

Advanced TOPCon solar cells with patterned p-type poly-Si fingers on the front side and vanishing metal induced recombination losses

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Abstract. The silicon photovoltaic industry is rapidly expanding production capacity for TOPCon solar cells and surveys such as the ITRPV 2024 forecast worldwide market dominance for this cell concept from the year 2024 and beyond. Already now, approaches such as laser doped selective emitter and alternative methods for contact formation such as laser-enhanced contact optimization (LECO) are increasingly used in industry to reduce metal induced recombination at the cell front side. However, in order to fully avoid recombination at the front contacts the application of local passivated contacts under the metal fingers would be desirable as final evolutionary step of both-side-contacted single-junction silicon solar cells via the high-temperature route. The present paper proposes a lean fabrication process to achieve this goal and provides detailed experimental results for solar cells with polycrystalline silicon passivated contacts for both polarities. It is shown that local passivated contacts can be integrated into standard TOPCon cells by adding only a few additional process steps to the current industrial baseline process. Crucially, it is shown that this cell concept can achieve vanishing metal induced charge carrier recombination with differences below 2 mV between implied open-circuit voltage of the non-metalized cell precursor and the external open-circuit voltage of the final solar cell. In the present study this enables a champion device with an external open-circuit voltage of 719 mV and an efficiency of 23.4%. While these results mark an important milestone on the way towards a fully passivated TOPCon cell, the paper also details the challenges related to the development and integration of local passivated contacts and the shortcomings that have to be addressed in order to achieve a relevant efficiency gain over standard TOPCon cells.

Keywords: TOPCon / local front passivated contacts / p⁺ poly-Si / laser activation

1 Introduction

The silicon photovoltaic (PV) industry is currently experiencing a swift transition in which tunnel oxide passivated contact (TOPCon) solar cells replace passivated emitter and rear cells (PERC) as the mainstream technology thanks to their superior conversion efficiency. Surface and contact passivation of the TOPCon rear side is achieved with a layer stack consisting of a thin interfacial oxide (SiO₂), a highly n⁺ doped polycrystalline silicon (poly-Si) layer, and a capping layer of silicon nitride (SiN_x) for hydrogenation. In contrast, the front side consists of a boron emitter that is diffused into the mono-crystalline (c-Si) wafer, passivated by a layer stack consisting of aluminum oxide (AlO_x) and SiN_x and contacted directly via screen-printed fire-through

silver-aluminum (AgAl) pastes [1]. So far, no passivated contacts have been used at the front side for TOPCon solar cells in industrial mass production. This is because of the high parasitic absorption of full-area poly-Si layers that are sufficiently thick for contact passivation [2], which necessitates a cost effective high-throughput process for integrating patterned poly-Si layers. The solar cell's external open-circuit voltage (V_{oc}) is therefore strongly limited by the front side. To minimize this limitation, different approaches have been employed. The implementation of a comparatively deep emitter, usually exceeding a junction depth of 1 μm, allows to reduce the metal-induced charge carrier recombination density (J_{0met}) for conventional TOPCon cells with homogeneous emitter, albeit at the cost of increased parasitic absorption and associated current loss [3]. More advanced improvements include approaches such as implementation of a laser doped selective emitter (LDSE) on the c-Si front side, where the junction depth is increased only locally under the

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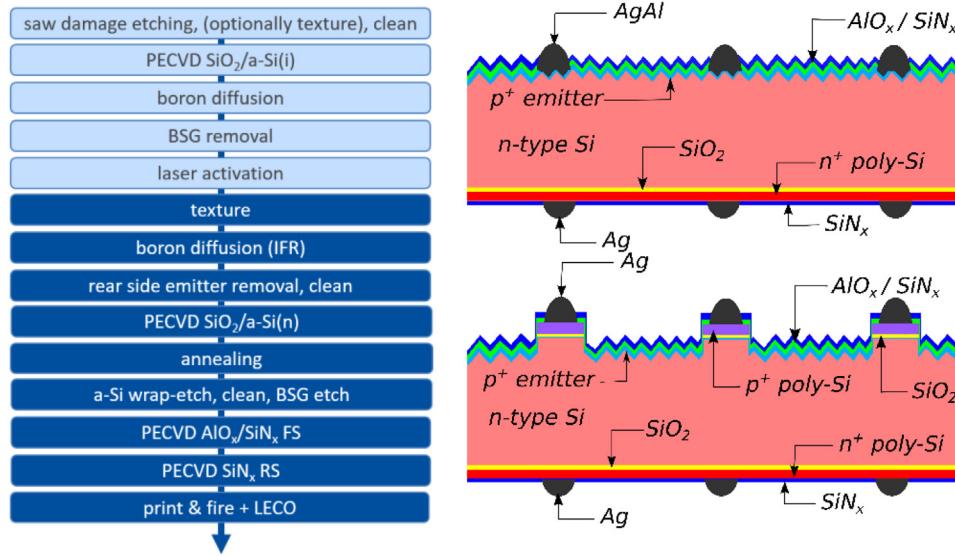


Fig. 1. TOPCon process flow (dark blue) and additional process steps (light blue) for integrating local passivated contacts on the front side (left). Schematics of a baseline TOPCon solar cell (top) and an advanced SelFi TOPCon solar cell (bottom) with local passivated contacts at the front side (right).

metal contacts using a laser doping process [4]. As an alternative, laser-enhanced contact optimization (LECO) has been proposed to limit $J_{0\text{met}}$ at the cell's front side and impressive results have been reported, demonstrating TOPCon solar cells with efficiencies beyond 25% [5,6]. However, in order to fully avoid recombination at the front contacts the application of local passivated contacts under the metal fingers would be desirable as final evolutionary step of both-side-contacted single-junction silicon solar cells.

The present paper proposes an industrially feasible process flow to integrate local passivated contacts at the TOPCon cell front side without relying on sacrificial layers for masking or other patterning technologies that might not be economically viable in the PV industry. The authors speculate that local passivated contacts have been used in efficiency record cells presented by large solar cell manufacturers – however, no details on the final cell structure or the production processes involved have been published to date. Within the published literature different approaches have been described to produce local passivated contacts. These include the development of rear-junction cells with local n-type passivated contacts at the front side using ink-jet masking and a chemical etching process, demonstrating efficiencies up to 22.5% [7,8]. Approaches for laser-based patterning of n-type poly-Si employ amorphization [9] or local oxidation of poly-Si layers by irradiation with UV-ps laser pulses to create etch selectivity in alkaline solution [10]. Local p-type poly-Si contacts have also been integrated at the front side of n-type solar cells by printing sacrificial etch-stops which locally protect the poly-Si in subsequent etching processes, enabling efficiencies up to 23.5% [11]. As an alternative to approaches based on wet-chemical local etch back of poly-Si, also a direct implementation of patterned poly-Si layers using deposition through shadow-masks has been studied [12].

A key aspect of the process proposed in the present paper is that all added process steps and the utilized equipment – deposition of intrinsic amorphous silicon, boron diffusion and local laser treatment with a green ns-laser – have a proven track record in large-scale industrial PV production. The relevance of the topic is underlined by the large and rapidly growing installed capacity of TOPCon production lines. A viable concept for upgrading these lines towards even higher efficiencies with moderate additional investment cost will certainly become of great interest in the near future.

