

Project “BUSSARD” – a holistic development of high-efficiency solar cells covering innovative front-end, metallization and interconnection approaches

Andreas Lorenz^{1,*}, Jörg Schube¹, Veronika Nikitina¹, Sebastian Mack¹, Sebastian Schweigert¹, Jonas Buddgard², Jonas Albrecht³, Maximilian Pospischil³, Achim Kraft¹, Andreas Wolf¹, Martin Hermle¹, and Florian Clement¹

¹ Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany

² Sticky Solar Power, Högsätravägen 2, 181 58 Lidingö, Sweden

³ Highline Technology GmbH, Tullastraße 87B, 79108 Freiburg, Germany

Received: 28 June 2024 / Accepted: 28 November 2024

Abstract. Within this work, we present key results of the transnational European research project “Bussard”. The aim of this project is the development and evaluation of various innovative approaches for highly efficient cell concepts such as tunnel oxide passivating contact (TOPCon) solar cells considering the whole process chain including front-end, back-end and module processing. We present atomic layer deposition (ALD) as a high-throughput alternative for the deposition of Al_2O_3 passivation layers on the front side of TOPCon solar cells enabling a substantial reduction of the emitter saturation current density down to $j_{0e} = 13 \text{ fA/cm}^2$. In the field of metallization, we evaluate and demonstrate three innovative approaches for the fine-line metallization of TOPCon solar cells. In this study we focus on multi-nozzle parallel dispensing, a technology that was developed as an alternative to standard screen-printing metallization and is used for the metallization of TOPCon solar cells for the first time. By optimizing the fabrication process at Fraunhofer ISE, we realize TOPCon solar cells ($156.75 \text{ mm} \times 156.75 \text{ mm}$) with a champion conversion efficiency of up to $\eta_{\text{max}} = 24.2\%$ (independently confirmed by Fraunhofer ISE CalLab PVCells). Finally, we present a comprehensive evaluation of the innovative *Tape Solution* interconnection concept for TOPCon cells and modules. We demonstrate the feasibility on small-scale and full-format modules and analyze the I - V results as well as cell-to-module (CTM) loss analysis using the simulation tool SmartCalc[®]. The results are compared to TOPCon modules interconnected via SmartWire Connection Technology (SWCT) and electrically conductive adhesive (ECA).

Keywords: TOPCon / atomic layer deposition / dispensing / tape solution / electric conductive adhesive / SmartWire

1 Introduction

High-efficiency solar cell concepts with carrier-selective contacts (often also denoted as “passivating contacts”) [1,2] have gained a substantial market share in industrial PV production throughout the last years [3]. A very successful approach is the so-called TOPCon (tunnel oxide passivating contacts) solar cell concept [4] which already gained a substantial market share in the global PV market and is expected to gradually replace the currently still dominant passivated emitter and rear contact (PERC) solar cell [3]. TOPCon enables high conversion efficiencies due to poly-Si/SiOx passivating contacts and

can be implemented with manageable effort in existing industrial PERC production lines [1]. At present, industrial n-type TOPCon cells achieve champion efficiencies of up to 26.7% [5]. Within the joint research project “Bussard” (Cofund ERA-NET Action, Grant Agreement N° 786483) we evaluate several innovative approaches for the passivation, metallization and interconnection of high efficiency cell concepts aiming at a comprehensive optimization throughout the whole process chain. The main focus of this work is the development and evaluation of alternative and industrially applicable approaches with focus on productivity, sustainability (silver reduction) and reduced cell-to-module losses.

With focus on frontend processing of TOPCon solar cells, we consider an industrially applicable passivation of the p^+ boron emitter using ALD deposition of the Al_2O_3

* e-mail: andreas.lorenz@ise.fraunhofer.de

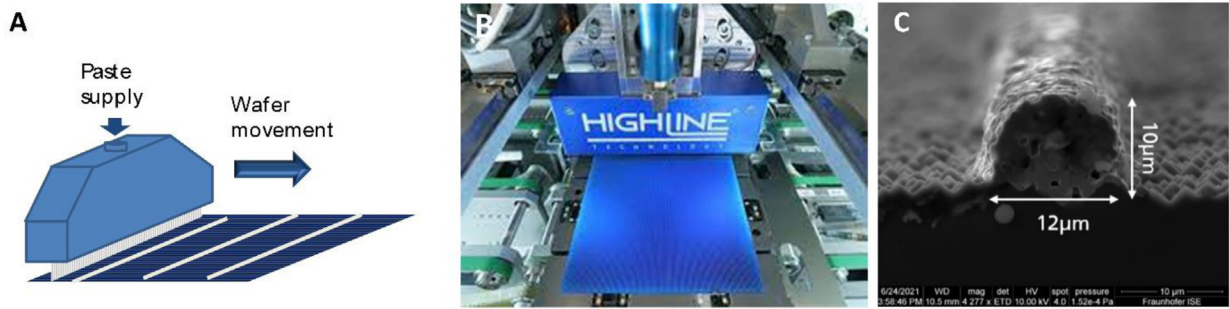


Fig. 1. Schematic view of the parallel dispensing process: A printhead with a nozzle plate containing small parallel nozzle openings directly applies the contacts onto the surface of laterally transported solar cell (A). Image of an industrial multi-nozzle parallel dispensing printhead (with courtesy of Highline Technology GmbH). Scanning electron microscopy (SEM) cross-section view of a dispensed fine line contact for front side metallization.

passivation layer. This approach is comprehensively evaluated and compared to the plasma-enhanced chemical vapor deposition (PECVD) reference process [6]. Currently, depositing a Al_2O_3 passivation layer on the rear side is the industrial standard for backside passivation of p-type PERC solar cells, whereas for industrial TOPCon solar cells, it is being used as a passivation layer for the front p^+ -doped emitter. Al_2O_3 layers generally allow very low surface recombination on p-doped silicon surfaces, both at (100) and (111) crystal planes. Since the layers also allow for very good passivation for higher doping level in the range of 10^{18} to 10^{19} cm^{-3} [7,8], Al_2O_3 is very well suitable to passivate boron-doped emitters on textured surfaces. The ALD process can be a promising technique for textured surfaces to meet high demands on passivation quality without a limitation regarding throughput. The developed system will enable a throughput of 1000 wafers per hour for an ALD processing tube (5000 wafers per hour per system) with an excellent passivation quality emitter saturation current density well below 20 fA/cm^2 .

Nowadays, the industrial fine-line front and rear side metallization for silicon solar cells is predominantly realized using flatbed screen-printing (FSP) technology [9]. While FSP is a robust, well-established technique, it also faces several drawbacks – mainly a potential limitation of throughput, costly consumables (high precision screens) and a non-efficient use of the silver paste due to partly insufficient finger geometry (e.g., mesh marks, or spreading) [10]. To meet these challenges, three competing innovative approaches for the front and rear side metallization of TOPCon solar cells are evaluated in “Bussard” and compared to FSP: FlexTrail printing [11], indirect gravure printing [12] and parallel dispensing [13,14]. Using FlexTrail and indirect gravure printing, promising results have been achieved and published previously: FlexTrail enables fine-line printing of $13 \mu\text{m}$ wide metal contacts, which are $6 \mu\text{m}$ in height [11]. Indirect gravure printing results in greater feature sizes but very low cycle times of 0.9 s per cell are achieved with a potential towards 0.5 s per cell and even below [12]. Within this work, the focus is set on parallel dispensing (Fig. 1) as a highly promising and industrially well applicable alternative for the fine line metallization of TOPCon solar cells.

