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ScienceDirect
Energy Procedia 55 (2014) 186 – 189
Energy Procedia

4th International Conference on Silicon Photovoltaics, SiliconPV 2014

# Experimental implementation of a silicon wafer tandem solar cell

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**Abstract**

We combine aluminum back surface field (Al-BSF) solar cell precursors with an additional rear side infrared active floating emitter in a tandem cell configuration. This emitter is implemented area selectively by fs-laser hyperdoping in a sulfurous atmosphere. Its design as a floating emitter conceals losses induced by the laser process as long as n-doping occurs. All processes are adapted and supplemented by just a single new process step.


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*Keywords:* silicon wafer; tandem solar cell; fs-laser; sulfur doping

## 1. Introduction

Multi-junction solar cells enable the efficient conversion of the solar spectrum. Although the Shockley-Queisser limit for single junction solar cells can be exceeded [1], silicon based approaches are mainly limited to defect rich thin film concepts. Therefore, efficiencies remain significantly below single junction solar cells fabricated on crystalline silicon wafers [2]. Crystalline silicon wafer solar cells, on the other hand, are well established and have the largest market share. In order to enable silicon wafer solar cells to additionally convert infrared light with energies below the silicon band gap, a tandem solar cell concept for silicon wafer solar cells was proposed in 2012 [3]. In this work we implement this concept experimentally, but without contacting the secondary emitter to avoid complicated interconnection into a solar panel. The so called floating emitter contributes to the overall photocurrent anyway as it is described by Ghannam [4].


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doi:10.1016/j.egypro.2014.08.114

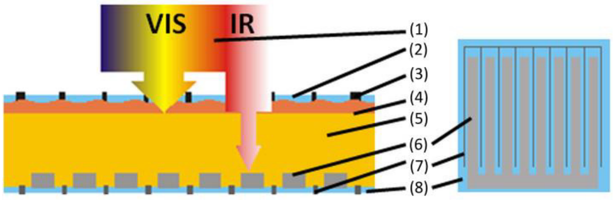


Fig. 1. Schematic tandem cell structure for silicon wafer solar cells with an additional fs-laser sulfur hyperdoped floating emitter at the rear; (left) cross section , (right) top view of the rear side., where back contact fingers are interdigitated between the laser processed areas. (1) Incident light schematically subdivided into visible (VIS) and infrared (IR) wavelengths ranges, (2) Front side anti reflection coating, (3) Ag front contact, (4) primary pn-junction, (5) base, (6) laser processed area creating the secondary pn-junction, (7) AgAl back contact, (8) rear passivation layer.

## 2. Experimental implementation

The silicon tandem solar cell design as shown in Fig.1 is manufactured with well established standard silicon solar cell process steps and completed with the laser processing step. The process flow is depicted in Fig. 2.

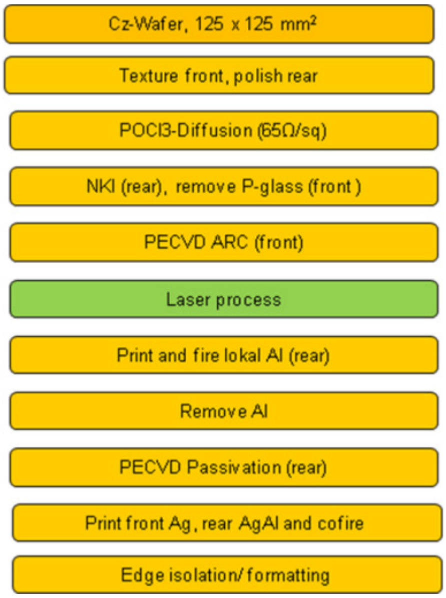


Fig. 2. Schematic process flow used to manufacture the silicon tandem solar cell with Al-BSF solar cell processes. The femtosecond laser processing is indicated in green as the only additional process step.

