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Low-Loss Singulation of TOPCon Half Solar Cells by TLS and Al_2O_3 Edge Passivation

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Abstract. This work addresses the separation of tunnel-oxide passivated contact (TOPCon) host solar cells into half solar cells. It demonstrates the feasibility of achieving almost loss-free cell performance after edge passivation by the passivated edge technology (PET). It is shown that edge passivation with aluminum oxide (Al_2O_3) is also compatible with TOPCon solar cells that have been fabricated with Al-free Ag screen printing paste for the front side finger contacts applying laser-enhanced contact optimization (LECO). The half solar cells, with an edge length of 182 mm x 91 mm, are separated from industrial pseudo-square M10-format TOPCon host solar cells by thermal laser separation (TLS) from the front side. An optimized TLS process results in an efficiency loss of only slightly above $0.1\%_{abs}$. A high-throughput prototype tool with a capacity of about 16,000 half solar cells per run is used for an Al_2O_3 layer deposition on the cut edges. Using optimized processes, the PET recovered approximately $85\%_{rel}$ of the cutting losses in pseudo fill factor by applying Al_2O_3 edge passivation and annealing. Thus, TLS in combination with high-throughput Al_2O_3 edge passivation is a viable approach for industrial fabrication of highly efficient TOPCon half solar cells, whether LECO and Al-free Ag pastes are applied or not.

Keywords: Edge Passivation, Passivated Edge Technology, TOPCon, Half Solar Cells, Thermal Laser Separation, TLS, Singulation, PE-ALD, Laser Enhanced Contact Optimization, LECO

1. Introduction

Tackling edge recombination at newly created edge surfaces after cell separation becomes more and more important [1]. Low-damage technologies for cell separation, like thermal laser separation (TLS) [2], laser induced cutting [3] or laser direct cleaving [4], are favorable. Nevertheless, after cell separation, the newly created edge surfaces suffer from increased charge carrier recombination [5]–[7]: This effect increases as the share of the unpassivated edge increases and/or as the performance potential of the host solar cell rises.

An option to minimize edge recombination is edge passivation [1],[8],[9]. Fraunhofer ISE filed patent applications for edge passivation in 2018. One year later, in 2019, Fraunhofer ISE introduced the post-metallization passivated edge technology (PET) on passivated emitter and rear cell (PERC) shingle solar cells [10],[11]. PET is a proprietary development of Fraunhofer

ISE to address the cutting losses in today's solar cells by a simple, high-throughput post-processing on separated solar cells. PET consists of the deposition of a dielectric passivation layer after cell separation, for example, an aluminum oxide (Al_2O_3) layer, and an optional subsequent annealing step for Al_2O_3 layer activation. Apart from PERC, PET has also already been demonstrated by Fraunhofer ISE on tunnel-oxide passivated contact (TOPCon) [12] shingle solar cells [13],[14] as well as on silicon heterojunction (SHJ) half solar cells [15]. The concept of the PET approach is being taken up by more and more players in the PV community on current cell devices as TOPCon solar cells [16],[17] or SHJ solar cells [18]–[20]. As the efficiency of current TOPCon solar cells is steadily increasing, the losses due to edge recombination are becoming relevant for half solar cells.

Recently, laser-enhanced contact optimization (LECO) has been introduced [21], proven for TOPCon solar cells [22], and applied to industrial TOPCon solar cell manufacturing [23]. Applying LECO allows for the usage of aluminum (Al) free silver (Ag) screen-printing paste for the front side finger contacts and modified properties of the front side boron emitter doping, to increase the performance of the cells.

Based on experimental data, this paper demonstrates low-damage solar cell separation and the effectiveness of edge passivation applying PET for TOPCon half solar cells, no matter if they have been fabricated applying the "classical route" with silver-aluminum (Ag-Al) front side finger metallization without LECO, or the "new" route with Ag front side contacts and LECO.

2. Experimental

The experiment plan is shown in Figure 1. The trial consists of two groups, Gr1 and Gr2, hosting n-type Czochralski-grown silicon (Cz-Si) TOPCon solar cells with 16 busbar contacts from an industrial cell manufacturer; see Figure 2. The solar cells are in pseudo-square M10 format with an edge length of 182 mm in both directions and a diameter of 247 mm.