2 Material and methods

2.1 Process flow

To fabricate advanced TOPCon solar cells with $\text{SiO}_2/\text{poly-Si}$ based passivated contacts for both polarities – in the following referred to as Selective Finger (SelFi) TOPCon solar cell – we propose the process flow that is shown in Figure 1. It is compatible with the standard TOPCon process sequence that is widely used in industrial production. The wafers are saw-damage etched in sodium hydroxide (NaOH) with a concentration of 22% at 80 °C and cleaned in a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2), followed by oxide removal in hydrofluoric acid (HF). Subsequently, a layer stack consisting of a thin interfacial oxide (SiO_2) and a boron doped silicon thin film are deposited on the wafer. For the present study the layer stack is produced by thermal oxidation of the substrate ($d_{\text{SiO}_2} = 2\text{--}3\text{ nm}$), followed by plasma enhanced chemical vapor deposition (PECVD, centrotherm cPLASMA) of intrinsic amorphous silicon (a-Si(i), thickness $\approx 200\text{ nm}$). Thereafter, a light boron diffusion at 830 °C is used for ex-situ doping of the silicon

Table 1. Experiment overview detailing p⁺ poly-Si interface oxide, emitter diffusion, p⁺ poly-Si finger width and front side paste of the different groups.

Group	p ⁺ poly-Si interface oxide	Emitter diffusion	p ⁺ poly-Si finger width (μm)	Front side paste
G1	–	T	–	AgAl reference
G2	TO1	S-1000	100	Ag Paste N
G3	TO1	S-1000	100	Ag Paste P
G4	TO1	S-970	100	Ag Paste P
G5	TO2	S-1000	100	Ag Paste P
G6	TO2	S-970	100	Ag Paste P
G7	TO2	S-1000	150	Ag Paste P
G8	TO2	S-1000	60	Ag Paste P

thin film using an industrial tube process and boron tribromide (BBr₃) as precursor. During this process, the amorphous layer also partially crystallizes to p-doped poly-Si. A simplified process with in-situ doped PECVD a-Si(p) deposition is currently under development but not yet included in the present study. After the light boron diffusion the borosilicate glass (BSG) is removed in HF. Subsequently, a laser-activation process is performed with a green nano-second laser (Innolas LINEXO) to locally achieve hyper-doping in the boron-doped poly-Si layer. Details on the laser process applied to silicon thin films deposited with low-pressure chemical vapor deposition (LPCVD) and the resulting doping profiles have been published elsewhere [13,14]. Because of the high electrically active boron concentration in the laser treated regions, the layer locally becomes etch resistant in alkaline solution [15]. This effect allows the layer to withstand the subsequent etching process that is used to remove the poly-Si layer and to texture the substrate in the non-laser treated inter-finger region (IFR) using potassium hydroxide (KOH) and conventional alkaline texturing additives. A similar process has been proposed to be used in the fabrication of interdigitated back contact solar cells (IBC) with passivated contacts [16,17].

Afterwards, a re-optimized standard TOPCon process can be applied. Firstly, a boron diffusion process is used to create the emitter in the IFR. This process can also lead to further diffusion of dopants from the p⁺ poly-Si into the bulk wafer and hence can affect the passivation quality of the p⁺ poly-Si fingers. Therefore, the properties of the interface oxide and the thermal budget of the diffusion have to be optimized mutually. Furthermore, the thermal budget of the diffusion process leads to partial deactivation of dopants in the p⁺ poly-Si [14]. Following the emitter diffusion, the production sequence consists of processes for rear side emitter removal, PECVD SiO₂/a-Si(n) deposition (centrotherm cPLASMA, $d_{\text{SiO}_2} \approx 2 \text{ nm}$, $d_{\text{a-Si(n)}} \approx 150 \text{ nm}$), a-Si(n) annealing in N₂ at $T_{\text{anneal}} \approx 925^\circ\text{C}$, and subsequent n⁺ poly-Si wrap-around removal on the front side. Both, the rear side emitter removal process and the n⁺ poly-Si wrap-around removal process, consist of a single-side HF inline etching step and an alkaline batch process with additives that enhance the Si/SiO₂ etch selectivity as commonly employed in industrial TOPCon processes [18,19]. Deviating from the industrial standard for TOPCon solar cells, the AlO_x layer for emitter passivation is

deposited via PECVD (centrotherm cPLASMA) instead of atomic layer deposition (ALD), owing to the lack of ALD deposition capability in our lab. For the homogenous emitter of the standard TOPCon cell, this limits the achievable emitter saturation current density to $J_{0e}^{\text{PECVD}} \approx 20 \text{ fA/cm}^2$, while $J_{0e}^{\text{ALD}} \approx 11 \text{ fA/cm}^2$ have been achieved on the same emitter with a reference ALD AlO_x process. This limitation has to be kept in mind when interpreting the cell results for both the standard TOPCon and the SelFi TOPCon cells, which would both profit from an enhanced emitter passivation. Following the PECVD deposition of front and rear antireflective coatings the cells are metallized with commercial screen-printed firing-through pastes and fired in an industrial conveyer belt furnace without a dedicated subsequent regeneration process that is commonly used in industrial TOPCon lines. While the standard TOPCon reference cells are metalized with AgAl paste on the front side, SelFi TOPCon cells are printed with silver (Ag) paste on front and rear side. The front side finger print is aligned to the p⁺ poly-Si fingers using fiducial alignment marks which are prepared in the same way as the p⁺ poly-Si fingers. All cells within the present study are fabricated using M6-sized wafers and feature 12 busbars per polarity. Additionally, the cells are treated with LECO (LECO lab tool, CE Cell Engineering) to assess the potential of LECO technology for contacting p⁺ poly-Si, a subject that so far has not yet been covered in the literature to our knowledge. The IV data (halm certisPV, class AAA) reported below refers to measurements on a non-reflective chuck that are calibrated to a third party certified M6 TOPCon reference cell and include busbar shading. A schematic comparison of a standard TOPCon cell and the advanced SelFi TOPCon cell is shown in Figure 1.

2.2 Experiment overview and variations

Results are presented for M6 sized n-type CZ wafers (produced by Norsun) with a base resistivity of 3.6 Ωcm and an initial thickness of 150 μm that were processed according to the process flow presented in Figure 1. A reference group with standard TOPCon cells was prepared without p⁺ poly-Si fingers on the front side. They feature a boron diffusion with a drive-in temperature of 1020 °C, optimized for best efficiencies with a homogenous emitter

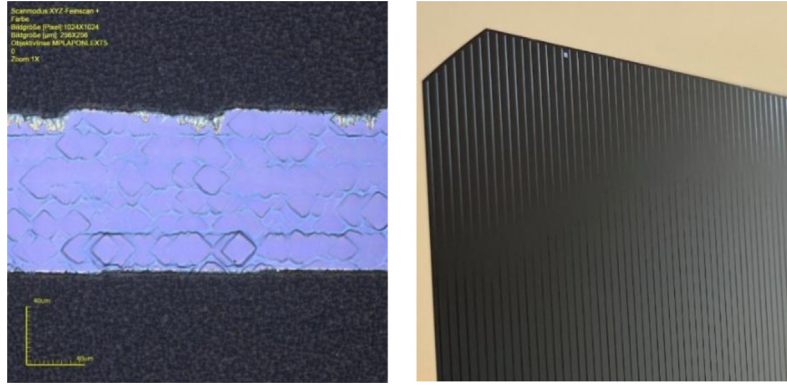


Fig. 2. Microscope image of a 100 µm wide p^+ poly-Si finger (left) and photograph of a corresponding cell precursor (right) after texturing. In the upper part of the right hand image one of the rectangular shaped fiducial marks can be seen as shiny feature in between two p^+ poly-Si fingers.

