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Bifacial Low Concentrator Argentum Free Crystalline Silicon Solar Cells Based On ARC Of TCO And Current Collecting Grid Of Copper Wire

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Abstract: Results obtained in frame of an innovative approach for fabrication of the bifacial low concentrator Ag free Cz silicon solar cells based on Indium-Tin-Oxide(ITO)/(p⁺nn⁺)Cz-Si/Indium-Fluorine-Oxide (IFO) structure (n-type cell) as well as on IFO/(n⁺pp⁺)Cz-Si/ITO structure (p-type cell) are presented in this work. The (p⁺nn⁺)Cz-Si and (n⁺pp⁺)Cz-Si structures were produced by diffusion of boron and phosphorus from deposited B- and P-containing glasses followed by an etch-back step. The n⁺ surface of the structures was textured, whereas the p⁺ surface remained planar. Transparent conducting oxide (TCO) films, which act as passivating and antireflection electrodes, were deposited by ultrasonic spray pyrolysis method on both sides. The contact pattern of copper wire was attached by the low-temperature (160 °C) lamination method simultaneously to the front and rear TCO layers as well as to the interconnecting ribbons arranged outside the structure. The shadowing from the contacts is in the range of ~4%. The resulting solar cells showed front/rear efficiencies of 18.6–19.0%/14.9–15.3% (p-type cell) and 17.5–17.9%/16.5–17.0% (n-type cell) respectively at 1–5 suns. Even for 1 sun illumination at 20–50% albedo, similar energy production corresponds to 21.6–26.1% (p-type cell) and 20.8–25.8% (n-type cell) efficiency of a monofacial cell.

Keywords: Solar cell; Crystalline Si; Bifacial; Concentrator; Ag free.

PACS: 88.40.jj;

INTRODUCTION

This paper presents results obtained for innovative bifacial concentrator solar cells based on the Laminated Grid Cell (LGCell) design [1]. The LGCells have been processed on the basis of p-Si as well as n-Si wafers without the usage of Ag pastes. These cells have a bifacial photosensitivity and have been optimized for application in systems with the sunlight concentration ratio of 1–5. The LGCells have the following structures: Indium Tin Oxide (ITO)/(p⁺nn⁺)Cz-Si/Indium Fluorine Oxide (IFO) (n-type cell) and IFO/(n⁺pp⁺)Cz-Si/ITO (p-type cell).

The LGCell design (Figure 1) is based on the following peculiarities: (i) implementation of Transparent Conducting Oxide (TCO) films as antireflection coating (ARC) as well as transparent passivating electrodes and (ii) copper wire based grids bonded on both, front and rear sides of a solar cell structure by a lamination technique.

Important to note that lamination of such grids to TCO can be done at relatively low-temperatures (around 160°C). Interconnecting ribbons in the proposed design are shifted from the solar cell surface and do not contribute to the shadowing of the solar cell

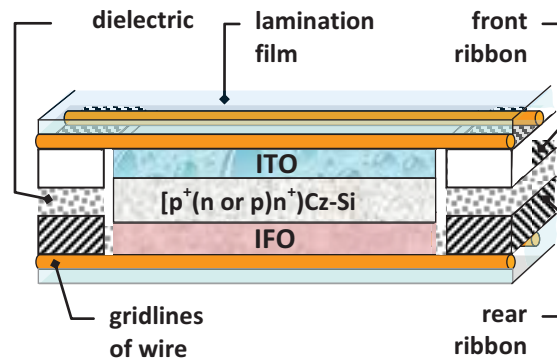


FIGURE 1. Schematic diagram of the bifacial LGCell silicon solar cell with ITO/[p⁺(n or p)n⁺]Cz-Si/IFO structure processed in this work

structure. As a result, such design excludes a direct contact of a soldering iron with the solar cell structure, thus, avoiding its damage during the assembly into a PV module.

Selection of TCO layers for LGCells has to be done using some specific requirements formulated in [2,3]. Following these requirements for the selection of TCO films for solar cells based on TCO/[p⁺(n or

p) n^+ Si/TCO structures with diffusion layers, it is necessary to use: (i) ITO film to form an ARC on the p^+ -Si surface, (ii) IFO ARC for the n^+ -Si surface.