The host cells in Gr1 were fabricated using an Ag-Al screen printing paste for the front side finger metallization, whereas the front side finger metallization for the host cells in Gr2 was screen-printed with an Ag paste (without Al). After contact firing, the host cells in Gr2 underwent LECO processing, while the host cells from Gr1 were not LECO treated. As the host cells in Gr2 are optimized for LECO, apart from the front side screen printing paste, also other properties, like the front side boron emitter, are different to those of the host cells from Gr1.

The initial current-voltage (*I-V*) testing is performed at host cell level whereby each of the 16 busbar contacts on the front side is contacted with its own contact bar. The rear side is contacted on its full area on a reflective gold-coated chuck that has vacuum channels for suction. Then, the host cells are separated into half solar cells by TLS from the front side. The *I-V* testing of the half cells is performed using the same setup. To prevent short-circuiting between the front contact bars and the chuck, the area which is not covered by the half cell is masked with a black plastic stencil.

For edge passivation applying the PET concept, the half cells are stacked onto each other and a 6 nm Al_2O_3 layer is deposited on the edge surfaces by plasma-enhanced atomic layer deposition (PE-ALD) using the high-throughput prototype tool from Plasma Electronic shown in Figure 3. The process chamber can accommodate about 16,000 stacked half cells per run. In this experiment, the process time of one run was about one hour. Subsequently, an annealing step is conducted within a convection chamber oven including a variation of the peak temperature. Finally, the half cells are *I-V* tested as before.

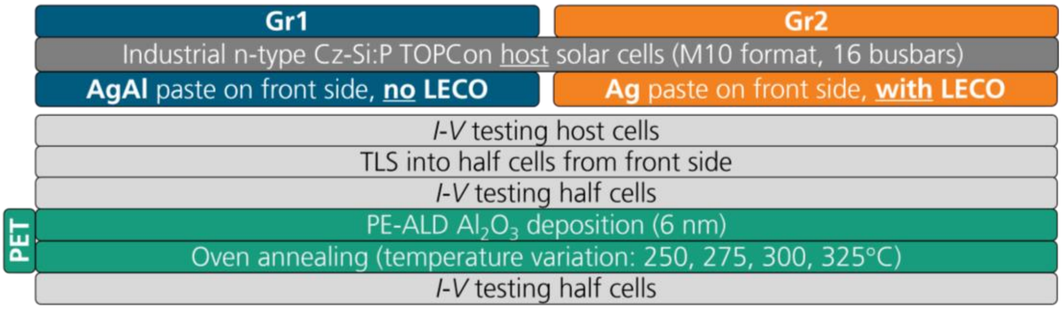

Figure 1. *Schematic process sequence of the experiment with two different TOPCon host solar cell groups. Commercially available TOPCon solar cells are used for this study*

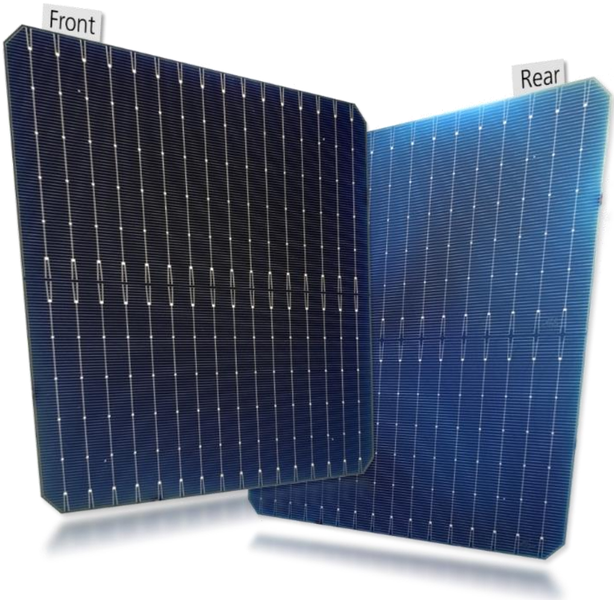

Figure 2. *Exemplary photographs of the front and rear side of the M10 format n-type Cz-Si TOPCon solar cells under investigation*

Figure 3. *Photograph of the high-throughput PE-ALD prototype tool located at Plasma Electronic in Neuenburg am Rhein, Germany*

3. Results

The mean power conversion efficiency of the TOPCon host solar cells is tested to be η = 24.2% (Gr1) and η = 24.8% (Gr2); see Figure 4(a). As open-circuit voltage V_{OC} and pseudo fill factor *pFF* are the most sensitive parameters regarding edge recombination, they are shown in Figure 4(b) and (c), respectively. The series resistance R_S is given in Figure 4(d). The fabrication route with Ag paste and LECO in Gr2 enables a remarkable improvement of the host cells with $\Delta V_{OC,mean}$ = +14 mV and ΔpFF_{mean} = +0.9%$_{abs}$; however, is accompanied by increased series resistance $\Delta R_{S,mean}$ = +0.17 Ωcm^2.

Cutting the host cells into half cells by TLS from the front side leads to a low mean V_{OC} loss of $\Delta V_{OC,mean}$ = -0.4 mV for both groups, while the mean *pFF* losses are ΔpFF_{mean} = -0.57%$_{abs}$ (Gr1) and ΔpFF_{mean} = -0.67%$_{abs}$ (Gr2). The corresponding mean efficiency losses are $\Delta\eta_{mean}$ = -0.11%$_{abs}$ (Gr1) and $\Delta\eta_{mean}$ = -0.13%$_{abs}$ (Gr2).

After PET with Al_2O_3 edge passivation with varied annealing temperatures, both groups profit significantly from recovered *pFF* values; Figure 4(c). Regarding R_S it is found that the half cells from Gr1 are robust against temperature treatment up to at least 325°C, see Figure 4(d). This annealing temperature also results in the largest *pFF* gain, almost fully compensating the former cutting loss.

For Gr2, R_S increases significantly for temperatures equal or above 300°C, while V_{OC} starts decreasing. Nevertheless, for 250°C and 275°C annealing temperature, the *pFF* gain is also almost compensating the former cutting loss. The data suggest that the front side contact of the half cells from Gr2 with Ag paste and LECO is not as temperature stable as the front side contact of the half cells from Gr1 with Ag-Al paste without LECO. Thus, it is important to optimize the applied PET sequence (Al_2O_3 deposition + annealing) with respect to the sample's history.

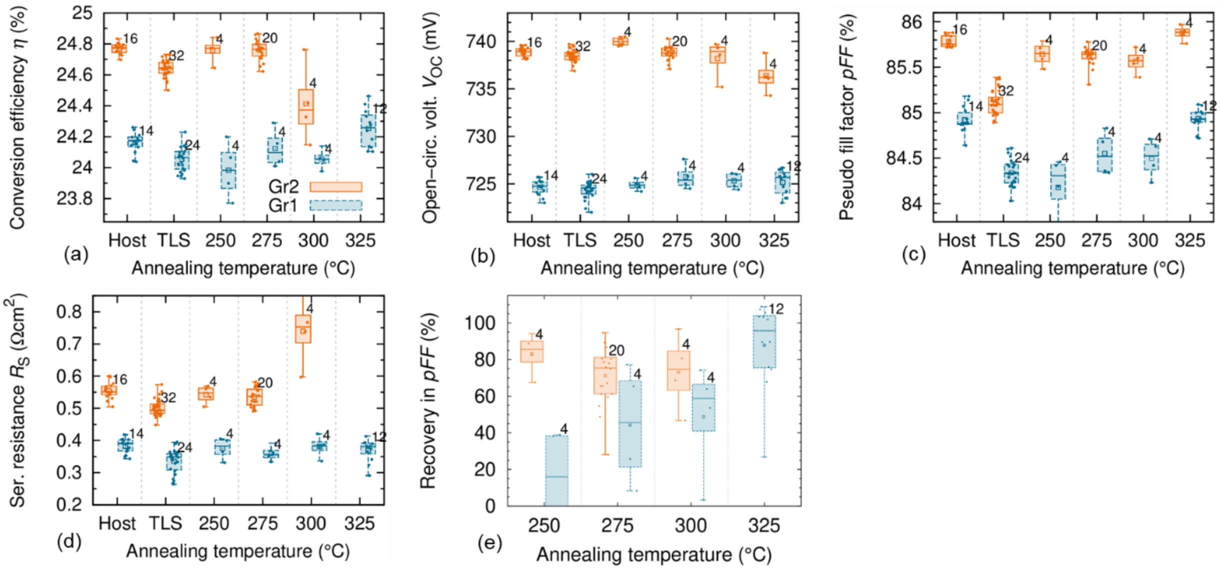

Figure 4. *(a-d) I-V data for the TOPCon solar cells in different states: (1) host cell, (2) half cell after TLS, and (3-6) after Al_2O_3 edge passivation and annealing at different peak temperatures. The mean R_S for Gr2 at 325°C annealing temperature is about 4 Ωcm². (e) Recovery of the cutting losses in pFF after Al_2O_3 edge passivation for the different annealing temperatures*

To demonstrate the impact of edge passivation on the *pFF* in more detail, Figure 4(e) gives the recovery in *pFF* after edge passivation. It is calculated by the quotient of the *pFF* gain on half cell level due to edge passivation and the *pFF* loss due to the cell separation from host cell to half cell. As already discussed, the trends for both groups regarding the annealing temperature are opposite: Gr1 requires higher annealing temperatures, while Gr2 already shows large recovery values for the lower annealing temperatures. The largest mean recovery values in *pFF* are 88% and 83% for Gr1 and Gr2, respectively. An overall improvement of the surface passivation by annealing might be present, which could explain the values exceeding 100% for 325°C annealing temperature.

Hence, also the “new” route with Ag paste and LECO for forming the front side contact in Gr2 is compatible with PET consisting of Al_2O_3 edge passivation with subsequent annealing. This concludes in the overall result that the initial efficiency loss of about 0.1%$_{abs}$ due to cell cutting by TLS can be almost fully compensated by the application of Al_2O_3 edge passivation; see Figure 4(a).

4. Discussion and conclusion

Applying PET by Al_2O_3 edge passivation, an almost loss-free cell separation in combination with TLS is demonstrated for TOPCon half solar cells. The PE-ALD Al_2O_3 deposition is performed in a high-throughput deposition tool followed by an annealing step in a convection chamber oven.

The mean recovery in pseudo fill factor, which mainly gives the percentage to which extend the cutting losses can be cured by edge passivation, is found to be in the range of 85% whether the “classical” route with Ag-Al paste on the front side and no LECO or the “new” route with Ag paste (without Al) on the front side and LECO is used. For both routes, the efficiency loss due to TLS with slightly above 0.1%$_{abs}$ is almost fully compensated by applying Al_2O_3 edge passivation.

Thus, combining TLS and high-throughput PE-ALD Al_2O_3 edge passivation allows for almost loss-free cell separation of the most up-to-date TOPCon solar cells in industrial mass production.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Elmar Lohmüller: Conceptualization, investigation, methodology, visualization, writing – original draft

Norbert Kohn: Investigation

Felix Maischner: Investigation, writing – review & editing

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Alexander Göbel: Investigation, writing – review & editing

Jonas D. Huyeng: Supervision, methodology, writing – review & editing

Pierre Saint-Cast: Project administration, writing – review & editing

Vivek Beladiya: Investigation, writing – review & editing

Saravanan Somasundaram: Resources, writing – review & editing

Ralf Preu: Supervision, writing – review & editing

Competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fraunhofer ISE reports equipment, supplies and writing assistance were provided by Plasma Electronic GmbH. Fraunhofer ISE reports financial support, equipment, supplies, and writing assistance were provided by Emmvee Photovoltaic Power Private Limited. Patent #DE 10 2018 123 485 B4 issued to Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.. Patent #US 11,508,863 B2 issued to Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.. Patent #CN 113169242 B issued to Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.. Patent #EP 19 778 933.2 issued to Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V..

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