We manufacture the silicon tandem cells on, 125 x 125 mm$^2$, boron doped 1 – 5 Ωcm Cz wafer, although they are not limited to that size or a monocrystalline substrate. After the samples are chemically textured at the front and polished at the rear, the primary phosphorus emitter is diffused via POCl3 tube diffusion to a sheet resistance of 65 Ω/sq. The phosphorus silicate glass is removed from the front and the emitter on the rear is removed by single sided polish etching (NKI). On the front side a SiN film is deposited by plasma enhanced chemical vapour deposition (PECVD) as an anti reflective coating (ARC). Then the rear side is laser processed. A titanium doped sapphire based regenerative amplifier system is used to generate fs laser pulses with fluencies of $E = 2$ J/cm$^2$ at a spot diameter (intensity 1/e) of $d = 80$ µm. More details on the laser process are given in Ref. [5]. According to the design in Fig. 1, the laser spot is scanned area selectively across the rear of the solar cell in a process chamber, which is optionally evacuated to a pressure $p < 0.1$ mbar or filled with sulfur hexafluoride ($SF_6$). The $SF_6$ ambient enables the incorporation of sulfur forming the secondary emitter during the process, since this sulfur enables n-doping [6] and absorption below the silicon band gap [7].

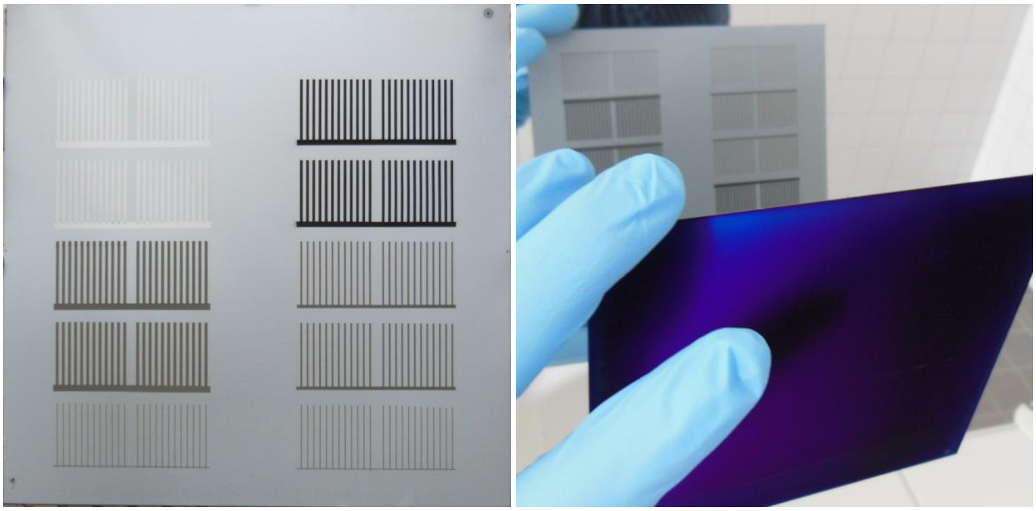

Fig. 3. Fotograph of a laser processed 125 x 125 mm$^2$ tandem solar cell precursor; (left ) rear side with 20 2 x2 cm² lasered silicon tandem solar cell structures, (right) held in front of a mirror with the precursor front in the foreground. Features at the rear are the laser structured areas which are laser cut to 20 differently processed silicon tandem solar cells plus 5 reference cells, which are located in the middle row on the wafer.

A typical silicon tandem solar cell precursor after the laser process is shown in Fig. 3. It is designed to yield up to 20 different solar cells plus 5 reference cells in a size of 20 x 20 mm$^2$ laser cut only before analysis. Basically any design, size or laser parameters can be adjusted. After the laser process an aluminum back contact is screen printed interdigitated between the laser processed areas and fired to form a back surface field. Finger grids as well as full area back contacts are deposited onto the reference cells. The aluminum is removed to keep the PECVD system clean in the subsequent step. A PECVD SiO/ SiN stack is chosen for rear passivation. Finally the front silver and rear silver-aluminum contacts are screen printed and are cofired in a belt furnace, contacting the emitter an base through the rear and front passivation layer. Then laser cut formatting and edge isolation is applied. For analysis the overall efficiencies of the silicon tandem solar cells are measured by AM 1.5, 100 W/cm$^2$ standard illumination and compared to the reference cells.

## 3. Results and discussion

Table 1 lists the results achieved by the silicon tandem and reference solar cells processed as described above. The reference solar cells reveal an average efficiency of 14.7%. Silicon tandem solar cells, which are area selectively structured in vacuum, only achieve 11.4%. Obviously losses are induced by the laser process in vacuum ambient likely due to structural defects [8]. Laser processing in sulfur hexafluoride enables silicon tandem solar cells with an average efficiency of 14.4%, which is very close to the average efficiency of the reference solar cells. It is unlikely that the losses are completely compensated by an additional infrared photocurrent generated by the sulfur emitter. In fact, a photocurrent in the spectral range below the silicon band gap can be detected [9,10]. As described by Guenther et al. [9] sulfur related energy levels are incorporated into the silicon band gap. Excess carriers below the silicon band gap are generated without bias only due to illumination at onset energies of 618eV, 310eV and 191eV below the conduction band [9]. At this stage its contribution cannot be quantified yet. The experiments show that the laser sulfur n-doping recovers the efficiency to the level of the reference solar cells. Most likely, the laser induced intrinsic defects are still present in the silicon tandem solar cells, but the laser n-doped floating emitter might conceal the losses as described by Ghannam [4]. Thus the losses can be compensated by a combination of the floating emitter design plus the additional infrared photocurrent. To overcome the reference solar cell's efficiency, the laser incorporated impurities in the silicon tandem solar cells need to be analyzed and passivated. A possible approach to do so might be an extra phosphorus n-doping in the sulfur laser doped region to keep intra gap energy levels filled as proposed by Keevers and Green [11].

Table 1. Efficiencies of reference solar cells, silicon tandem solar cells laser structured in vacuum and with laser structured in sulfur hexafluoride. References with full area as well as finger grid back contacts achieve approximately the same efficiency.

| Cell type | reference | rear laser structured in vacuum | rear laser structured with sulfur emitter |
|---|---|---|---|
| $\eta$ (%) | 14.7 | 11.4 | 14.4 |
| standard deviation | 0.6 | 3.0 | 0.5 |

## 4. Conclusion

We implemented a concept for silicon wafer tandem solar cells experimentally. We find that laser structuring causes efficiency losses, most probable due to silicon crystal lattice damage. These losses are compensated by recombination suppression due to the floating emitter and by the additional photocurrent originating from infrared photons with energies below the silicon band gap. By reducing the laser damage or by increasing the conversion efficiency of infrared photons, a net efficiency increase is possible. Thus, as shown in this work, an upgrade of Al-BSF silicon solar cells by means of an infrared active secondary laser sulfur n-doped emitter is an attractive path towards higher efficiencies and intermediate band photovoltaics.

## References


[1] W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", Journal of Applied Physics 32 (3), 510-519 (1961).

[2] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 42)", Progress in Photovoltaics: Research and Applications 21 (5), 827–37 (2013).

[3] K.-M. Günther, A. L. Baumann, T. Gimpel, S. Kontermann, and W. Schade, "Tandem Solar Cell Concept Using Black Silicon for Enhanced Infrared Absorption", Energy Procedia 27 (0), 555–60 (2012).

[4] M. Y. Ghannam, "A new n+pn+ structure with back side floating junction for high efficiency silicon solar cells", IEEE Photovoltaic Specialists Conference, 284–289 vol.1., (1991)

[5] S. Kontermann, T. Gimpel, A. L. Baumann, K.-M. Günther, and W. Schade, "Laser Processed Black Silicon for Photovoltaic Applications", Energy Procedia 27 (0), 390–95 (2012).

[6] K.-M. Guenther, T. Gimpel, S. Kontermann, and W. Schade, "Investigation of the sulfur doping profile in femtosecond-laser processed silicon", Applied Physics Letters 102 (20), 202104–4 (2013).

[7] C. H. Crouch, J. E. Carey, M. Shen, E. Mazur, and F. Y. Génin, "Infrared absorption by sulfur-doped silicon formed by femtosecond laser irradiation", Applied Physics A: Materials Science & Processing 79, 1635-1641 (2004).

[8] T. Gimpel, I. Höger, F. Falk, W. Schade, and S. Kontermann, "Electron backscatter diffraction on femtosecond laser sulfur hyperdoped silicon", Applied Physics Letters 101 (11), 111911–3 (2012).

[9] K.-M. Guenther, " Excess carrier generation in femtosecond-laser processed sulfur doped silicon by means of sub-bandgap illumination ", Applied Physics Letters 104 (4),42107 (2014)..

[10] J. E. Carey, C. H. Crouch, M. Y. Shen, and E. Mazur, "Visible and near-infrared responsivity of femtosecond-laser microstructured silicon photodiodes", Optics Letters 30 (14), 1773–75 (2005).

[11] M. J. Keevers and M. A. Green, "Efficiency improvements of silicon solar cells by the impurity photovoltaic effect", Journal of Applied Physics 75 (8), 4022 (1994).