(diffusion “T” for “TOPCon”, $R_{\text{sheet}} \approx 160 \, \Omega/\text{sq}$) that can be contacted without LECO. One challenge for the Selfi TOPCon cell concept is to co-optimize the passivation (J_{0e}) and the sheet resistance in the IFR on the one hand and the passivation of the p^+ poly-Si fingers (J_{0p+}) on the other hand. The latter, among other things, depends on the interface oxide under the p^+ poly-Si layer and the thermal budget of the subsequent high temperature processes, in particular of the boron diffusion that creates the emitter in the IFR and the n^+ poly-Si annealing step. An excessive thermal budget leads to a deep diffusion of boron dopants through the interface oxide into the bulk silicon, causing a loss of passivation [20, 21]. Therefore, two emitter diffusion processes with different thermal budgets and sheet resistance (R_{sheet}) values were used in combination with two thermal oxides with different thicknesses (TO1 and TO2 with $d_{\text{SiO}_2}^{\text{TO1}} < d_{\text{SiO}_2}^{\text{TO2}}$). Diffusion “S-1000” (“S” for “Selfi” and the number denoting the drive-in temperature) features a drive-in for 60 min at 1000 °C and yields $R_{\text{sheet}} \approx 170 \, \Omega/\text{sq}$, while diffusion “S-970” has a longer drive-in of 90 min but at a lower temperature of 970 °C, resulting in $R_{\text{sheet}} \approx 240 \, \Omega/\text{sq}$.

One of the key challenges inherent to the Selfi TOPCon cell concept is to limit the current loss that arises from reflection and absorption in the p^+ poly-Si fingers. Ideally, the width of the poly-Si fingers is limited to the width of the metal fingers that are printed on top. However, because of screen alignment tolerances and possible screen distortion over the screen’s lifetime, some margin has to be considered to avoid (local) misalignment. These protruding parts of the p^+ poly-Si fingers cause optical losses. The present study aims at demonstrating the feasibility of the cell concept with a focus on passivation and contact properties, and, hence, the p^+ poly-Si finger width has been chosen conservatively using a baseline width of 100 µm to prevent artifacts from misalignment. However, additional groups with 150 µm and 60 µm have been tested in order to extrapolate the current loss as a function of p^+ poly-Si finger width.

Finally, two different Ag pastes were compared for front side metallization. Paste “N” is a standard Ag paste for n^+ poly-Si contacting, which is also printed on the rear

side of the cells, while paste “P” is optimized for p^+ poly-Si contacting according to the supplier. Both the firing and the LECO process were applied according to the best known method from previous trials. An overview of the group split indicating the different process conditions is given in Table 1. All groups consist of eight to nine metallized solar cells (after mechanical yield loss) and each two cell precursors that were fired without metal contacts to assess the cell precursor passivation.

3 Results and discussion

3.1 Integration of p^+ poly-Si fingers

The process flow shown in Figure 1 allows to successfully integrate local p^+ poly-Si fingers into the TOPCon baseline process. This is exemplified by Figure 2, where a microscope image of an etch-stable p^+ poly-Si finger (left hand side), and a photograph of a cell precursor (right hand side) are shown after texturing the non-laser treated parts of the wafer.

Following the alkaline texturing process, the samples are subjected to a boron diffusion process to create the emitter in the IFR. Such a boron diffusion consists of a deposition phase, followed by a drive-in and an oxidation phase [22]. The purpose of the oxidation during drive-in is – among other things – to create a SiO_2 layer on the surface of the sample that is required to protect the cell’s front side during the wet chemical emitter and n^+ poly-Si wrap around removal processes to be carried out later in the process sequence (c.f. Fig. 1). Additionally, the oxidation of the surface during cool-down is used to deplete the boron concentration at the surface of the IFR to allow for better surface passivation [23]. The oxidation of the surface in the IFR inevitably leads to oxidation of the p^+ poly-Si fingers, and, hence, reduces the initial poly-Si thickness. In order to assess this loss of polysilicon, the SiO_2 thickness is measured by spectral ellipsometry (Sentech SE800) on the flat p^+ poly-Si surfaces for the different diffusion recipes. The ellipsometer measurement is performed on four rectangular shaped fiducial marks close to the wafer

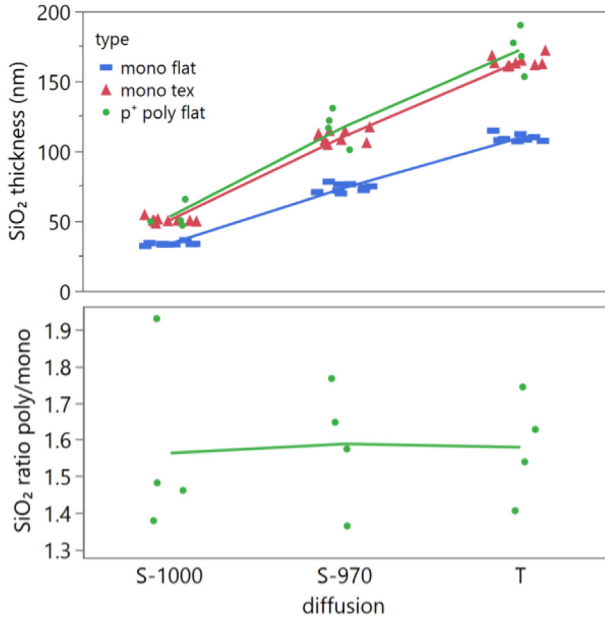


Fig. 3. SiO₂ thickness on flat mono-crystalline and p⁺ poly-Si surfaces as measured by spectral ellipsometry and estimated SiO₂ thickness on textured mono-crystalline substrates for different emitter diffusions. Additionally, the ratio between the SiO₂ thickness on flat p⁺ poly-Si and flat mono-crystalline surfaces is shown. The lines connect the respective mean values and are shown to guide the eye.

edge (c.f. Fig. 2, right). Those fiducials are produced analogously to the p⁺ poly-Si fingers via laser activation and used for screen alignment during the printing procedure. After the diffusion, the p⁺ poly-Si is covered by a layer stack consisting of thermally grown SiO₂ and a BSG layer deposited on top. Both components can be modeled as a single layer of silicon oxide for ellipsometry and SiO₂ thickness values reported below refer to the combined thickness in cases where the BSG has not yet been etched. It has been shown for a comparable BBr₃ deposition process, that the BSG layer etches at a faster rate compared to the SiO₂ layer and that BSG layer itself has a thickness of up to 15 nm [22].

