill factor, FF, and power conversion efficiency were measured on complete cells under 1 sun illumination (1000 W/m^2, AM1.5G) using a ELH halogen light source, Advantest TR6143 DC Source Measurement Unit and Labview software for data collection. The illumination was calibrated using the known short-circuit current of a reference mono-crystalline Si screen-printed solar cell.

A LEO 1550 Scanning Electron Microscope (SEM) was used to characterize the nanostructured surface topology.

Suns-V_{OC} [32,33] measurements were performed using a Sinton WCT-120 Lifetime tester. The J_{SC} value from the IV-measurement was used.

Reflectance was measured using a Perkin Elmer integrating sphere and spectrometer. The absorptance was measured using a center mount sample holder inside the integrating sphere.

External Quantum Efficiency (EQE) was measured without bias light using a PV Measurement QE system and Internal Quantum Efficiency (IQE) was calculated based on the EQE and reflectance measurements.

Photoluminescence (PL) [34] was measured at open-circuit conditions using a BTi luminescence imaging tool. Cross-sectional Focused Ion Beam (FIB)/SEM images of the plated Ni/Cu