It has to be noted also that this work can be considered as an extension of our developments for n-Si based bifacial non-concentrator LGCells with the front/rear efficiencies of 16.3%/14.5% (confirmed by Sandia National Laboratories) [4], and also a bifacial concentrator LGCells with the front/rear efficiencies of 16.6%–17.3%/14.6–15.3% respectively under 1-7 suns [5], 16.5–16.7%/15.1–15.3% [6] and 16.7–16.9%/16.3–16.5% under 1-3 suns [7] reported earlier. For p-Si based bifacial concentrator LGCells previous result was of 17.7%–18.0%/13.3–13.7% for front/rear illumination respectively under 1-6 suns [8]. In this work we applied recently optimized condition of ITO [9] and IFO [10] films deposition, and a new lamination film.

DEVICE FABRICATION

The process sequence for fabrication of bifacial LGCells is similar for both n-Si and p-Si based solar cells. It can be seen in Figure 2.

Basic fabrication steps of such cells for 200 μm thick $125 \times 125 \text{ mm}^2$ 2–3 $\Omega \cdot \text{cm}$ 100-oriented n-type and p-type Czochralski silicon substrates included: (i) standard RCA cleaning which was applied after a saw damage removal; (ii) boron diffusion, which was performed in a conventional tube furnace from a spin-on deposited boron silicate glass (BSG); (iii) texturing (p^+ surface remained planar); (iv) phosphorus diffusion from a spin-on deposited phosphorus silicate glass (PSG). After diffusions, the sheet resistance R_p of the p^+ layer was of 26 Ω/\square (n-type cell) and 18 Ω/\square (p-type cell); the sheet resistance of the n^+ layer R_n – 50 Ω/\square (n-type cell) and 64 Ω/\square (p-type cell).

After removing the spin-on glasses in 4% HF, n^+ and p^+ layers were separately thinned by etch-back in an $\text{HNO}_3:\text{H}_2\text{O}:\text{HF}$ solution. As a result, R_p values increased up to 74 Ω/\square (n-type cell) and 39 Ω/\square (p-type cell), whereas the R_n values increased up to 88 Ω/\square (n-type cell) and 84 Ω/\square (p-type cell). The TCO films with a thickness of $\sim 100 \text{ nm}$ were deposited using the ultrasonic spray pyrolysis (pyrosol) method, which has been described in [11]. Before deposition of each type of the TCO film, solar cell structures were subjected to the RCA cleaning.

As a first step, IFO based ARC was deposited on the n^+ -Si surface of a solar cell structure. Film forming solution (FFS) consisting of 0.2 M InCl_3 + 0.05 M NH_4F + 0.1 M H_2O in methanol has been used. Deposition process was realized at 475 $^\circ\text{C}$ using Ar + 5% O_2 as a carrier-gas followed by an annealing at 375 $^\circ\text{C}$ in an Ar-methanol vapors mixture for 5 min.

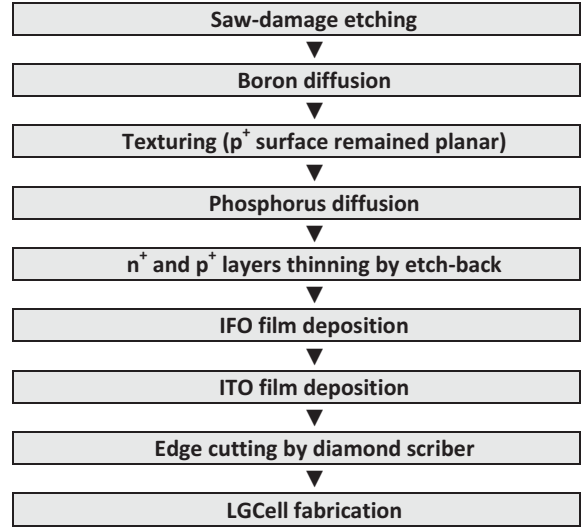


FIGURE 2. Processing sequence for fabrication of bifacial LGCells based on the IFO/ (n^+pp^+) Cz-Si/ITO (p-type cell) and ITO/ (p^+nn^+) Cz-Si/IFO (n-type cell) structures.