As shown in Figure 3 diffusion “S-1000” yields a SiO₂ thickness of $d_{\text{SiO}_2}^{\text{S-1000}} = (53 \pm 8)$ nm, while diffusion “S-970” yields $d_{\text{SiO}_2}^{\text{S-970}} = (118 \pm 12)$ nm, out of which ≈ 15 nm are contributed by the BSG layer. The given uncertainties show the standard deviation of the measurements on the four fiducials close to the wafer edges. Assuming the consumed poly-Si thickness to be 44% of the remaining thermal SiO₂ thickness [24], it can be estimated that the initial poly-Si thickness is reduced from ≈ 200 nm to $d_{\text{poly}}^{\text{S-1000}} \approx 180$ nm for diffusion “S-1000” and to $d_{\text{poly}}^{\text{S-970}} \approx 150$ nm for diffusion “S-970”. These estimated final poly-Si thicknesses are relevant, since a certain minimal poly-Si thickness is required for good contact passivation, depending on the paste and the contact formation conditions [25].

Additionally, Figure 3 shows that the SiO₂ thickness measured on p⁺ poly-Si is thicker than the SiO₂ thickness measured on a flat (100) surface of a corresponding

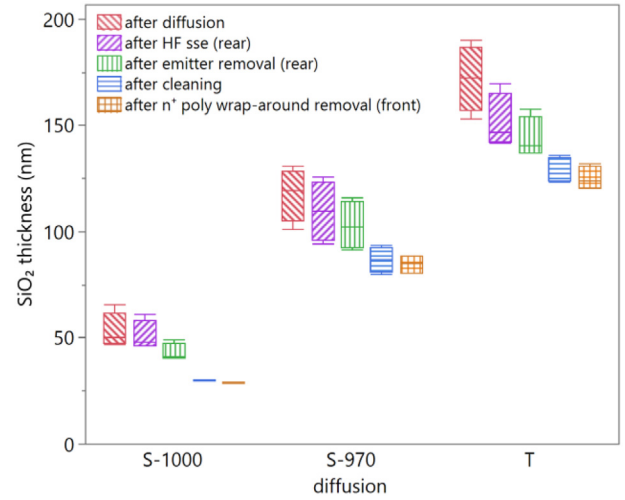


Fig. 4. SiO₂ thickness on flat p⁺ poly-Si for different diffusions after various process steps, as measured on each four fiducial marks close to the wafer edge. The box plots indicate the median value, the 25% and 75% quantiles and the minimum and maximum of the distribution. Each distribution contains four measurement points which are omitted to reduce clutter.

mono-crystalline test wafer. This is presumably due to differences in the active doping concentration and in crystal orientation of some fraction of the poly-Si grains [26]. The difference is approximately a factor of 1.6 ± 0.2 . Coincidentally, this causes the SiO₂ thickness on the p⁺ poly-Si fingers to be very similar to the expected SiO₂ thickness grown on the (111) surfaces of the textured IFR. The latter is estimated assuming a factor of ≈ 1.5 for the growth differences between (100) and (111) Si surfaces [24].

Figure 4 shows how the initial SiO₂ thickness on top of the p⁺ poly-Si fingers is reduced along the process chain. It is also observed that the width of the thickness distribution decreases along the process chain. This is likely related to the different etch rates for BSG and SiO₂ as described in [22]. Crucially, it is found that even for the thin SiO₂ of diffusion “S-1000” approximately 29 nm of SiO₂ is left after the wet chemical processes for emitter and n⁺ poly-Si wrap-around removal. The remaining SiO₂ is removed before PECVD AlO_x deposition for emitter passivation. Visual inspection confirms that both poly-Si fingers and the texture in the IFR are intact for all groups and cells after the last etching step.

3.2 Cell precursor passivation

Figure 5 shows the results for iV_{oc} and the total recombination current density ($J_{0\text{tot}}$) derived from quasi-steady-state photo-conductance (QSSPC, Sinton WCT-120) measurements of non-metalized, fired cell precursors [27,28]. The parameter $J_{0\text{tot}}$ is a lumped property that describes the sum of all surface recombination current density contributions from the front and the rear side of the cell precursor. Since there are no differences in rear side passivation ($J_{0\text{n+}}$) between groups within this study, differences in $J_{0\text{tot}}$ can be interpreted as differences in

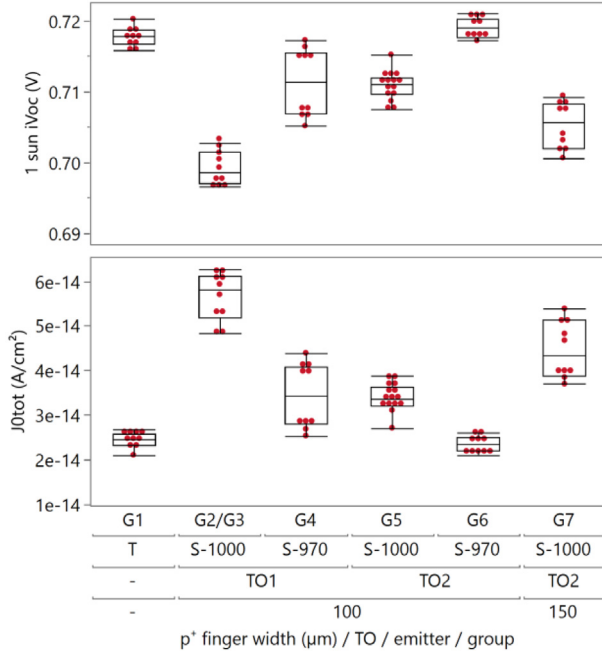


Fig. 5. Implied V_{oc} and total recombination current density (J_{0tot}) of non-metalized and fired cell precursors for a TOPCon reference group (G1) and various SelFi TOPCon groups (G2-G7). The point markers show the individual measurement points (five points for each two cell precursors per group) and the box plots indicate the median value, the 25% and 75% quantiles and the minimum and maximum of the distribution.

surface passivation of the IFR (J_{0e}) and the p⁺ poly-Si fingers (J_{0p+}). A detailed breakdown of the individual J_0 contributions requires further studies that shall be presented in future publications.

The device specific input parameters for the QSSPC measurement are the sample thickness of $(125 \pm 2) \mu\text{m}$ derived from the sample weight and the base resistivity of the wafer of $(3.6 \pm 0.2) \Omega \text{ cm}$, where the uncertainties are determined from the variations within a typical batch size. Furthermore, an optical parameter of 1.1 ± 0.05 is required as input to describe the relative absorbance of the excitation flash by the sample. The central value is the standard value for textured wafers with blue anti-reflective coating and the uncertainty is a conservative estimate that takes into account that the front side of SelFi cell precursors have locally increased reflectivity. A reflectivity loss of 17% at the p⁺ fingers (c.f. Sect. 3.3.2) and an area fraction of 13% (conservative estimate for group with the widest p⁺ poly-Si fingers) are considered. An upper bound of the associated uncertainty on iV_{oc} and J_{0tot} is estimated by varying all input parameters together in the direction that increases iV_{oc} (base resistivity $\searrow$, thickness $\searrow$, optical parameter $\nearrow$) and in the opposite direction, respectively. For a cell precursor with $iV_{oc} = 720.4 \text{ mV}$ and $J_{0tot} = 21.9 \text{ fA/cm}^2$, this results in absolute variations of $\pm 1.1 \text{ mV}$ for iV_{oc} and $\pm 0.3 \text{ fA/cm}^2$. Since these uncertainties are significantly smaller than the process induced variations



Fig. 6. Zoomed view of one corner of an exemplary photoluminescence image of SelFi TOPCon cell from G6 with the p⁺ poly-Si fingers visible as darker horizontal lines.

within the groups they are neglected in the following and only the median values of the parameter distributions are reported.

