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Energy Procedia 27 (2012) 555 – 560

Energy Procedia

SiliconPV: April 03-05, 2012, Leuven, Belgium

Tandem solar cell concept using Black Silicon for enhanced infrared absorption

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Abstract

In this work we present a novel tandem solar cell concept that is based on enhanced below band gap infrared absorption. The solar cell structure is based on silicon and infrared activated Black Silicon. Infrared active Black Silicon is produced by exposing silicon to fs-laser pulses. It features an enhanced IR absorption, when processed under a sulfur-containing atmosphere. Then sulfur is incorporated into the silicon lattice during laser processing providing energy states in the band gap. This silicon based tandem cell thus absorbs light with wavelengths beyond 1.1 µm. This can potentially increase the overall efficiency. In this paper we present the first experimental realization of this concept. We use a standard aluminium-back-surface-field (Al-BSF) silicon solar cell and implement a Black Silicon solar cell on its rear side for enhanced IR absorption. Current and voltage measurements show the feasibility of our concept.

Keywords: tandem solar cell; Black Silicon; infrared absorption

1. Introduction

The absorption ability of silicon solar cells is limited to light with energies larger than the silicon bandgap $E_G = 1.12$ eV. Therefore, the efficiency of silicon based solar cells is restricted because the infrared (IR) region of the solar spectrum is left unexploited [1].

In recent studies, it was discovered that the irradiation of silicon with fs-laser pulses under a sulphur containing atmosphere leads to a microstructured surface which enhances the light absorption in the

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doi:10.1016/j.egypro.2012.07.109

visible as well as in the IR spectral range [2-4]. This material is called Black Silicon. A similar texturization without the IR absorptance can be achieved by plasma immersion ion implantation [5] or chemical etching processes [6]. In contrast to conventional etching techniques, the laser texturing is independent on crystal orientations and can be performed on various substrates [4]. Additionally to the IR absorption, the sulphur is a donor and enables n-doping. Hence, with a single laser processing step, the pn-junction, the antireflective surface as well as the IR absorption can be realized. Based on Black Silicon we could demonstrate a laserprocessed Black Silicon solar cell with a record efficiency of η = 4.5 % [7].

2. Black Silicon properties

Depending on the number of pulses per spot we can achieve obvious planar surfaces as well as grey and black appearing structures as depicted in the top row of Fig. 1 for SF_6 treated samples. In the bottom line of Fig. 1 it can be seen that the surface is definitely already influenced by one fs-laser pulse per spot. Increasing the number of pulses per spot to 5 causes smooth contoured structures with heights of about 200 nm. 500 pulses per spot form sharp conical spikes with a base diameter of several micrometers and a height of about 10 µm.

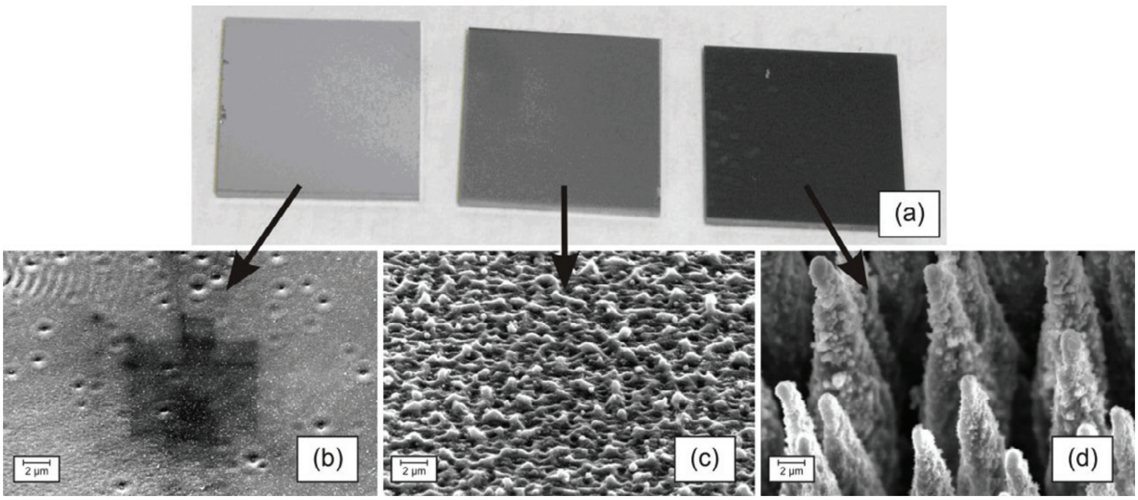

Fig. 1. Photograph (a) and SEM micrographs (b - d) of different silicon surfaces structured in SF6 ambient; (b): 1 puls per spot, (c): 5 pulses per spot, (d): 500 pulses per spot

The aborption spectra of Fig. 2 show the following results: Near unity absorption in the visible and near infrared spectral range occurs for Black Silicon processed in SF_6. Black Silicon processed in vacuum has an enhanced NIR absorption because of the size of the cones which enable multiple reflections of longer wavelengths into the material and increase the absorption length within the material but it clearly drops for longer wavelengths. The reason for the drop can be seen if we look closer at the Grey Silicon samples. Their lower absorption in the visible is obviously due to the lower surface roughness; at the band edge the absorption drops but remains nearly constant around 65 % for SF_6 processed samples. Vacuum processed Grey Silicon samples have almost no enhanced infrared absorption. That reduces the high absorption at longer wavelengths due to the missing implementation of sulfur.

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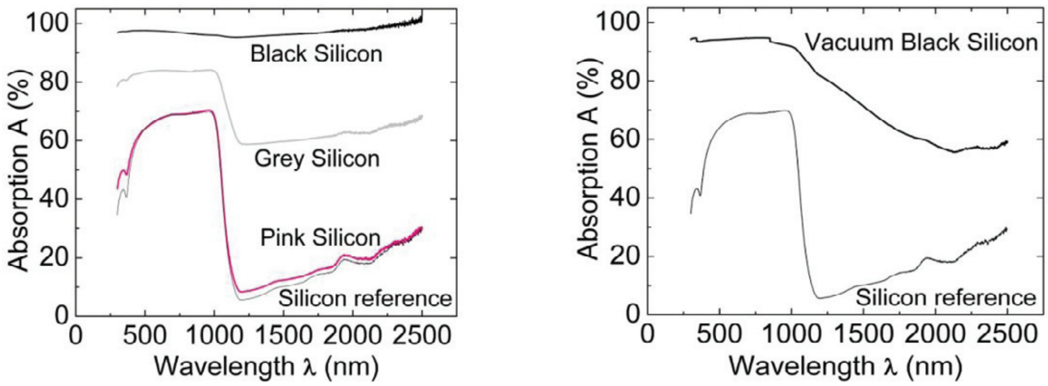
Even silicon processed with one pulse per spot in SF_6 has a slightly enhanced infrared absorption compared to the silicon reference.



(a) (b)

Fig. 2. Absorption of fs-laser structured silicon with (a) 1, 5 and 500 pulse per spot in SF_6 ambient; (b) 500 pulses per spot in vacuum

3. The tandem cell concept

The basic idea of our tandem cell concept is to add the IR light conversion ability of Black Silicon to an industrial Al-BSF silicon solar cell [8]. For that reason, we integrate a secondary pn-junction formed by an area of Black Silicon on the back side of a standard industrial solar cell as shown in Fig. 3. As a consequence, the p-type substrate of the primary cell acts as a base for both pn-junctions. This kind of npn-double junction solar cells was investigated by Ghannam in 1991 [9]. He could show that this structure has the potential to reduce the back surface recombination velocity and predicts efficiencies around 25% for standard emitter solar cells [9]. The function of this design is illustrated in Fig. 3 on the right side. The visual part of the solar spectrum (VIS) is mainly absorbed at the primary cell on the front side. The IR part of the spectrum passes the primary pn-junction and can be harvested at the secondary Black Silicon pn-junction at the back side.

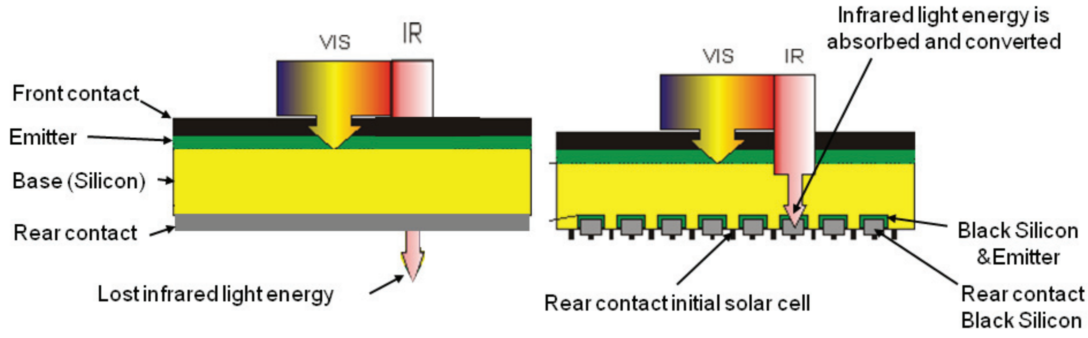


Fig. 3. A standard Al-BSF silicon solar cell (left) compared to our tandem cell concept using Black Silicon (right)

4. Experimental and results

We fabricate a sample by partly removing the Al rear contact from an industrial Al-BSF silicon solar cell with hydrofluoric acid (HF). After laser processing the surface in this area (5 laser pulses per spot, 100 µJ pulse energy, 80 µm spot diameter), a Ti/Pd/Ag contact for the Black Silicon is evaporated.

We measure the current-voltage curve of the secondary Black Silicon pn-junction continuously with and without a front side illumination from an AM 1.5 solar spectrum. The result is shown in Fig. 4. As can be seen, the light which passes through the primary pn-junction produces a small open circuit voltage of $V_{oc} \approx 17$ mV and a noticeable short circuit current density of $J_{sc} \approx 1$ mA/cm² at the secondary cell. As the solar cell area, we take the whole sample although the secondary cell had to be made smaller because some space is needed for the rear contact (see Fig. 3).

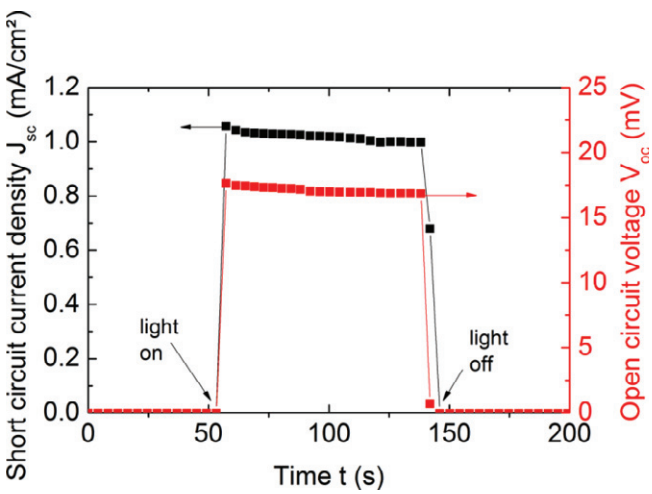


Fig. 4. Measured V_{oc} and J_{sc} at the secondary Black Silicon pn-junction under front side illumination with an AM 1.5 solar spectrum

5. Discussion

These first experimental results prove the feasibility of our tandem cell concept. A significant part of the solar spectrum passes the primary pn-junction and is harvested at the secondary cell. We assume that some fraction of the visible light reaches the Black Silicon as well and that the measured effect is not solely caused by IR light. Additionally, the processing parameters used for the Black Silicon cell are optimized for stand-alone Black Silicon solar cells. Therefore, further studies are necessary to adapt the material parameters for an optimized tandem cell.

For this first experiment the primary cell lost about half of its efficiency due to the partial removal of the rear contact. This was expected because the original cell was not intentionally produced for such a treatment. Future experiments should be performed on specially prepared solar cells as raw material. Additionally, the Black Silicon surface has to be passivated in order to get lower Schottky-Read-Hall recombinations. Recently, Otto et al. demonstrated extremely low surface recombination velocities in plasma etched black silicon by using an Al_2O_3 passivation layer [10]. The excellent results suggest that this passivation process could probably be adapted for our material.

In general, it should be investigated how the laser structuring and the sulfur states influence the carrier lifetime of the primary cell. Therefore, we pursue an approach to tailor the Black Silicon parameters with laser pulse shaping. The sulfur states are measured by deep-level transient spectroscopy (DLTS) and the carrier lifetime is observed with quasi-steady-state-photoconductance (QSSPC) measurements [7]. With these efforts, we expect a net benefit for the efficiency of an optimized Black Silicon tandem solar cell.

6. Conclusion

We presented a novel concept for a tandem solar cell which uses Black Silicon. With this material it is possible to enhance the IR absorption ability of the tandem cell. We show that the secondary Black Silicon cell converts light, when the tandem cell is illuminated through the front side. This proves the feasibility of our tandem cell concept.

Nomenclature

E_G	energy band gap (eV)
η	solar cell efficiency (%)
V_{oc}	open circuit voltage (V)
J_{sc}	short circuit current density (mA/cm²)
NIR	near infrared
DLTS	deep-level transient spectroscopy
QSSPC	quasi-steady-state-photoconductance measurement

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