The sheet resistance of the IFO layer was of 35 Ω/\square . Second step has been done as follows: an ITO film was deposited on the p^+ -Si emitter from the FFS consisting of 0.1M InCl_3 + 0.003M SnCl_4 + 7M H_2O in methanol. Deposition process was realized at 375 $^\circ\text{C}$ using Ar as a carrier-gas [9]. The sheet resistance of the ITO layer was of 55 Ω/\square .

Afterwards solar cell structures were cut into pieces with the size of 25 \times 25 mm^2 by means of a diamond cutting tool. Front and rear sides contact grids consisting of 60 μm diameter copper wires coated by a special contact composition were bonded by a lamination film to TCO ARCs as well as to the interconnecting ribbons using a low-temperature (~ 160 $^\circ\text{C}$) lamination. In this work, a new lamination film 40 μm thick based on polypropylene was used instead of PET (polyethylene terephthalate) film, which has been used before. The distance between the wires was 1.5 mm. The longitudinal resistance of the wire contacts was $\sim 60 \text{ m}\Omega/\text{cm}$ (defined by the resistivity of copper). The resistivity of the contact to the TCO film did not exceed 1 $\text{m}\Omega \cdot \text{cm}^2$ [12].

RESULTS AND DISCUSSION

For the developed LGCells the External Quantum Efficiency (EQE) measurements and IV curves recorded under elevated intensity flash illumination were performed in the PV Lab of the Ioffe Physical-Technical Institute. Measurements of the total reflection spectra $R(\lambda)$ were carried out with the use of an integrating sphere.

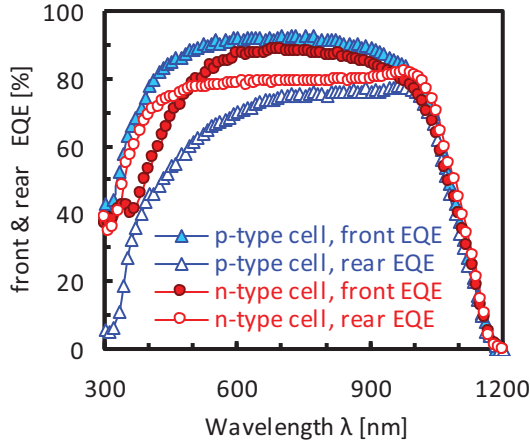


FIGURE 3. External quantum efficiency spectra EQE of the LGCells for front and rear illumination

Characterization Of The LGCells At One-Sun Conditions

Figures 3 and 4 show, respectively, the results of external quantum efficiency (EQE) and reflection $R(\lambda)$ spectra measurements for LGCells. Reflection from the textured side is less than the reflection from the planar side. The minimal reflection coefficient values for the textured side (about 5%) is a little less than previously obtained [7], because the refraction index of the polypropylene is less compared to PET.

It is necessary to note that minimal reflection from a solar cell of the LGCell design is somewhat greater than that from the conventional solar cells, which have grids and bus bars processed using screen printing method. This difference can be attributed to a lamination film, which is used to coat LGCells. However, parameters presented for an LGCell are rather close for those, which can be obtained for the solar cell modules.

Some parameters of the bifacial LGCells, which were measured at 1X illumination for front and rear

TABLE 1. Efficiency η , short-circuit current density J_{sc} , open-circuit voltage V_{oc} and fill factor FF values of the ITO/(p^+n^+)Cz-Si/IFO (n-type cell) and IFO/(n^+pp^+)Cz-Si/ITO (p-type cell) LGCells at front and rear 1X (AM1.5G) illumination (25°C).

Parameter	n-type cell		p-type cell	
	front	rear	front	rear
J_{sc} [mA/cm ²]	35.0	33.8	37.7	30.1
V_{oc} [mV]	631	629	630	627
FF [%]	79.1	78.9	78.4	78.9
η [%]	17.5	16.5	18.65	14.9
η [%] at 20% albedo	20.8		21.6	
η [%] at 50% albedo	25.75		26.1	

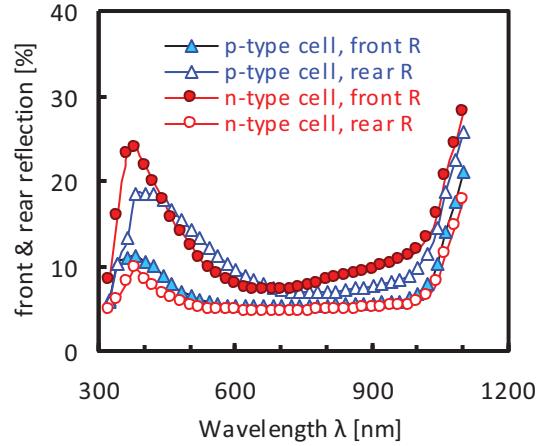


FIGURE 4. Reflection spectra $R(\lambda)$ of the LGCells for front and rear illumination

sides, are presented in Table 1. For the n-type cell, efficiency was 17.5% for the front side illumination and 16.5% – for the rear side (bifaciality is 94%). This result is considerably greater than previously obtained [7] mainly due to the higher value of the open circuit voltage V_{oc} (+22 mV). For the p-type cell efficiency was 18.7% for the front side illumination and 14.9% – for the rear side (bifaciality is 80.5%). This result also is considerably greater than previously obtained mainly due to the higher value of the short-circuit current J_{sc} .

Rather high bifaciality became possible due to the high minority carrier lifetime τ in the Si wafers and also due to passivation of the rear surface with an back-surface field and an TCO film. At 20–50% albedo, bifacial solar cells with such a bifaciality produce more electricity compared to conventional monofacial solar cells; similar energy production corresponds to 20.8–25.8% (n-type cell) and 21.6–26.1% (p-type cell) efficiency of a monofacial cell.

Analysis of the literature shows that 17.5%/16.5% for the front/rear efficiency, respectively, obtained in this work for the bifacial LGCell based on n-Si, as well as 18.7%/14.9% for the front/rear efficiency, respectively, for the bifacial LGCell based on p-Si are not inferior to other cells including even those that have been fabricated with the use of evaporated contacts. However, LGCells are concentrator ones.

Characterization Of The LGCells At Concentrated Illumination

Parameters of the bifacial LGCells as a function of the sun light concentration ratio C at the front side illumination conditions are shown in Fig. 5. From Fig. 5 it can be seen that in the range of the optimum

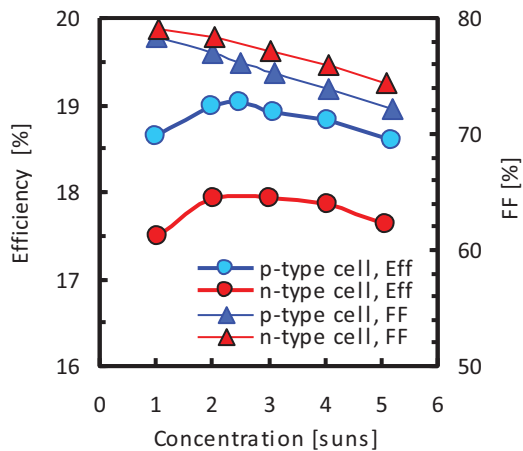


FIGURE 5. Efficiency η and fill factor FF of the bifacial LGCells with ITO/(p⁺nn⁺)Cz-Si/IFO structure (n-type cell) and IFO/(n⁺pp⁺)Cz-Si/ITO structure (p-type cell) as a function of sunlight concentration ratio at front side illumination condition

sunlight concentration ratios (1–5X), the efficiency of a front side illuminated cell varies from 18.65% to 19.0% for the p-type cell and from 17.5% to 17.9% for the n-type cell.

CONCLUSIONS

In this work it is demonstrated that the LGCells, which are bifacial (bifaciality is 80–94%), low-concentrator (1–5X) devices, can be fabricated on the basis of Czochralski n-Si as well as p-Si without the using of Ag containing metallization. The interconnecting ribbons in the proposed design are arranged outside the solar cell structure and do not contribute in the shadowing. This simplifies the module assembly and also excludes contact of the cell with a soldering iron avoiding its damage in assembling the module.

It has been demonstrated that at the one-sun conditions, the front/rear efficiencies of the LGCells were, respectively, 18.65/14.9% (p-type cell) and 17.5/16.5% (n-type cell). For the albedo of about 20–50%, such a cell will generate the power amount, similar to that produced by a monofacial solar cell of 20.8–25.8% (n-type cell) and 21.6–26.1% (p-type cell) efficiency.

These results have been obtained using application of TCO films as transparent, antireflection and passivating electrodes on both surfaces of the (p⁺nn⁺)Cz-Si structure with diffused layers (n⁺-Si and p⁺-Si highly doped by P and B layers, correspondingly). Application of TCO films has allowed to decrease the series resistance R_s .

Application of wire contact gridlines (wire diameter – 60 μm) also contributed in a reduction of the R_s value. The achieved decrease of the series resistance has made possible to use the described LGCells in the low-concentrator systems without decreasing their efficiency. At the 1–5X illumination, the front LGCell efficiency was 18.6–19.0%/17.5–17.9% for p-/n-type cell, respectively.

It should be noted that the LGCell has been fabricated from the 200 μm thick Si wafers. Feasibility for further decrease of the LGCell thickness depends on the design of the contact system, which is formed by the low-temperature lamination based method. An additional advantage of the proposed design is based on the absence of a contact between the wafer and the interconnecting ribbons.

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REFERENCES

- G. G. Untila, T. N. Kost, A. B. Chebotareva, M. B. Zaks, A. M. Sitnikov, and O. I. Solodukha, *Semiconductors* **39**, 1346-1351 (2005).
- G. G. Untila, T. N. Kost, A. B. Chebotareva, M. B. Zaks, A. M. Sitnikov, and O. I. Solodukha, *Semiconductors* **42**, 406-413 (2008).
- G. G. Untila, T. N. Kost, and A. B. Chebotareva, *Thin Solid Films* **518**, 1345-1349 (2009).
- G. Untila, A. Osipov, T. Kost, A. Chebotareva, M. Zaks, A. Sitnikov, O. Solodukha, and A. Pinov, 17th EUPVSEC Proceedings, 2001, pp. 1793-1795.
- G. G. Untila, T. N. Kost, A. B. Chebotareva, M. B. Zaks, A. M. Sitnikov, O. I. Solodukha, and M. Z. Shvarts, 26th EUPVSEC Proceedings, 2011, pp. 629-633.
- G. G. Untila, T. N. Kost, A. B. Chebotareva, M. B. Zaks, A. M. Sitnikov, O. I. Solodukha, and M. Z. Shvarts, *Semiconductors* **46**, 1194-1200 (2012).
- G. G. Untila, T. N. Kost, A. B. Chebotareva, M. B. Zaks, A. M. Sitnikov, O. I. Solodukha, and M. Z. Shvarts, 27th EUPVSEC Proceedings, 2012; pp. 271-273.
- G. G. Untila, T. N. Kost, A. B. Chebotareva, M. B. Zaks, A. M. Sitnikov, O. I. Solodukha, and M. Z. Shvarts, 25th EUPVSEC Proceedings, 2010; pp. 2588-2591.
- G. G. Untila, T. N. Kost, A. B. Chebotareva, and M. A. Timofeyev, *Semiconductors* **46**, 962-968 (2012).
- G. G. Untila, T. N. Kost, A. B. Chebotareva, and M. A. Timofeyev, *Semiconductors* **47**, 415-421 (2013).
- A. B. Chebotareva, G. G. Untila, T. N. Kost, S. Jorgensen, A. G. Ulyashin, *Thin Solid Films* **515**, 8505–8510 (2007)
- G. Untila, A. Osipov, T. Kost, A. Chebotareva, 17th EUPVSEC Proceedings, 2001, pp. 265–268.