The standard TOPCon reference group (G1) achieves a median $iV_{oc} = 717.7 \text{ mV}$ ($J_{0tot} = 24.6 \text{ fA/cm}^2$). Notably, the passivation of SelFi TOPCon cell precursors strongly varies between groups, indicating a significant dependence on the interface oxide under the p⁺ poly-Si fingers, the emitter diffusion and the p⁺ poly-Si finger width. Diffusion “S-970” ($240 \Omega/\text{sq}$) clearly outperforms diffusion “S-1000” ($170 \Omega/\text{sq}$) and the thicker interface oxide TO2 improves the passivation with respect to TO1, presumably by limiting the diffusion of boron from the p⁺ poly-Si finger into the bulk. Combining diffusion “S-970” and TO2 leads to the best SelFi TOPCon precursor group (G6) with a median $iV_{oc} = 719.0 \text{ mV}$ ($J_{0tot} = 23.4 \text{ fA/cm}^2$), slightly outperforming the reference group G1.

Utilizing $150 \mu\text{m}$ wide p⁺ poly-Si fingers (G7) instead of $100 \mu\text{m}$ fingers (G5) causes a loss of passivation of 5.3 mV (9.8 fA/cm^2), indicating that the passivation of the p⁺ poly fingers is worse than in the IFR (here for diffusion “S-1000”). This shows that further optimization of the passivation of the p⁺ poly-Si regions is needed. A zoomed view of an exemplary photoluminescence (PL) image of one SelFi TOPCon precursor of G6 is shown in Figure 6, where the p⁺ poly-Si fingers are visible as dark horizontal lines. The reduced PL intensity in the p⁺ poly-Si regions is caused by increased recombination and additional optical losses associated with the flat surface of the poly-Si fingers (c.f. Sect. 3.3.2).

3.3 Solar cells

3.3.1 IV results

Current–voltage (IV) measurement results obtained under standard test conditions (STC) are presented in [Figure 7](#) for all cells after firing and treatment with an optimized LECO process. Relevant differences before and after LECO treatment are described separately in [Section 3.3.4](#). Statistical uncertainties of the IV parameters that are relevant to interpret variations between different cells and groups are estimated based on the measurement repeatability of a standard TOPCon reference cell. The following standard deviations have been obtained: $\sigma_{V_{oc}} < 0.3 \text{ mV}$, $\sigma_{J_{sc}} < 0.01 \text{ mA/cm}^2$, $\sigma_{FF} < 0.1\%^{abs}$, and $\sigma_{\eta} < 0.03\%^{abs}$. These variations are significantly smaller than the width of typical parameter distributions within a batch of identically processed solar cells, where data scattering is mainly caused by process related variations. The statistical uncertainties are therefore neglected in the following and the median and the maximum values of the respective distributions are reported.

The best SelfFi TOPCon group (G6) achieves a median $V_{oc} = 717.4 \text{ mV}$ and a maximum $V_{oc} = 719.1 \text{ mV}$, clearly outperforming the TOPCon reference group (G1), which achieves a median $V_{oc} = 706.4 \text{ mV}$. Concerning the variations of emitter diffusion and interface oxide, the same conclusions can be drawn as for the cell precursor results: diffusion “S-970” allows to achieve higher V_{oc} values than diffusion “S-1000” and TO2 is superior to TO1 for both diffusions. The same trends are observed for pFF, where G6 achieves a median value of 86.3%, while the TOPCon reference achieves 85.8%.

The SelfFi TOPCon cells clearly lack behind the TOPCon reference cells in terms of J_{sc} , by approximately -0.7 mA/cm^2 for groups with $100 \mu\text{m}$ wide p^+ poly-Si fingers. This limitation was expected because of optical losses arising from the p^+ poly-Si finger margins next to the metal fingers as described in [Section 2.2](#). It is additionally aggravated by the fact that both Ag pastes used here to metalize the SelfFi TOPCon front side only have mediocre fine-line printability. Paste “P” yields a metal finger width of $\approx 30 \mu\text{m}$ and paste “N” even $\approx 45 \mu\text{m}$ while the AgAl paste of the TOPCon reference group achieves $\approx 23 \mu\text{m}$ using the same screen. As expected, a strong influence on J_{sc} is observed when varying the p^+ poly-Si finger width. This will be further quantified in [Section 3.3.2](#).

Contacting of the p^+ poly-Si works sufficiently well to achieve median fill factors (FFs) of 81.8 to 81.9% for groups with paste “P”. Slightly higher FFs are achieved for paste “N”, however, this does not translate into an efficiency gain because of an even lower J_{sc} for paste “N”. This current loss is attributed to more pronounced paste spreading (G2 vs. G3). The series resistance associated with the solar cell’s front side consist of several contributions: the contact resistance between metal and p^+ poly-Si, the transition resistance through the interfacial oxide under the p^+ poly-Si and the emitter sheet resistance in the IFR. Additionally, also the sheet resistance under the p^+ poly-Si fingers may influence the series resistance, depending on the diffusion of

dopants from p^+ poly-Si into the bulk wafer. A detailed breakdown of the different contributions requires further scrutiny and is beyond the scope of this work. Nevertheless, some insights can be gained from the following observations. No significant difference in FF arises from the differences in R_{sheet} of the two different emitter diffusions (G3 vs. G4 and G5 vs. G6), hinting that emitter sheet resistance is not a limiting factor of the series resistance in the present study. However, groups with the thicker interface oxide TO2 have a median FF that is $\approx 0.1\%^{abs}$ lower than the corresponding groups with TO1 (G3 vs. G5 and G4 vs. G6). While the effect is small compared to the data spread and requires further scrutiny, it is plausible that the difference stems from an increased series resistance contribution of the thicker interface oxide. Overall, the SelfFi TOPCon cells do not yet achieve the FF of the TOPCon reference group of 82.4%, despite a higher pFF. Transfer length measurements (TLM) on cut solar cells indicate that this is caused by an increased front side contact resistance with $\rho_c^{Ag,p+poly} = (14 \pm 5) \text{ m}\Omega \text{ cm}^2$ that is significantly higher than for the TOPCon reference group with $\rho_c^{AgAl} = (1.1 \pm 0.2) \text{ m}\Omega \text{ cm}^2$. The uncertainties represent the variations between individual measurements (each three measurement on nine SelfFi TOPCon cells and three measurements on one TOPCon reference cell, respectively). However, there might be other systematic uncertainties in the TLM measurement of SelfFi TOPCon cells, given that the magnitude of the contact resistance appears to be in tension with observed FFs of close to 82% based on Quokka3 simulations [29]. More detailed studies are also needed to break down the individual contributions stemming from the metal-to-poly contact resistance and the oxide resistance. Aside from losses caused by contact resistance, further FF losses can be attributed to the occurrence of finger interruptions arising from insufficient fine-line printability of the Ag pastes used in this experiment. Even the SelfFi TOPCon champion cell exhibits an appreciable amount of finger interruptions at the wafer edges.