Starting in 2010, the dispensing technology was developed as an alternative to screen-printing metallization at Fraunhofer ISE [15]. Initially developed

as a single-needle process on a laboratory scale, this approach was further developed in several steps towards an industry-scale system with a parallelized print head [13,16] and commercialized by the Fraunhofer ISE spin-off Highline Technology GmbH [17]. Parallel dispensing enables a parallel, contactless application of finest, linear electrodes with a printing velocity of more than 700 mm/s [14,18]. The dispensing finger geometry enables a significant reduction of shading losses compared to screen-printing (due to narrower fingers and improved optics in the module). Due to the uniform contact finger geometry, the applied amount of silver paste is used more efficiently for lateral current conduction [14,19,20]. Previous work demonstrated an efficiency increase of $\Delta\eta = 0.26\%_{\text{abs}}$ at a reduced silver paste laydown of $-50\%_{\text{rel}}$ compared to FSP on silicon heterojunction solar cells (SHJ) using low-temperature silver pastes [20]. Another major advantage is the usability of commercial metallization pastes without substantial adaption which makes it easy to implement the process with existing materials. Several very demanding technological challenges on the way to an industrially reliable application were successfully overcome: ensuring high process stability (no breakage of the ultra-fine, parallel dispensed paste threads over tens of thousands of cycles) [14], reproducibility for the finest parallel dispensed contacts at high process speeds, ensuring a reliable start-stop mechanism at the beginning and end of the cell [21], reducing the contact finger width to less than $20 \mu\text{m}$ [17,21] and finally an easy implementation of the system into flatbed screen-printing modules of existing PV production lines through a “plug & play” system [21]. The successful application of parallel dispensing for various cell concepts such as passivated emitter and rear contact (PERC) [17], silicon heterojunction solar cells (SHJ) [14] and CIGS modules [20] has been demonstrated with substantial advantages over flatbed screen-printing metallization. Within this work, the application of parallel dispensing for the metallization of TOPCon solar cells is explored and demonstrated for the first time. The application of this technique for TOPCon is particularly challenging due to specific characteristics of the TOPCon metallization pastes i.e., due to comparatively large aluminium (Al) and glass frit particles which could lead to clogging of the fine nozzle openings.

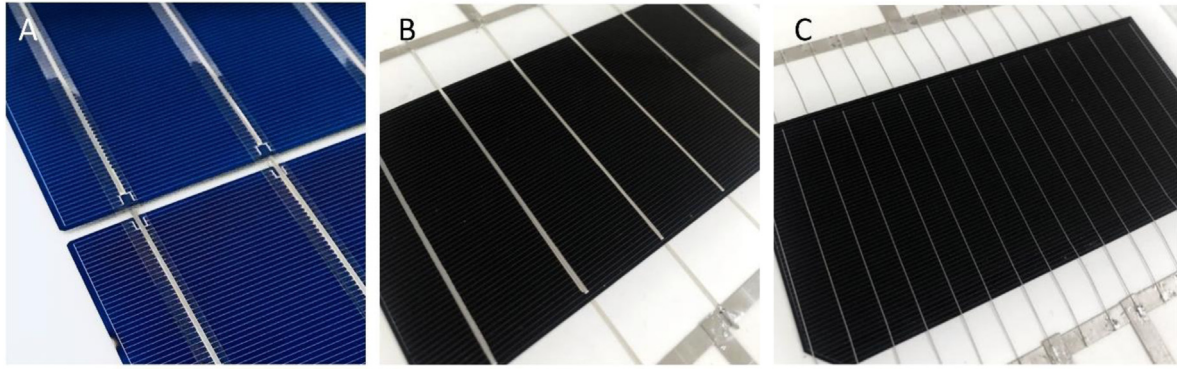


Fig. 2. Interconnection concepts considered within this work: (A) *Tape Solution* concept: Adhesive stripes with embedded Cu wires coated with a low-temperature solder alloy are applied on the front and rear solar cells to interconnect the strings (Source: Sticky Solar Power AB); (B) ECA interconnection: ribbons are glued to the cell surface via temperature activating electrically conductive adhesive; (C) Smart Wire Connection Technology: Interconnection via multiple wires coated with low-temperature solder alloy and fixed on a single polymer sheet. Analogically to *Tape Solution*, final interconnection takes place during lamination, where solder alloy melts.

With focus on interconnection and module fabrication, we evaluate the *Tape Solution* approach [22,23] of Sticky Solar Power. *Tape Solution* utilizes parallel adhesive tapes with incorporated flat wires to interconnect the cells to strings. During the production process, the tape with interconnectors is placed on front and rear sides of the cells, applying moderate pressure at room temperature. After stringing, polymer tapes keep the interconnectors in place for module layout. Final electrical interconnection of the solar cells takes place during module lamination, where the low-temperature solder coating of the flat wires melts and creates the bond with cell metallization. *Tape Solution* offers several benefits compared to conventional soldering – namely the prevention of lead usage, reduced silver consumption due to relaxed busbar metallization requirement, potentially lower production costs due to room temperature stringing and a general simplification of the interconnection process. In comparison to the conventional soldering, where SnPb/SnPbAg solder is utilized on busbar metallization, typically consisting of pads connected with a redundancy line, *Tape Solution* approach requires no busbar metallization whatsoever. Thus, a significant silver consumption reduction can be achieved. Furthermore, since the soldering step is carried out during lamination at significantly lower temperatures than conventional soldering ($<160^{\circ}\text{C}$), it is particularly beneficial for temperature-sensitive cell concepts like silicon heterojunction (SHJ) or perovskite-based tandem solar cells [24].

Conventional soldering of busbarless cells is very challenging due to the absent busbar metallization, where solder could form mechanically and electrically stable joints. Additionally, the metallization pastes used for TOPCon cells often contain Aluminium, which may pose challenges when soldered [25]. Within this work, we evaluate the compatibility of the *Tape Solution* approach with busbarless TOPCon cells and compare the results to established technologies for such cells – namely *Smart Wire* connection technology (SWCT) [26] and electrically conductive adhesive (ECA) [27–29] (Fig. 2). The performance of the fabricated modules is evaluated through I - V measurement. A cell-to-module analysis using the

Fraunhofer ISE simulation tool SmartCalc[®] [30] provides a deep insight regarding electric, geometric and optical characteristics of the interconnection and module components as well as potential loss factors.

It is the aim of this work to evaluate and demonstrate the feasibility of *Tape Solution* innovative approach for high-efficiency busbarless TOPCon cells as well as compare *Tape Solution*, ECA and SWCT between one another.

2 Materials and methods

2.1 Evaluation of atomic layer deposition for the passivation of TOPCon solar cells

One important aim of the project “Bussard” is the evaluation and implementation of ALD as an alternative method for the deposition of the front side p^{+} boron emitter Al_2O_3 passivation layer. To realize this process at Fraunhofer ISE, an existing five-deck *Tempress* tube furnace is modified to enable ALD deposition of Al_2O_3 layers on TOPCon solar cells. The development of the atomic layer deposition process starts with the control of layer growth. Using ALD, the growth of the layer is limited at each cycle, meaning that there is no continuous growth rate but one growth per cycle (GPC). Each material is characterized by a specific layer thickness per cycle. For Al_2O_3 it is about 0.13 nm per combined cycle of Al precursor and oxidation. In contrast to CVD (chemical vapor deposition) methods, the gas precursors are injected at different times into the chamber and react sequentially on the wafer surface. The very large volume of the chamber used for this project poses a challenge to the ALD process, as the gas can be trapped between cycles. Controlling layer homogeneity and GPC makes it possible to assess whether the CVD part of the growth process is limited. The growth per cycle, the homogeneity of the layer thickness and the refractive index can be determined by ellipsometry. In a first experiment, a set of parameters for deposition and outgassing of the layer is evaluated, as well as different approaches for integration into the solar cell process. In a second experiment, the parameter space for the deposition

Dispensing			Screen printing		
Gr. 1	Gr. 2	Gr. 3	Gr. 4	Gr. 5	Gr. 6
Rear side: screen printing					
196 F ($w_n = 24 \mu\text{m}$), 12 pseudo-BB ($w_{bb} = 60 \mu\text{m}$) Drying 1 min @ 250° C					
Front side: dispensing (paste A)			Front side: screen printing (paste B)		
150 F ($w_n = 22 \mu\text{m}$), no BB Drying 1 min @ 200° C			121 F ($w_n = 24 \mu\text{m}$), no BB Drying 1 min @ 200° C		
Fast firing: $v = 6\text{m/min}$ Post firing anneal 30 s @ 500° C					
$T_{\text{set1}} = 770^\circ \text{C}$	$T_{\text{set2}} = 790^\circ \text{C}$	$T_{\text{set3}} = 810^\circ \text{C}$	$T_{\text{set1}} = 770^\circ \text{C}$	$T_{\text{set2}} = 790^\circ \text{C}$	$T_{\text{set3}} = 810^\circ \text{C}$
Characterization					
I-V measurements Confocal microscopy					

Fig. 3. Experimental design of the cell batch – comparison of dispensing and screen-printing on TOPCon solar cells.

and necessary outgassing of the layer is expanded in a thermal step, with the aim of further reducing recombination at the surface.

2.2 Fabrication of TOPCon solar cells with ALD passivation

The newly implemented ALD deposition process is used to fabricate industrial TOPCon solar cells. The solar cells are made from commercially available n-doped silicon wafers with an edge length of 156.75 mm and starting thickness of 180 μm . In the final solar cell, the emitter (sheet resistance 118 $\Omega/\text{sq.}$, depth 1.2 μm , maximum concentration $1 \cdot 10^{19} \text{ cm}^{-3}$) is located on the front side. The TOPCon passivation layer is formed by chemical vapor deposition at low pressure (LPCVD) onto an in-situ thermally grown SiO_x tunnel oxide layer. The n-type doping of the layer takes place in-situ during deposition. Within the experiment, two variants are processed: TOPCon solar cells with ALD Al_2O_3 layer deposition and PECVD layer deposition as a reference. Within the ALD groups, it is further investigated how the results differ when the samples are placed alone in a slot of the quartz boat during ALD deposition (single slot) or two samples in a slot, with the non-coated back side facing inwards (back-to-back, btb). Since the Al_2O_3 layer is only required on the front of the solar cell, this effectively enables a doubling of the throughput of the system (1200 instead of 600 wafers per run).

2.3 Evaluation of parallel dispensing for the fine-line metallization of TOPCon solar cells

Within “Bussard”, three innovative metallization approaches for TOPCon cells are considered and compared to standard screen-printing. Within this work, we focus on parallel dispensing which from these three is closest to an industrial large-scale implementation. An experiment is set up to evaluate the performance of the dispensing process compared to standard FSP metallization (Fig. 3). Pre-fabricated TOPCon solar cell precursors with an edge length of 156.75 mm are manufactured in-house at Fraunhofer ISE with the established reference process

featuring single slot ALD Al_2O_3 deposition, using M2 sized n-type Si wafers. After deposition of the front and rear passivation layers by means of PECVD, the wafers are distributed into six groups.

Within the experiment, two variants of solar cells are fabricated: variant 1 (three groups with three peak set firing temperatures) with parallel-dispensed front side metallization and variant 2 (three groups with three peak set firing temperatures) with screen-printed front side metallization as a reference (see Fig. 3). The rear side metallization of all groups is realized with FSP using a commercially available Ag paste. A busbarless grid layout with 196 fingers (nominal finger width $w_n = 24 \mu\text{m}$) is selected for the rear side. The front side is metallized with a busbarless grid which is different for dispensing (150 fingers, nozzle opening $d_n = 22 \mu\text{m}$) and FSP (121 fingers; nominal finger width $w_n = 24 \mu\text{m}$). For the screen-printing process, a fine line screen with 520 wires/inch, a wire thickness of 11 μm and a mesh angle of 22.5° ($520 \times 0.011 \times 22.5^\circ$) is used. Due to the specific requirements for the dispensing process it is not possible to use exactly the same paste for the front-side metallization. The screen-printing process (Groups 4–6) is carried out using a commercially available silver paste for TOPCon. For the parallel dispensing process, a commercially available Ag paste is used which has been identified as suitable for dispensing in previous tests. To prepare the paste for the dispensing process and avoid clogging of the small nozzle openings, the paste is pre-filtered using cascading nylon filters with pore sizes of 20 μm and 11 μm . The dispensing process itself is carried out using the laboratory print head “Gecko” [31] equipped with 15 parallel nozzles with an average diameter of $d_n = 22 \mu\text{m}$. Process pressure and speed vary depending on the stability of the printing process and the paste level in the reservoir between 3.0 and 4.3 bar setting pressure and 300–450 mm/s printhead velocity. The distance between nozzle and substrate is 300 μm . All cells are dried in an inline oven at a temperature of $T = 200^\circ \text{C}$ for $t = 1 \text{ min}$. Subsequently, a firing variation with peak set temperatures $T_1 = 770^\circ \text{C}$, $T_2 = 790^\circ \text{C}$ and $T_3 = 810^\circ \text{C}$ is applied for both variants (resulting in 3 groups per metallization technique). Prior to the *current-voltage* (*I-V*) characterization on the cell tester, the cells are treated with the LECO (Laser Enhanced Contact Optimization) process [32]. The

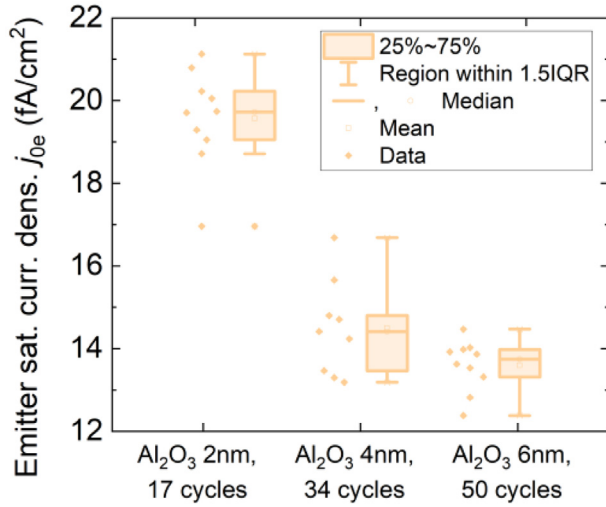


Fig. 4. Emitter saturation current density j_{oe} for three different Al_2O_3 layer thicknesses.

finger geometry of the dispensed and screen-printed front side metallization is analyzed using an *Olympus LEXT* laser-scanning confocal microscope and the image analysis software “Dash” [33] which has been developed at *Fraunhofer ISE*.

2.4 Microscopic analysis of *Tape Solution* interconnection

Focusing on the interconnection and module fabrication using TOPCon solar cells, we evaluate the interconnection properties of the *Tape Solution* approach on TOPCon solar cells using optical microscopy on cross-section samples.

2.5 Analysis and comparison of full-format modules with *Tape Solution* and ECA interconnection

In a further step, full-format modules with all *Tape Solution* and ECA interconnection technologies are produced using screen-printed busbarless TOPCon cells fabricated at *Fraunhofer ISE* as described in Section 2.2. The strings for the *Tape Solution* interconnection are manufactured utilizing the *Tape Solution* stringer and sent to *Fraunhofer ISE* afterwards for layup, lamination and characterization. ECA-based interconnection is performed on the *Team Technik* TT1600ECA stringer using a continuous ECA print layout and laterally conductive adhesive to enable a sufficient electron transport in the absence of a busbar without major resistance losses. Module production and characterization is realized at *Fraunhofer ISE*.

2.6 Cell-to-module loss analysis

To estimate the potential and the primary dissipation factors on module level, *Tape Solution*, ECA and additionally SWCT interconnection technologies are compared with a simulation application using the *SmartCalc* tool [30] developed at *Fraunhofer ISE*. As I - V input parameters for the cell, the measured I - V results

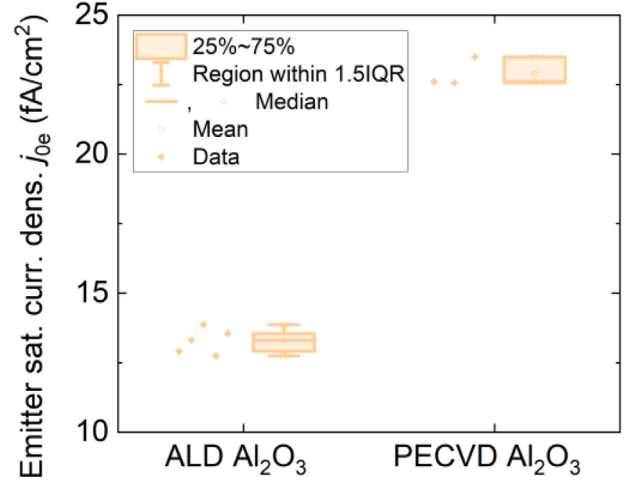


Fig. 5. Emitter saturation current density j_{oe} for the non-contacted, passivated solar cell front for two different deposition methods of the Al_2O_3 layer.

of fabricated TOPCon cells with busbarless layout and screen-printed metallization from the previous experiments are used.

3 Results and discussion

3.1 Evaluation of atomic layer deposition for the passivation of TOPCon solar cells

Using the ALD process developed in “BUSSARD”, we achieve a deposition rate of 0.13 nm per cycle and a refractive index of 1.64, both of which are typical values for Al_2O_3 . The thickness homogeneity variation is less than 2.5% on the wafer and about 2.3% on the boat which is more than acceptable for our needs. First results reveal the formation of bubbles as a result of gas bubbles at the interface between the Si layers within the passivation layer after the contact firing process. These bubbles lead to optical and passive failure of the coated layer.

Figure 4 plots the emitter saturation current density j_{oe} for three Al_2O_3 layer thicknesses. In the case of thick Al_2O_3 layers (6 nm), bubble formation is observed after firing while in the case of low Al_2O_3 layer thickness (2 nm) j_{oe} increases. Small j_{oe} values are obtained at an Al_2O_3 layer thickness of 4 nm, while no bubble formation is observed. Thus, it is the preferred option for further processing.

Figure 5 shows the emitter saturation current density j_{oe} of the implemented ALD deposition process and the PECVD (plasma enhanced chemical vapor deposition) reference process determined after SiN_x surface layer deposition and firing step activation. The results clearly show the advantages of the ALD approach with a reduction in emitter saturation current density from about $j_{oe, \text{PECVD}} = 23 \text{ fA/cm}^2$ (PECVD) to $j_{oe, \text{ALD}} = 13 \text{ fA/cm}^2$ (ALD) which corresponds to a reduction of more than 40%. This is particularly relevant for the cell performance as the majority of recombination losses typically occurs on the front side, where the passivated surface accounts for about 94–95% of the total area, and thus a significant reduction of j_{oe} will result in a large increase in V_{oc} .

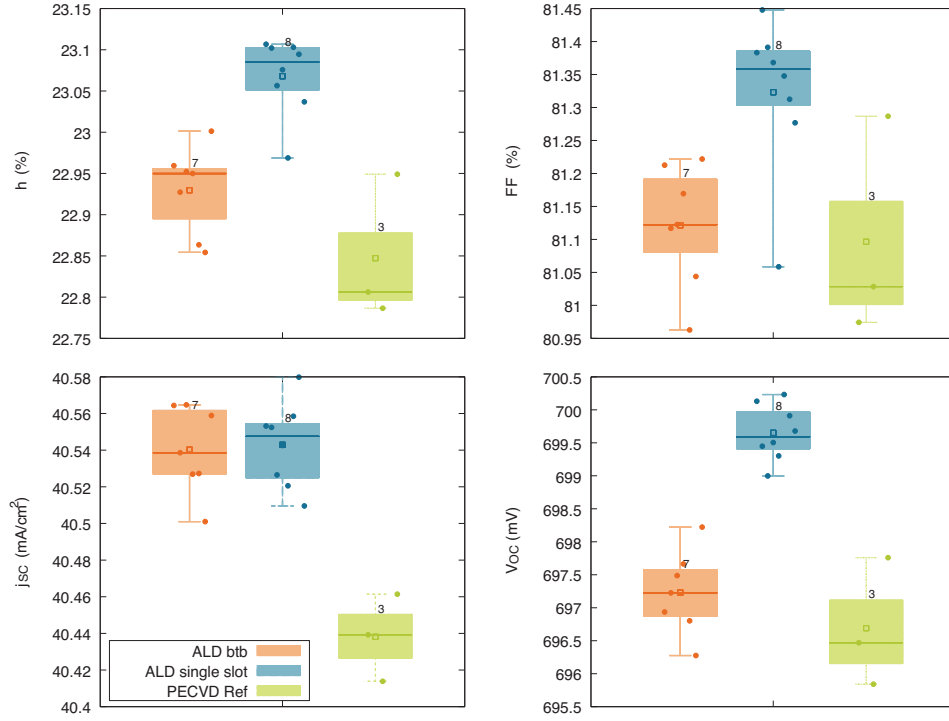


Fig. 6. I - V results of the TOPCon solar cells with varying front side passivation, measured on an industrial cell tester after contact optimization (LECO). The area of the solar cells is 244 cm^2 .

3.2 Fabrication of TOPCon solar cells with ALD passivation

TOPCon solar cells with ALD front-side passivation are fabricated using the developed process as presented in the previous section. The I - V results are shown in Figure 6. Even with at this early stage of development, the ALD process shows a significant increase in efficiency compared to the PECVD reference process. This results from an increase in the open circuit voltage V_{oc} and the fill factor FF. The increase in efficiency is in the order of 0.2 to 0.3%_{abs} which corresponds to a gain of roughly 1%_{rel}. The highest efficiencies are achieved when the samples are positioned in a single-slot configuration for the ALD process. It is known from literature that Al_2O_3 layers deposited on TOPCon layers can improve hydrogenation during thermal activation, which could be a reason for the increased V_{oc} compared to btb positioning [34]. Another possible explanation is a reduced contact formation due to the Al_2O_3 layer on the back, thus reducing metallization related recombination. A btb configuration of the samples is generally beneficial with regard to throughput, and the shown benefit here for single slot placement of the wafers and thus an Al_2O_3 layer on the rear side could also be achieved for btb loading and adaption of the process parameters during rear SiN_x layer deposition.

In a further follow-up experiment, improved process parameters are used to fabricate TOPCon solar cells. These solar cells are metallized using state-of-the-art metallization screens and pastes. Within this experiment, the efficiency of the solar cells could be increased even

further, to 23.5%. The improved parameters for ALD Al_2O_3 (single slot placement of wafers) and outgassing are once again confirmed. Furthermore, the basic process for solar cell production is further optimized, including the partial improvements for the solar cell front side passivation. This results in a new internal solar cell record for large-area TOPCon solar cells (M2 format) with screen-printed contacting of $\eta_{\max} = 24.2\%$ (champion cell, result confirmed by Fraunhofer ISE CalLab PV Cells) – see Table 1.

At the time of the experiment, our lab was able to process wafer up to M4 size. Currently, Fraunhofer ISE is upgrading all tools and processes to the larger M10 size, which is the dominating format at this point, and we expect this process to be finished by end of 2024. The overall findings described in this paper should be independent from the actual wafer size. As far as overall efficiency levels are concerned, compared to average production efficiencies in industry, we trail about 1% efficiency absolute, and we work on reducing this gap by process optimizations.

3.3 Fine-line metallization of TOPCon solar cells using parallel dispensing

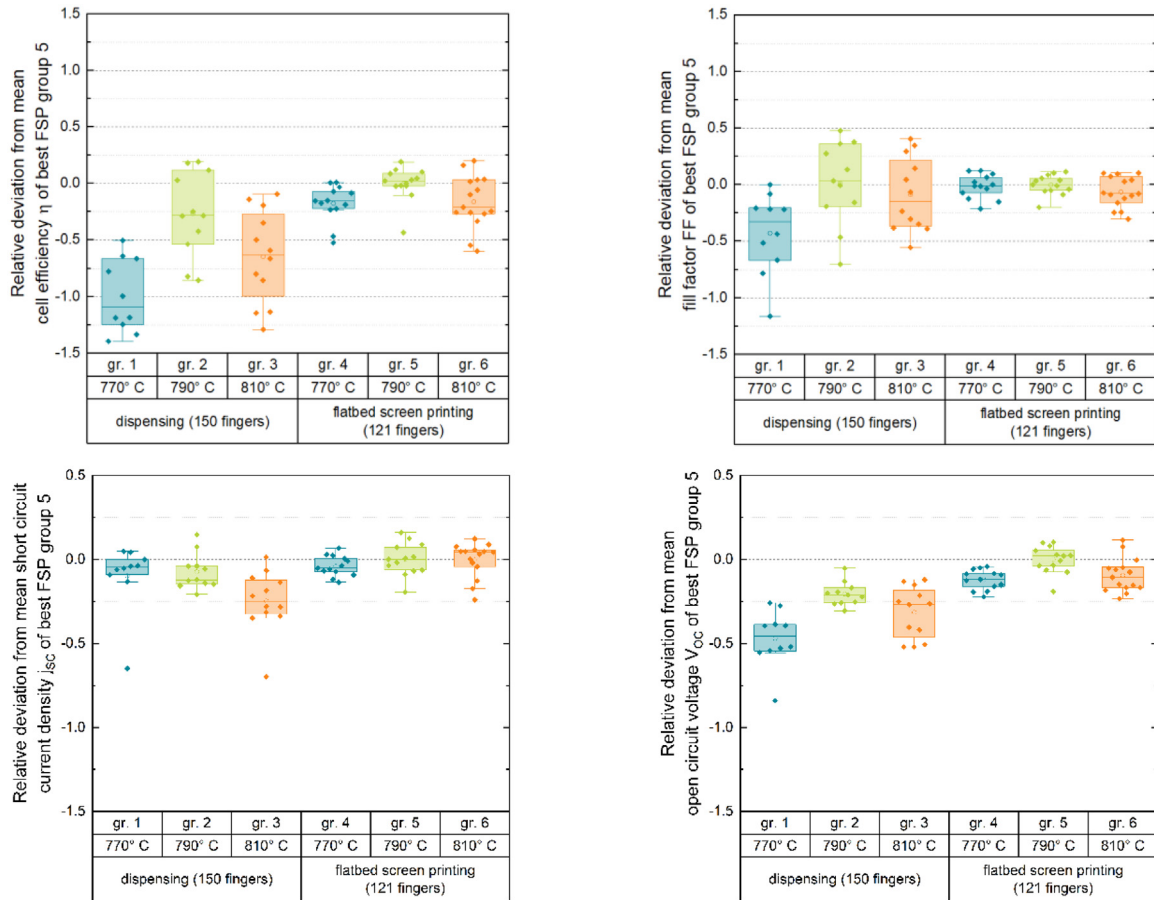
The TOPCon solar cells with dispensed and screen-printed front side metallization are successfully metallized, processed and analyzed regarding I - V results and finger geometry. Both variants obtain the best results at a medium peak set firing temperature of $T_2 = 790 \text{ }^\circ\text{C}$. The I - V parameters of the finalized TOPCon cells are shown in Table 2 and Figure 7.

Table 1. I - V measurement of the champion TOPCon solar cell fabricated at Fraunhofer ISE, confirmed by Fraunhofer ISE CalLab PV Cells.

	V_{OC} [mV]	j_{SC} [$\text{mA} \cdot \text{cm}^{-2}$]	FF [%]	η [%]	Area [cm^2]
Champion Cell	714.4	41.4	81.7	24.2	244.5

Table 2. Comparison of I - V data for the two champion groups with highest conversion efficiency metallized with parallel dispensing and screen-printing.

Front side metallization	# fingers	V_{OC} [mV]	j_{SC} [$\text{mA} \cdot \text{cm}^{-2}$]	FF [%]	η [%]
Screen-printing (Group 5)	121	708.8 ± 0.6	40.81 ± 0.04	80.5 ± 0.1	23.30 ± 0.04
Dispensing (Group 2)	150	707.4 ± 0.5	40.78 ± 0.04	80.6 ± 0.3	23.24 ± 0.09

**Fig. 7.** I - V results of all experimental groups using dispensing and flatbed screen-printing for the front side metallization. The varying number of contact fingers in the front side grid layout for dispensing and screen-printing has to be considered when comparing the two variants.

The champion dispensing group obtains an average conversion efficiency of $\eta_{DIS} = (23.24 \pm 0.09)\%$ while the screen-printed pendant achieves an average efficiency of $\eta_{FSP} = (23.30 \pm 0.04)\%$. The best cells of both technologies obtain a similar efficiency of $\eta_{max} = 23.35\%$. Regarding the fill factor FF , an average $FF_{DIS} = 80.6 \pm 0.3\%$ (dispensing) and $FF_{FSP} = 80.5 \pm 0.1\%$ (screen-printing) is obtained. It is

further obvious that the deviation of the results is significantly higher for the dispensing groups compared to the screen-printed reference groups. It is likely that this effect is caused by the instability of the utilized “Gecko” dispensing setup with a laboratory print head, which leads to several finger interruptions on individual cells. The potential for dispensing is shown by analyzing a cell with

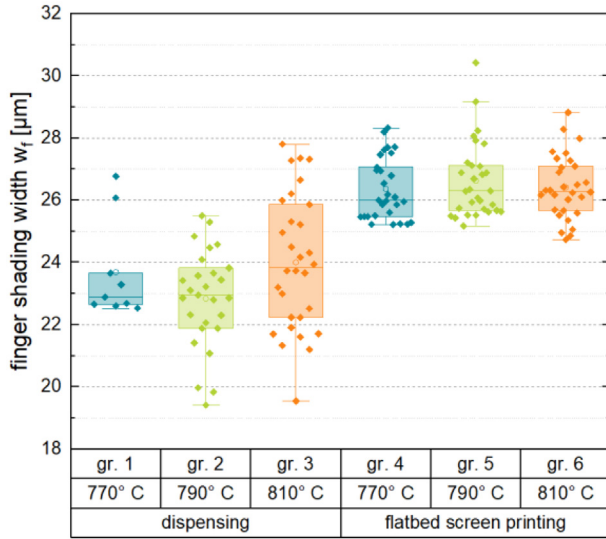


Fig. 8. Shading finger width w_f of the experimental groups. It is clearly visible that the dispensing groups 1–3 obtained smaller finger widths.

100% print quality for dispensing. This cell achieves a maximum FF of $FF_{DIS,max} = 80.93\%$ which corresponds to a gain of $0.28\%_{abs}$ compared to the highest FF of the SD reference cells. This individual result underlines the advantage of the very uniform finger geometry of parallel dispensed contacts.

Looking at the results achieved for V_{oc} and j_{sc} , it must be taken into account that both variants (dispensing and screen-printing) were metallized with a different number of fingers and set finger widths as well as different pastes (see experimental section). Despite the higher amount of contact fingers for group 1–3, short-circuit current density j_{sc} does not differ significantly for both pastes and technologies ($j_{sc,DIS} = (40.75 \pm 0.07) \text{ mA/cm}^2$ and $j_{sc,FSP} = (40.81 \pm 0.04) \text{ mA/cm}^2$). The smaller average finger width of the dispensed contacts roughly compensates for the higher number of fingers, so that the total metallized area is in a similar range. Considering the open circuit voltage V_{oc} , slightly lower level is obtained for the dispensing groups 1–3 compared to the screen-printing reference (group 4–6). It is assumed that the cause of this deviation is a varying degree of metallization-related recombination $j_{0,met}$ of paste A and B after contact firing.

Figures 8, 9 and Table 3 show the results of the finger geometry analysis. The optical characterization of the contact finger geometry reveals a substantially narrower mean shading finger width $w_{f,DIS} = 23.5 \pm 1.9 \mu\text{m}$ for the dispensed front side grids compared to the screen-printed grid ($w_{f,FSP} = 26.4 \pm 1.1 \mu\text{m}$). However, the dispensed contact fingers show major deviations, which are likely caused by printing parameter adjustments during printing. The need for these parameter adjustments lies in a non-optimal combination of paste properties, nozzle diameter and pre-filtration for the addressed process. It is likely that substantially smaller contact fingers can be obtained when applying a stable dispensing process (i.e., with an industrial dispensing printhead using optimal parameters). The potential of an optimized, reproducible dispensing process

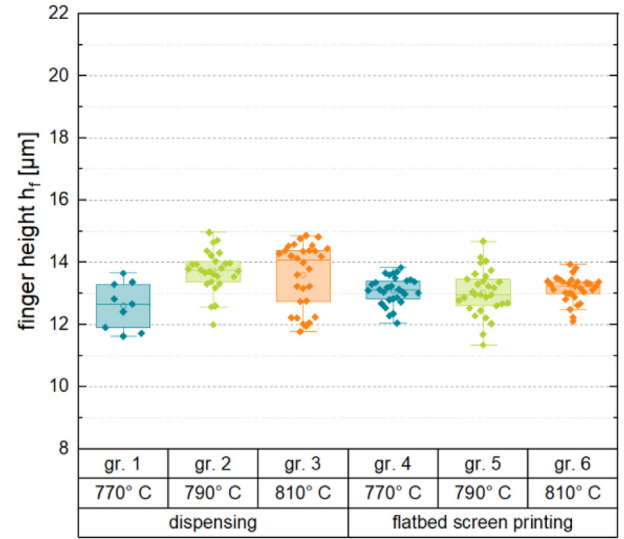


Fig. 9. Finger height h_f of the experimental groups. Both variants (dispensing and screen-printing) obtained comparable results.

can be estimated by considering the smallest measured finger width (to $w_{f,DIS,min} = 19 \mu\text{m}$) compared to screen-printing ($w_{f,FSP,min} = 25 \mu\text{m}$).

The results of this experiment demonstrate the feasibility of parallel dispensing for the front side metallization of TOPCon solar cells for the first time and prove the competitiveness with an industrial screen-printing process. It should be considered that the obtained results are limited in terms of stability and reproducibility due to the utilized laboratory setup. Furthermore, the number of front-side contacts selected for the dispensing process is not optimized. Thus, it is very likely that parallel dispensing will achieve substantially higher conversion efficiencies if both aspects would be optimized towards cell performance. Nevertheless, achieving comparable results to FSP with this setup underlines the potential of the dispensing process for the front-side metallization of TOPCon solar cells.

3.4 Microscopic analysis of Tape Solution interconnection

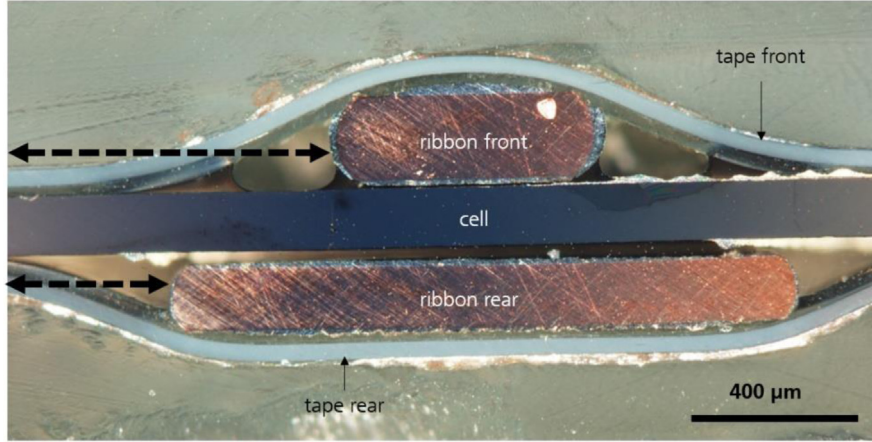
Figure 10 shows a microscopic image of the cross-section of a *Tape Solution* interconnection on a TOPCon solar cell. The width of the tape is the same for the front and back, although the connector widths differ greatly – $0.5 \text{ mm} \times 0.25 \text{ mm}$ at the front and $1.5 \text{ mm} \times 0.2 \text{ mm}$ at the back. On the front side, where the connectors are significantly narrower, the interaction surface between the tape and the cell is larger which is likely to contribute to a better adhesion.

3.5 Full-format module integration with Tape Solution and ECA interconnection

Using TOPCon solar cells manufactured at Fraunhofer ISE, full format TOPCon modules with *Tape Solution* and ECA interconnection technologies were fabricated (Fig. 11). The Al_2O_3 layer was formed by ALD, placing

Table 3. Evaluation of the geometry data of dispensed and screen-printed metal contacts on the front of TOPCon solar cells. Mean values and standard deviations are presented.

Variation	Avg. finger width w_f [μm]	Avg. finger height h_f [μm]	Avg. cross-section area A_f [μm^2]
Screen-printing	26.5 ± 1.1	13.1 ± 0.6	197 ± 10
Dispensing	23.4 ± 1.9	13.5 ± 0.9	210 ± 24

**Fig. 10.** Cross-section view of a cell with *Tape solution* interconnection. The width of the ribbon connector differs substantially on the front and rear side which might be an explanation for the difference of F_p .

the wafers single-slot. The results of the I - V measurement after lamination shows differences between the interconnection approaches (Fig. 12). The full-format module with ECA interconnection demonstrates the peak power of $P_{\text{MPP}} = 340.0 \text{ W}$, corresponding to the experimental cell-to-module change (CTM) of +2.1%. The gain in P_{MPP} is most likely to be attributed to the use of structured interconnectors that promote I_{SC} increase by redirecting the incoming light within the module instead of reflecting it [28]. The module with *Tape Solution* interconnection shows a peak power of $P_{\text{MPP}} = 332.9 \text{ W}$, which corresponds to 0% CTM losses after module production. This demonstrates the general suitability of the *Tape Solution* interconnection technology for busbarless TOPCon cells.

Closer look in the experimental cell-to-module values reveal, that both technologies result in I_{SC} gain (+2.8% and +4.0% for *Tape Solution* and ECA, respectively). The +2.8% I_{SC} gain for *Tape Solution* is most likely attributed to the optical properties of the interconnector carrying polymer tapes, whereas +4.0% is due to the light-capturing structure at the surface of the ribbons utilized for the ECA interconnection. As for the fill factor, *Tape Solution* and ECA show FF loss of -3.2% and -1.9%, respectively. Both approaches used 5 busbars on identically metallized cells, which means that the generated current travels the same distance through the fingers with identical electrical characteristics (line resistance R_{LINE}) causing same resistivity effect. The joint resistivity and, as a result, series resistance must however be higher for *Tape Solution* than ECA module, judging from the FF loss difference.

3.6 Results of the cell-to-module loss analysis

Figure 13 shows the results of the simulated cell-to-module analysis for the three considered interconnection technologies carried out with the SmartCalc[®] tool developed at Fraunhofer ISE. I - V characteristics of the busbarless TOPCon cells produced at Fraunhofer ISE and utilized for the fabrication of the full-format modules were used as a key input. Other inputs included geometric, optical and electrical characteristics of the module components (cell, interconnectors, encapsulation polymer, rear side foil and front glass) as well as their interplay. The most significant differences between the interconnection technologies are identified in interconnection shading (Fig. 13, factor k7), coupling of cell and encapsulant (Fig. 13, factor k8) and interconnector coupling (Fig. 13, factor k10). The 1 mm wide connectors in ECA cause the most shading from the photoactive cell surface. Factor k8 shows how the short-circuit current (I_{SC}) of the cell changes after interconnection and encapsulation (without considering the glass). Here, ECA and *Tape Solution* have significantly higher values than SWCT due to structured ribbons and optical properties of the ribbon bearing polymer tape, respectively. Factor k10 takes the effective width of the connector into account which in this case underlines SWCT due to the advantageous round wires.

Comparing the results of the simulation with the I - V characteristics of the full-format modules it is clear, that the simulation overestimates the losses connected with cell interconnection and module integration. According to the

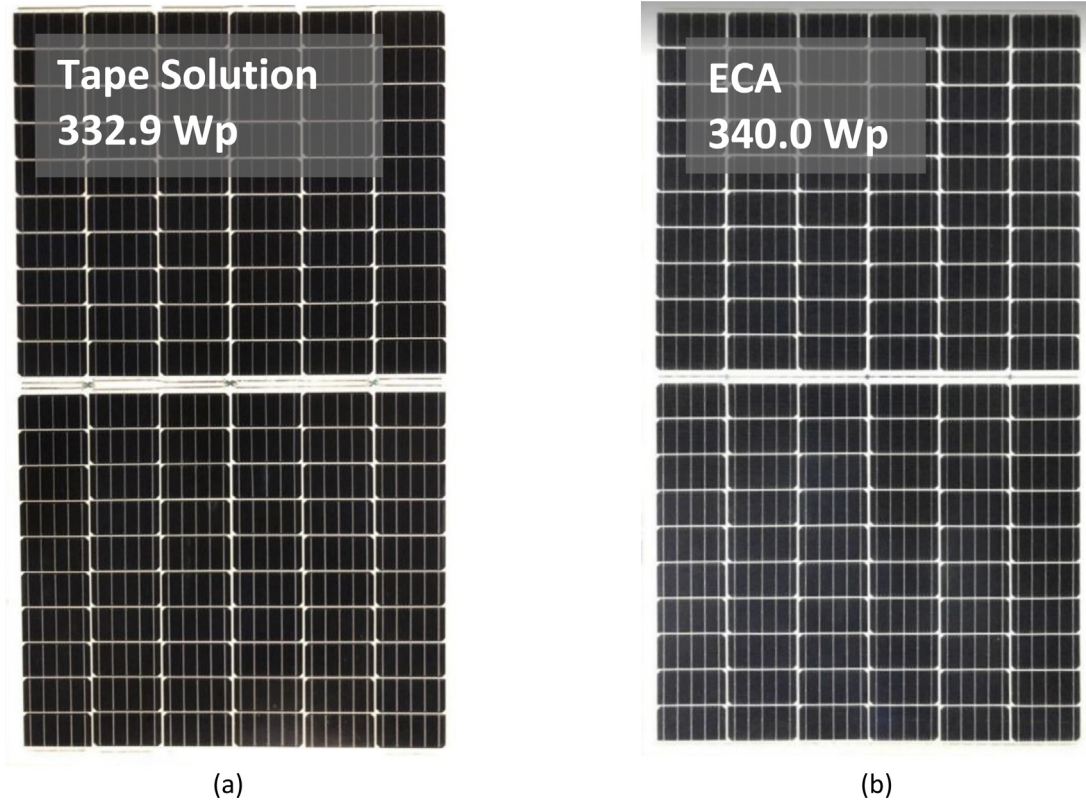


Fig. 11. Full-format modules with (a) *Tape Solution* and (b) ECA-interconnected busbarless TOPCon cells, produced at Fraunhofer ISE. Modules feature “butterfly” design with 120 half-cells each.

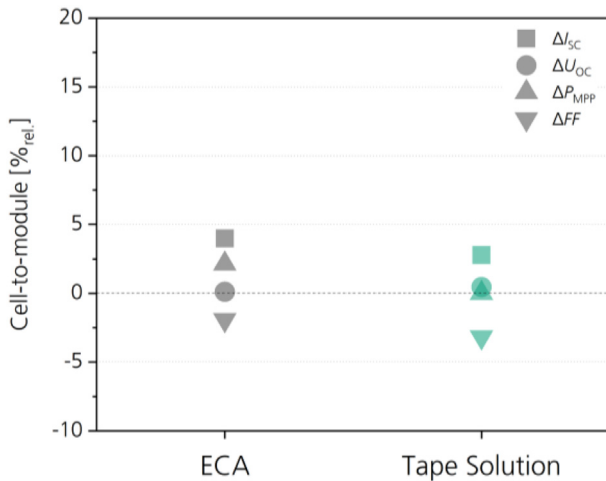


Fig. 12. Experimental cell-to-module change in I - V parameters after the fabrication of the full-format modules with Ise-produced busbarless TOPCon cells.

simulation, *Tape Solution* module with busbarless TOPCon cells would result in 324.1 W (against real-life 332.9 W) and ECA module has the potential of reaching 330.1 W (while in fact measuring 340.0 W). Such discrepancy is most likely due to assumptions regarding the optical properties (reflectance and transmission) of the encapsulation polymer used.

4 Conclusion

Within this work, we developed and investigated several innovative approaches for the industrial fabrication of high-efficiency TOPCon solar cells and modules. With respect to the frontend processing of TOPCon solar cells, we implemented an atomic layer deposition (ALD) process as an alternative to the PECVD deposition reference process. We investigated the feasibility and performance of ALD as an alternative method for the Al_2O_3 passivation of the front p^+ boron emitter. We identified an Al_2O_3 layer thickness of 4 nm as being optimal for a low emitter saturation current density on the one hand and a homogeneous deposition (no blistering) on the other hand. Using a corresponding process, we demonstrated a substantially lower emitter saturation current density of $j_{oe,ALD} = 13 \text{ fA/cm}^2$ for the ALD-deposited Al_2O_3 compared to the PECVD-deposited passivation layer with $j_{oe,PECVD} = 23 \text{ fA/cm}^2$. Thus, it is shown that the ALD process has substantial benefits with respect to the performance of the passivation layer as well as the throughput rate of the process. Using an optimized process sequence, TOPCon solar cells with ALD passivation have been fabricated and achieved a champion efficiency of $\eta_{max} = 24.2\%$ (confirmed by Fraunhofer ISE CalLab PV Cells). In the field of fine-line metallization of TOPCon solar cells, three innovative approaches (FlexTrail, dispensing and indirect gravure printing) have been evaluated. Within this work, we focused on multi-nozzle parallel dispensing which has been

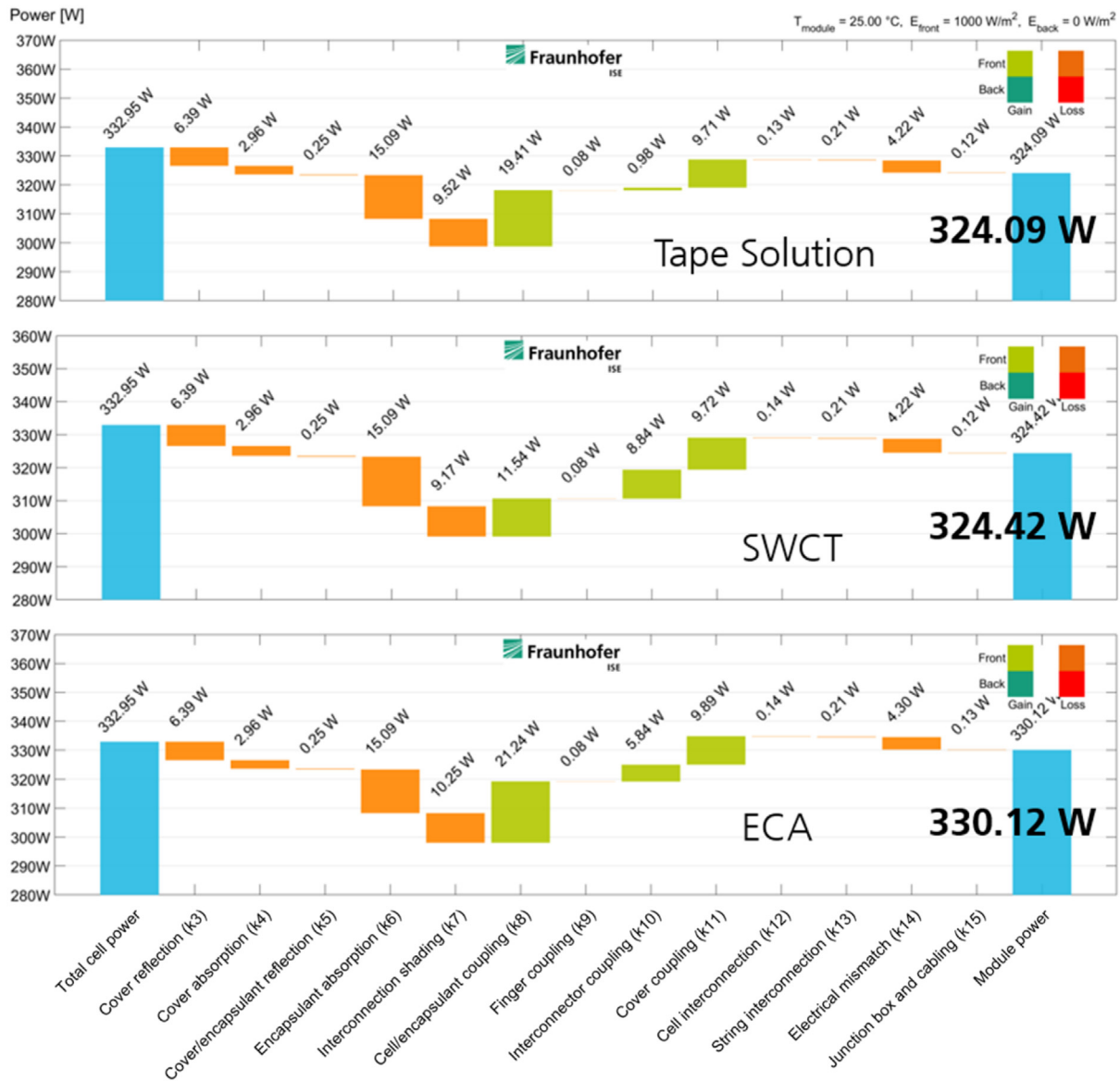


Fig. 13. Cell-to-module analysis for *Tape Solution*, SWCT and ECA interconnection technologies performed with SmartCalc[®] tool in combination with busbarless TOPCon cells fabricated at Fraunhofer ISE in this work.

applied for the first time for TOPCon solar cells. The group of TOPCon cells with dispensed front side contacts and optimal firing conditions obtained a similar average conversion efficiency as reference cells with screen-printed metallization. The champion efficiency of solar cells metallized with both technologies is exactly on the same level. Considering that a laboratory printhead has been used which does not provide the same quality and stability as an industrial printhead it is likely that parallel dispensing has the potential to obtain substantially better results compared to screen-printing. Previous work has also shown that dispensing is able to reduce the silver consumption on the front side compared to screen-printing while allowing also even higher conversion efficiencies. Focusing on interconnection and module fabrication, the innovative *Tape Solution* approach has been evaluated

and compared to established interconnection technologies (Smart Wire Connection Technology and electrically conductive adhesive). Full-format modules have been fabricated and compared. Here, a module with ECA interconnection obtained the champion power result with $P_{MPP} = 340.0$ W while the module with *Tape Solution* demonstrated the P_{MPP} of 332.9 W. An additional simulation of the theoretical cell-to-module loss factors with SmartCalc[®] underlined the potential of *Tape Solution* as a suitable interconnection approach alongside SWCT and ECA for the fabrication of modules with busbarless TOPCon cells. Further optimization of *Tape Solution* approach should include incorporation of larger amounts of interconnectors to lower series resistance losses and the reduction of the wire dimensions to minimize cell shading. In summary, we successfully demonstrated several

innovative approaches for the front side passivation, metallization and interconnection of industrial TOPCon solar cells which have the potential to substantially increase the performance on cell and module level and in parallel reduce the production costs (e.g., less silver), the total cost of ownership (TCO) as well as the levelized cost of electricity (LCoE).

Acknowledgments

This work has been done within the research project “BUSSARD” which was partly funded under the umbrella of SOLAR-ERA.NET Cofund by German Federal Ministry for Economic Affairs and Energy under contract number 03EE1071A. SOLAR-ERA.NET was supported by the European Commission within the EU Framework Programme for Research and Innovation HORIZON 2020 (Cofund ERA-NET Action, Grant Agreement No. 786483). The authors would like to thank Tempres Systems B.V. for support and fruitful discussions as well as all co-workers at Fraunhofer ISE who have been involved in this work.

Funding

This work has been done within the research project “BUSSARD” which was partly funded under the umbrella of SOLAR-ERA.NET Cofund by German Federal Ministry for Economic Affairs and Energy under contract number 03EE1071A. SOLAR-ERA.NET was supported by the European Commission within the EU Framework Programme for Research and Innovation HORIZON 2020 (Cofund ERA-NET Action, Grant Agreement No. 786483).

Conflicts of interest

We hereby confirm that there are no known conflicts of interest associated with this publication and that there was no significant financial support for this work that could have influenced its outcome.

Data availability statement

This article has no associated data generated and data associated with this article cannot be disclosed due to other reason.

Author contribution statement

Conceptualization, J. Schube, V. Nikitina, S. Mack, J. Buddgard, S. Schweigert and A. Lorenz; Methodology, V. Nikitina, J. Schube, S. Mack, J. Buddgard, J. Albrecht and S. Schweigert; Validation, V. Nikitina, J. Schube, S. Mack and S. Schweigert; Formal Analysis, J. Schube, V. Nikitina, S. Mack and S. Schweigert; Investigation, V. Nikitina, J. Schube, S. Mack, J. Buddgard, J. Albrecht and S. Schweigert; Writing – Original Draft Preparation, A. Lorenz; Writing – Review & Editing, J. Schube, V. Nikitina, S. Mack, M. Pospischil and S. Schweigert; Visualization, V. Nikitina, J. Schube, S. Mack and S. Schweigert; Supervision, A. Lorenz, J. Schube; Project Administration, A. Lorenz, J. Schube, A. Kraft, A. Wolf and M. Hermle; Funding Acquisition, F. Clement, A. Wolf and A. Kraft.

References

1. J. Schmidt, R. Peibst, R. Brendel, Surface passivation of crystalline silicon solar cells: present and future, *Sol. Energy Mater. Sol. Cells* **187**, 39 (2018). <https://doi.org/10.1016/j.solmat.2018.06.047>
2. M. Hermle, F. Feldmann, M. Bivour, J.C. Goldschmidt, S.W. Glunz, Passivating contacts and tandem concepts: Approaches for the highest silicon-based solar cell efficiencies, *Appl. Phys. Rev.* **7**, 21305 (2020). <https://doi.org/10.1063/1.5139202>
3. ITRPV, International Technology Roadmap for Photovoltaics (ITRPV): Results 2022, 14th edn. (2023)
4. S.W. Glunz, B. Steinhauser, J.-I. Polzin, C. Luderer, B. Grübel, T. Niewelt, A.M.O.M. Okasha, M. Bories, H. Nagel, K. Krieg, F. Feldmann, A. Richter, M. Bivour, M. Hermle, Silicon-based passivating contacts: the TOPCon route, *Prog. Photovolt.: Res. Appl.* **31**, 341 (2023). <https://doi.org/10.1002/pip.3522>
5. E. Bellini, Jolywood claims 26.7% efficiency for n-type TOPCon solar cell, *PV Magazine*, 2023. <https://www.pv-magazine.com/2023/04/12/jolywood-claims-26-7-efficiency-for-n-type-topcon-solar-cell/#:~:text=The%20China%20Academy%20of%20Metrology,rating%20for%20a%20similar%20cell>. (accessed 26 April 2024)
6. F. Feldmann, B. Steinhauser, T. Pernau, H. Nagel, T. Fellmeth, S. Mack, D. Ourinson, E. Lohmüller, J. Polzin, A. Moldovan, M. Bivour, F. Clement, J. Rentsch, M. Hermle, S. Glunz, Industrial TOPCon solar cells realized by a PECVD tube process, in *Proc. of the 37th European Photovoltaic Conference (EUPVSEC)* (Virtual Conference, 2020)
7. B. Hoex, J. Schmidt, R. Bock, P.P. Altermatt, M.C.M. van de Sanden, W.M.M. Kessels, Excellent passivation of highly doped p-type Si surfaces by the negative-charge-dielectric Al₂O₃, *Appl. Phys. Lett.* **91**, 112107 (2007). <https://doi.org/10.1063/1.2784168>
8. A. Richter, M. Hermle, S.W. Glunz, Reassessment of the limiting efficiency for crystalline silicon solar cells, *IEEE J. