High-Efficiency Silicon Solar Cells With Boron Local Back Surface Fields Formed by Laser Chemical Processing

Sven Kluska and F. Granek

***Abstract*—The successful implementation of industrially feasible local boron dopings as local back surface field (LBSF) for high-efficiency silicon solar cells processed with laser chemical processing (LCP) is demonstrated for the first time. The processed passivated-emitter rear locally diffused solar cells with LCP LBSFs show cell efficiencies of up to 20.9% with a cell efficiency benefit of up to 0.3–0.4%abs. in comparison to the reference passivated emitter and rear cells processed with a doping-free LCP opening. The results show the potential of LCP to create boron dopings in order to decrease the contact resistance and reduce the minority carrier recombination at the local metal contacts in order to improve the fill factor and the open-circuit voltage, respectively.**

***Index Terms*—Boron doping, laser chemical processing (LCP), local back surface field (LBSF), silicon solar cell.**

I. Introduction

STATE-OF-THE-ART high-efficiency silicon solar cells such as passivated-emitter rear locally diffused (PERL) solar cells [1] use passivation layers and local dopings in order to reduce the recombination losses and to improve the contact resistance. The laboratory approach to create local dopings requires cost-intensive and time-consuming processes such as photolithography. Different approaches to create industrially feasible selective emitter structures at the front side of the solar cell (for a review of state-of-the-art selective emitter techniques, see [2]) exist, as well as different techniques to create a passivated rear-side structure with local rear-side contacts [3]–[5].

An industrially feasible approach for front- and rear-side processing is the local opening of the passivation layers and the simultaneous doping of the silicon underneath with laser chemical processing (LCP) [6]. The coupling of a laser beam into a liquid jet enables the formation of local n-type [6] or p-type [7] dopings with LCP in order to create selective emitter and/or local back surface field (LBSF) structures for either p- or n-type solar cells. The formation of an n-type selective emitter with LCP already showed good results on the laboratory scale [8] and with screen-printed [9] solar cells.

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The authors are with Fraunhofer ISE, 79110 Freiburg, Germany (e-mail: sven.kluska@ise.fraunhofer.de; filip.granek@ise.fraunhofer.de).

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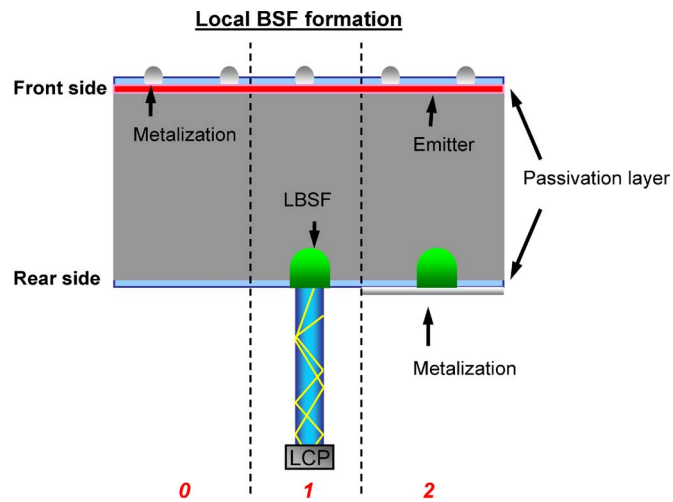

Fig. 1. Process scheme for the formation of an LCP LBSF.

II. Solar Cell Fabrication

High-efficiency p-type PERL silicon solar cell structures were processed in order to evaluate the application of LCP boron doping as LBSF for solar cells. The substrates were 0.5 $\Omega \cdot$ cm p-type FZ-Si wafers with a thickness of 250 μm. The cell sizes were 2×2 cm^2. The front side was textured with an inverted pyramid structure and has a 120 Ω/sq. deep diffused phosphorus diffusion as emitter. The front and the rear side are passivated with a 105 nm thermal SiO_2 layer, which acts as passivation layer and antireflection coating for the front side. It has to be mentioned that there is no additional selective emitter diffusion on the front side. The front-side metal contacts were processed with photolithography in combination with an evaporated stack of Ti–Pd–Ag that was thickened with Ag plating.

On the rear side, the passivation layer was locally opened with LCP, which at the same time creates local boron doping in the opened area (see step 1 in Fig. 1). The LCP boron-doped openings act as LBSF in this structure and were metalized with an evaporated aluminum layer of 2 μm thickness (see step 2 in Fig. 1). The applied contact design on the rear side was a line structure with a varying pitch in the range of 1000–2500 μm, a line length of 2 cm (equals cell length), and a line width of about 50 μm.

The boron source for the LCP process was an alkaline aqueous boron solution [7]. Fig. 2 shows the measured doping profiles for different laser pulse energies. The shown data are

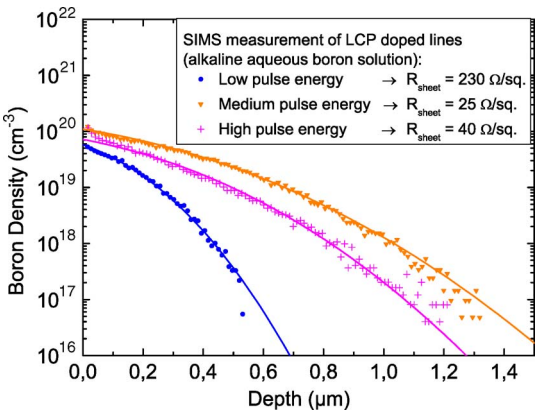

Fig. 2. Processed doping profile for different laser pulse energies measured by SIMS. The drawn lines are guides to the eye, and the given sheet resistances are calculated from the profiles.

the mean doping concentrations in the circular secondary ion mass spectroscopy (SIMS) measurement area with a diameter of about 10 μm in the middle of an LCP line with a width of about 50 μm. The sheet resistance decreases for low to medium pulse energy due to an increased melting depth. This effect changes for higher pulse energies due to increasing evaporation of the molten silicon.

The line dopings were processed with an overlap of single LCP laser pulses with a pulse distance of 1.4 μm on the sample, a wavelength of 532 nm, a pulse energy before the liquid jet of 20 μJ (same range as "medium pulse energy" in Fig. 2), and a pulse duration of about 10 ns.

In order to evaluate the quality of the LCP boron doping as LBSF, reference cells with no LCP boron doping on the rear side were processed. The solar cell design of the reference cells is the same as that for the LCP-PERL solar cells, except that, in the reference case, the rear-side openings were processed with deionized (DI) water as LCP medium. This results in nondoped rear-side openings, which means that the reference cells have a passivated emitter and rear cell (PERC) solar cell design [10] without an LBSF doping on the rear side. This reference design was chosen because it assures the same rear-side geometry for the processed PERL and PERC solar cells. This makes it easier to compare the processed cells and avoids any geometry-related influences on the cell parameters. Unfortunately, in this case, the possible laser damage would affect both cell types and cannot be investigated. This has to be investigated in a future comparison with photolithographic rear contact openings.

III. Results and Discussion

Table I shows the cell efficiency η, the fill factor FF, the short-circuit current density J_{sc}, the open-circuit voltage V_{oc}, the pseudo fill factor PFF (measured by $SunsV_{\mathrm{oc}}$ [11]), and the measured series resistance R_s (measured by comparison of light $I-V$ curve with $SunsV_{\mathrm{oc}}$ measurements [12]) of the best LCP-PERL and LCP-PERC solar cells. The best LCP-PERL solar cell shows a maximum cell efficiency of $\eta = 20.9\%$. This cell shows a cell efficiency benefit of $\Delta\eta = 0.4\%$abs. to the reference cell with the same pitch and $\Delta\eta = 0.3\%$abs. to the best reference solar cell with a smaller rear-side pitch of 1000 μm.

TABLE I
Best Solar Cell Parameters for the LCP-PERL Solar Cells With LCP Boron LBSF and the Reference LCP-PERC Solar Cells With Undoped Rear-Side Openings

	PERL (best cell)	PERC (same pitch)	PERC (best cell)	PERL (same pitch)
η [%]	20.9	20.5	20.6	20.4
V_{oc} [mV]	675	670	666	665
J_{sc} [mA/cm^2]	38.7	38.7	38.7	38.0
FF [%]	80.0	79.0	79.9	80.8
PFF [%]	82.9	83.0	82.7	82.8
R_s [Ωcm^2]	0.49	0.63	0.50	0.33
Pitch [µm]	2500	2500	1000	1000
LCP- liquid	boron solution	H_2O	H_2O	boron solution

The cell efficiency benefit is a consequence of two different effects. On the one hand, there is a fill factor benefit due to a decreased series resistance, which is assumed to be caused by a reduction of the contact resistance of the rear-side metal contacts due to the highly doped boron LBSF. The comparison of the series resistances in Table I for the PERL and PERC structures shows that there is a series resistance benefit for the PERL cells even in comparison to a reference cell with a pitch that is half as big as for the best PERL cell, which supports the assumption that the fill factor benefit is caused by a pitch-independent improvement of the contact resistance.

In order to analyze the influence of the rear-side geometry on the solar cell parameters, the pitch of the rear contacts was varied in the range of 1000–2500 μm. Fig. 3 shows the results of the solar cell parameters as a function of the rear-side pitch. Due to a limited amount of cells (two to three cells per parameter) in this study, the shown values are the cell parameters of the cells with the best cell efficiency for each pitch rather than the averaged values.

The fill factor of the LCP-PERL solar cells decreases with increasing pitch and is improved in comparison to the reference solar cells due to a decreased contact resistance of the LBSF contacts. The pitch dependence is caused by an increasing lateral component of the base resistance for large pitch. The series resistances of the LCP-PERL solar cells shown in Fig. 3 reveal a benefit of 0.04–0.16 $\Omega \cdot \mathrm{cm}^2$ in comparison to the LCP-PERC solar cells.

On the other hand, the boron doping should decrease the rear-side recombination due to shielding of the minority carriers from the highly recombinative rear-side metal contacts [13]. This effect leads to an improved open-circuit voltage of the PERL solar cells in comparison to the PERC reference solar cells. In contrast to the fill factor behavior, the open-circuit voltage rises with increasing pitch, which correlates with the increase of the area fraction of the passivated areas on the rear side. The reason for the surprisingly good open-circuit voltage of the reference cell with a pitch of 1000 μm is unknown. One possible explanation could be a random better emitter saturation current density for this cell. Future experiments are needed to analyze this effect in detail.

IV. Conclusion

For the first time, it has been shown that the industrially feasible boron LCP process can be used to create LBSFs for

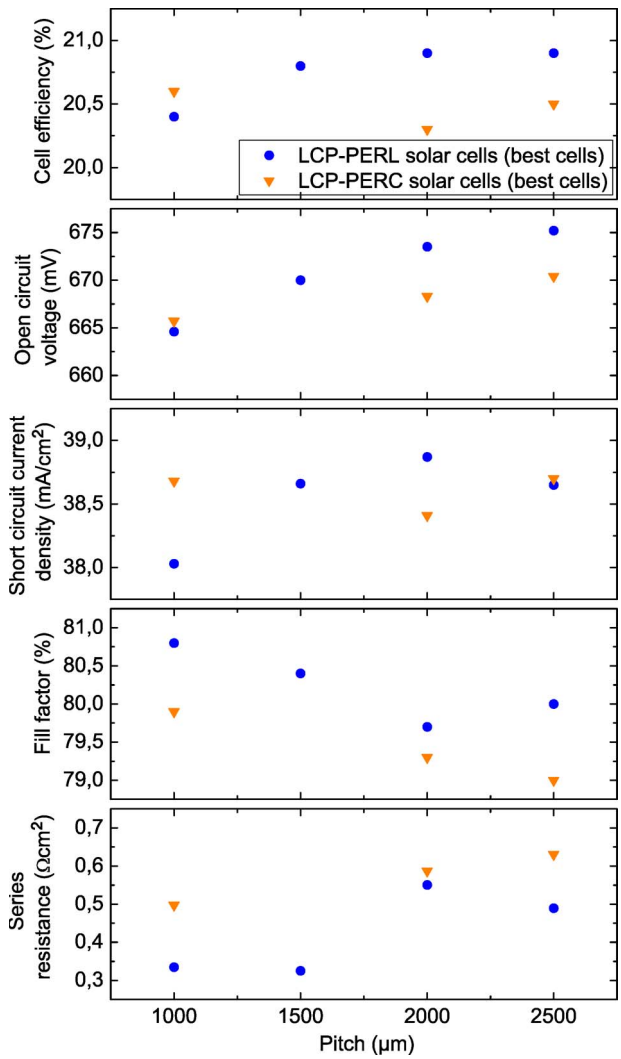

Fig. 3. Cell results of the processed LCP-PERL and LCP-PERC solar cells (cells with the best cell efficiency).

high-efficiency silicon solar cells. The best PERL solar cells showed efficiencies of up to $\eta = 20.9\%$ with an efficiency benefit of $\Delta\eta = 0.3\text{-}0.4\%$abs. to the reference PERC solar cells. The cell efficiency benefit is mostly caused by a fill factor and open-circuit voltage improvement due to decreased contact resistance and formation of LBSF doping, respectively.

The next step to further evaluate the quality of the processed LCP boron LBSF dopings should be the analysis of the influence of the base resistivity on the back surface field quality and a comparison with other rear contacting schemes such as laser-fired contacts.

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