[Figure 7](#) further shows that the SelfFi TOPCon group G6 achieves a median conversion efficiency of 23.2% with a champion efficiency of 23.4%. This is falling short of the TOPCon reference group by only $0.2\%^{abs}$ (median) and $0.1\%^{abs}$ (max), respectively. Given the limitations above, this is an encouraging intermediate result. Finally, [Figure 7](#) shows that all SelfFi TOPCon cells are reasonable well edge isolated with reverse currents well below 0.5 A at a reverse bias of -13 V , a criterion that, to our knowledge, is even 1 V stricter than usual reverse current requirements in industry. This validates the compatibility of SelfFi TOPCon cell production with the industrial TOPCon baseline process. For the SelfFi TOPCon groups even lower reverse currents are observed compared with the reference group. This is likely caused by the different SiO_2 thicknesses that are grown on the emitter during the different diffusion processes and the fact that such differences necessitate individual optimization of the edge isolation process. However, such fine-tuning of the reverse current was not within the scope of this study.

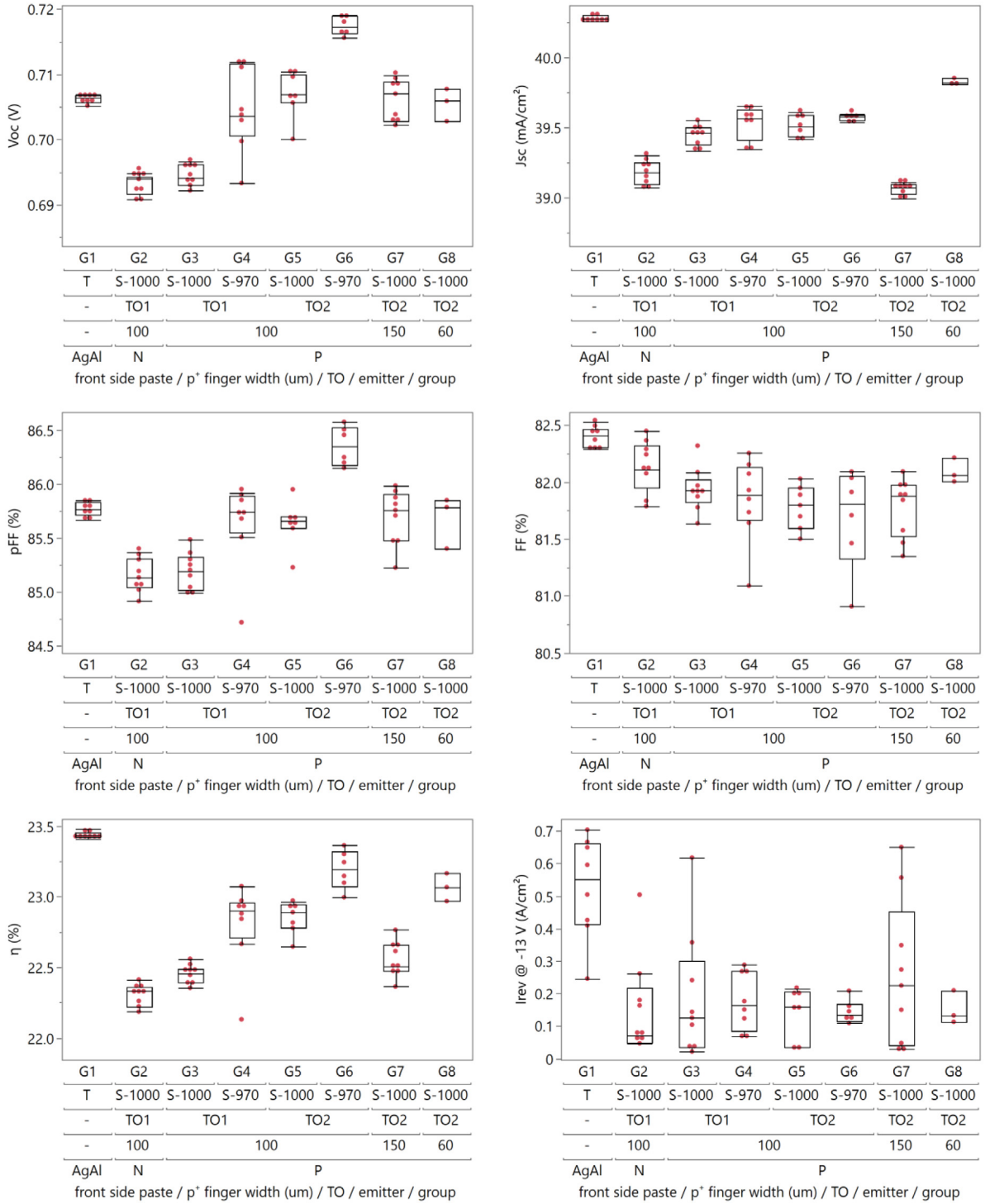


Fig. 7. IV results obtained under standard test conditions for the TOPCon reference group (G1) and the various Selfi TOPCon groups (G2-G8, c.f. Tab. 1) after LECO treatment. The point markers show the individual measurement points (one per solar cell) and the box plots indicate the median value, the 25% and 75% quantiles and the minimum and maximum of the distribution.

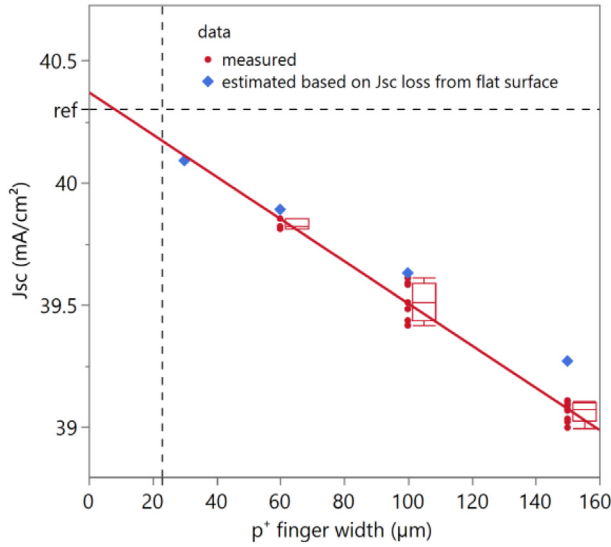


Fig. 8. Measured J_{sc} as a function of p^+ poly-Si finger width and a linear fit to the data. The horizontal dashed line indicates the current of the TOPCon reference group (G1). The point markers show the individual measurement points and the box plots indicate the median value, the 25% and 75% quantiles and the minimum and maximum of the distribution. Additionally, an estimated value for J_{sc} is shown. This estimate only takes into account the expected current loss arising from the flat surface of the p^+ poly-Si fingers but not the absorption within the p^+ poly-Si itself.

3.3.2 Analysis of current loss as a function of p^+ poly-Si finger width

As shown above the mitigation of current loss is one of the key challenges of the Selfi TOPCon cell concept and strongly depends on the p^+ poly-Si line width that can be metalized reliably without misalignment. Figure 8 shows that the measured J_{sc} linearly depends on the p^+ poly-Si finger width as expected. For comparison $J_{sc} = 40.3 \text{ mA/cm}^2$ of the TOPCon reference group is shown as horizontal dashed line. If the current loss of Selfi TOPCon cells were to arise only from optical losses induced by the p^+ poly-Si finger margins, a linear fit to the data should intersect with the reference current approximately at a p^+ poly-Si finger width of $\approx 23 \mu\text{m}$, i.e. the metal finger width of the TOPCon reference cell (vertical dashed line). However, this intersection occurs at a lower current, hinting additional optical losses that stem from the wider metal fingers of the Selfi TOPCon cells. This problem has to be addressed by improving the fine-line printability of the paste, while keeping its advantageous contacting properties. Considering the additional shading that is induced by $\approx 30 \mu\text{m}$ wide metal fingers compared to a finger width of $\approx 23 \mu\text{m}$ of the reference group, a J_{sc} loss of the order of $\approx 0.25 \text{ mA/cm}^2$ can be estimated.

Figure 8 further shows that up to 0.3 mA/cm^2 of J_{sc} can be gained when reducing the p^+ poly-Si finger width from $100 \mu\text{m}$ to $60 \mu\text{m}$. For the best Selfi TOPCon group of this study (G6, $100 \mu\text{m}$) this would translate into an efficiency

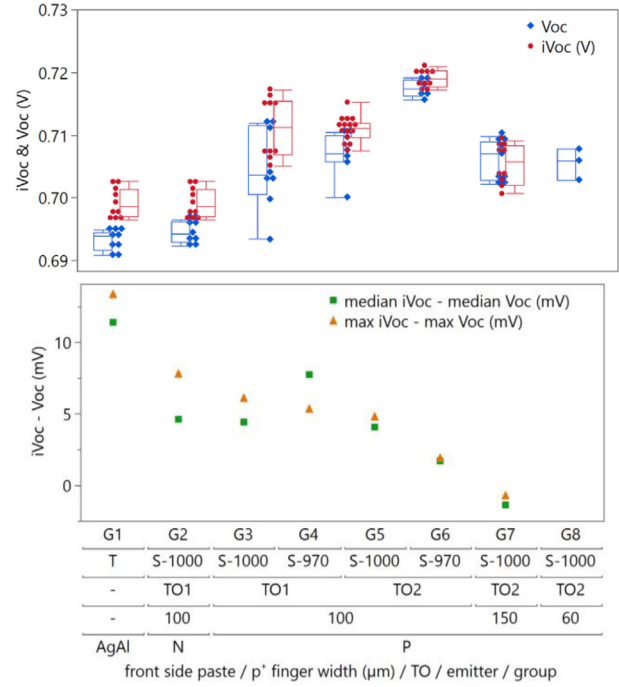


Fig. 9. Comparison of iV_{oc} , V_{oc} and derived iV_{oc} -to- V_{oc} loss based on the median (green) and maximum (orange) observed for the two distributions for the TOPCon reference group (G1) and various Selfi TOPCon groups (G2-G7). The point markers show the individual measurement points and the box plots indicate the median value, the 25% and 75% quantiles and the minimum and maximum of the distribution.

gain of $\approx 0.2\%_{abs}$. Notably, Figure 7 does not indicate any loss in V_{oc} or FF when reducing the p^+ poly-Si finger width to $60 \mu\text{m}$ (G5 vs. G8).

In the following the current loss contributions arising from reflection of the flat surface of the p^+ poly-Si fingers on the one hand and from parasitic absorption within the protruding parts of the p^+ poly-Si itself on the other hand will be estimated. To this end a ray tracing simulation [30] has been conducted using the texture properties and the layer stack of the TOPCon reference cell. The resulting photogeneration current is then compared with the corresponding simulation for a flat front surface. The latter simulation also takes into account that the front dielectric layers of the anti-reflective coating are thicker by a factor of ≈ 1.4 when deposited on a flat surface. The resulting current loss amounts to $\approx 17\%$ assuming a flat area on the entire wafer surface. Based on this number the current loss expected from the flat surface morphology of the local p^+ poly-Si fingers is shown in Figure 8. A comparison with the measured data shows that the largest part of the current loss with increasing p^+ poly-Si finger width originates from reflective losses. The remaining difference to the measured data can be attributed to parasitic absorption within the p^+ poly-Si. This highlights that an implementation of local p^+ poly-Si passivation layers on textured surface morphologies would be beneficial – a development that is currently ongoing but not yet covered in this article.

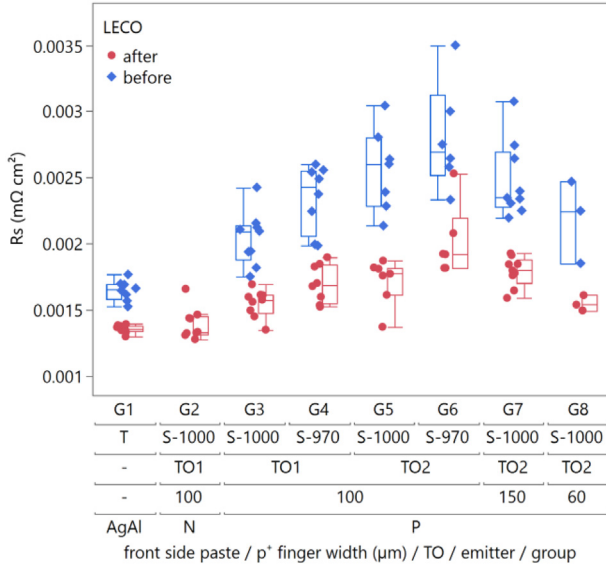


Fig. 10. Series resistance for the TOPCon reference group (G1) and various SelfFi TOPCon groups (G2-G8) before and after LECO treatment. Note that the series resistance of group G2 (paste “N”) is 0.152Ω before LECO and thus outside of the displayed range.

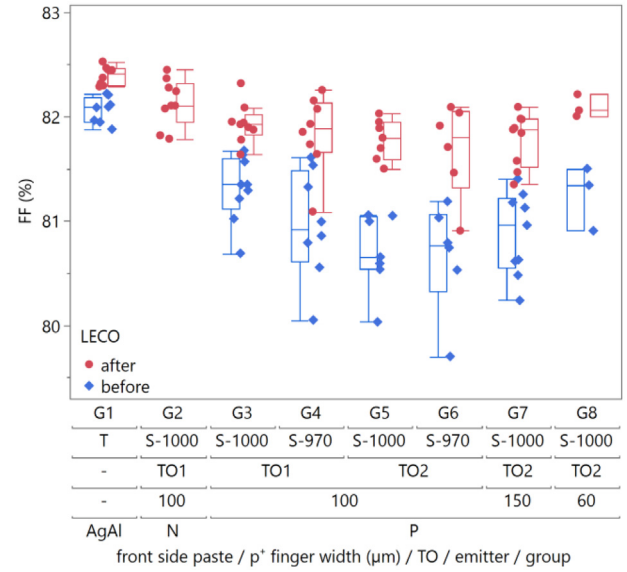


Fig. 11. FF for the TOPCon reference group (G1) and various SelfFi TOPCon groups (G2-G8) before and after LECO treatment. Note that FF of group G2 (paste “N”) is 27% before LECO and thus outside of the displayed range.

3.3.3 Analysis of metal induced recombination losses

Figure 9 shows a comparison of iV_{oc} , V_{oc} and derived iV_{oc} -to- V_{oc} loss for the TOPCon reference group (G1) and various SelfFi TOPCon groups (G2-G7) and serves to quantify the metal induced recombination losses. Since no cell precursors were extracted for G8 due to the limited group size after mechanical losses, no iV_{oc} -to- V_{oc} loss can be derived for this group. As discussed above the systematic uncertainty on iV_{oc} values is estimated to be ± 1.1 mV. The systematic uncertainty on V_{oc} as given by the third party certification laboratory is ± 2.3 mV. Propagating these values yields a systematic uncertainty of ± 2.5 mV on the iV_{oc} -to- V_{oc} loss. However, it has to be considered that V_{oc} and iV_{oc} have to be measured on two different subsets of samples, which may be influenced by local sporadic defects, e.g., from sample handling. Therefore, two values are given for the iV_{oc} -to- V_{oc} loss to improve the robustness of the analysis: one is based on the difference of the medians of the two distributions and one based on the two respective maxima. Figure 9 shows that there is reasonably close agreement between the two values. While the iV_{oc} -to- V_{oc} loss is ≈ 12 mV for the TOPCon reference group, the SelfFi TOPCon groups consistently show a significantly lower loss owing to the enhanced front contact passivation. For G6, the group featuring the highest iV_{oc} , V_{oc} , and efficiency in the present study the iV_{oc} -to- V_{oc} loss is even below 2 mV for both median and maximum of the observed voltages and hence in the same range as the systematic uncertainty of this value. For group G7, featuring wider p^+ poly-Si fingers, there is no iV_{oc} -to- V_{oc} loss observed at all. Despite the above-mentioned restrictions regarding sample selection,

these results constitute a strong indication that SelfFi TOPCon cells with vanishing metal induced recombination have been successfully realized. Nevertheless, further experiments with better statistical power are needed to assess if there is a causal relation between the observed differences in iV_{oc} -to- V_{oc} loss of the different SelfFi TOPCon cell groups and the respective differences in process parameters.

3.3.4 Effect of LECO on SelfFi TOPCon solar cells

Figures 10 and 11 show the series resistance (R_s , determined from light and dark measurement) and the FF of all cells before and after the application of an optimized LECO process using a lab tool by CE Cell Engineering. While no significant differences are observed in all other IV parameters, LECO significantly reduces the series resistance, and, hence, it increases the FF of all cells within this study, including the TOPCon reference group.

The most prominent LECO effect is observed for group G2, for which the p^+ poly-Si fingers are metalized with paste “N” (a n^+ poly-Si contacting paste that is also used for the TOPCon rear side). Before LECO hardly any contact is established with $R_s = 0.152 \Omega$ and $FF = 27\%$ outside of the displayed range in the respective figures, in order not to hide the differences between the other groups. After LECO R_s of group G2 matches the values measured for the TOPCon reference group, indicating a very strong LECO effect for this paste. The remaining difference in FF can presumably be attributed to a difference in pFF (c.f. Fig. 7).

For Selfi TOPCon groups metalized with paste “P”, reasonable contact is already established by firing without LECO. However, LECO still leads to an appreciable reduction of the median R_s values by 0.5–0.8 m Ω . This entails a FF gain of 0.6–1.0%^{abs} and boosts the efficiency by 0.16–0.29%^{abs}. The largest FF and efficiency gains are observed for the groups with the thicker interface oxide TO2 under the p⁺ poly-Si fingers (G5, G6). This can be interpreted as a vague indication that LECO not only reduces the contact resistance between metal and poly-Si but might also contribute to reducing the interface oxide resistance for thick oxides. Figure 10 shows that R_s increases when increasing the interface oxide thickness (G3 vs. G5 and G4 vs. G6) and when increasing the sheet resistance of the emitter diffusion (G3 vs. G4 and G5 vs. G6). This observation fits the expectation and holds true before and after LECO.

The efficiency gain by LECO is substantially larger for Selfi TOPCon cells compared to the TOPCon reference group which improves only by 0.08%^{abs}. For the best Selfi TOPCon group (G6) a gain of 0.28%^{abs} has been observed. However, it has to be noted that neither the reference group nor the Selfi TOPCon cells are specifically optimized for LECO yet.

4 Conclusion and outlook

The present paper describes a process flow and experimental results related to the development of advanced Selfi TOPCon solar cells with local p⁺ poly-Si passivated contacts under the front side metallization. It is demonstrated that such a solar cell concept can be realized by adding just a few additional process steps to a conventional industrial TOPCon production line. All added process steps – deposition of intrinsic amorphous silicon, boron diffusion and local laser treatment with a green ns-laser – have a proven track record in large-scale industrial PV production. It is shown that such advanced TOPCon solar cells clearly outperform conventional TOPCon solar cells with a homogenous emitter in terms of V_{oc} and feature vanishing metal induced recombination losses. Presently, the efficiency of these cells lacks behind the TOPCon reference by 0.1–0.2%^{abs}, owing to increased contact resistance at the p⁺ poly-Si contact and to optical losses that mainly arise from reflection caused by protruding stripes of non-textured p⁺ poly-Si and wider metal fingers.

The results outlined in this paper give a clear indication on how to further improve the efficiency of such advanced TOPCon solar cells. The feasibility of aligning the front grid to 60 μ m wide p⁺ poly-Si fingers was validated (G8) and can be applied to the group with the best efficiency within this study (G6, 100 μ m) without further optimization. An efficiency gain of $\approx$ 0.2%^{abs} can be expected. Further reduction of the p⁺ poly-Si finger width will be investigated but requires improved alignment and process control. Additionally, the front side metallization has to be improved to reduce optical losses caused by paste spreading, and, hence, wider metal fingers compared to the reference group. Further efficiency gains can be expected from an improved metallization by reducing

the amount of finger interruptions observed in the present study. Both aspects will be addressed by adjusted pastes. Reducing the contact resistance of the p⁺ poly-Si contact will be a focus of the future development to minimize series resistance losses. In order to optimize the cell precursor passivation, further co-optimization of the passivation of the p⁺ poly-Si and the IFR is needed, e.g. by further increasing the interface oxide thickness and the sheet resistance of the diffusion, as both measures lead to efficiency gains in this study.

Recently significant progress has been reported in reducing metal induced recombination at the front side of TOPCon cells with homogenous, high sheet resistance emitters by using aluminum-free silver metallization and contacting via LECO. Impressively low J_{0met} values of < 160 fA/cm² have been reported for such cells without the application of passivated contacts at the front side. It is obvious that these developments constitute a fierce competition to the Selfi TOPCon cell concept proposed in this article. Nevertheless, the authors are convinced that local passivated front contacts will be needed in the future to suppress the remaining recombination contributions and the current development of cells with flat p⁺ poly-Si fingers aims at laying the foundations for such cell concepts. More advanced developments that may be integrated into the Selfi TOPCon cell concept in the future therefore include pre-texturing of the p⁺ poly-Si fingers to reduce reflective losses from the protruding parts of the layer next to the metal fingers. Additionally, the deposition of in-situ boron doped a-Si(p) layers via PECVD will be investigated to further simplify the process sequence.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Reported data can be provided upon request.

Author contribution statement

Conceptualization: J.H. and S.S.K.; Methodology: J.H., S.S.K., M.C., P.P., J.Li., F.B.; Formal Analysis: J.H.; Investigation: J.H., S.S.K., P.P.; Resources: J.Lo., L.K. and F.B.; Data Curation: J. H.; Writing – Original Draft Preparation: J.H.; Writing – Review & Editing: J.H., F.B., S.S.K., J.Lo. and L.J.; Visualiza-

tion: J.H.; Supervision: J.H.; Project Administration: J.H.; Funding Acquisition: J.H. and J.Lo. All authors have read and agreed to the published version of the manuscript.

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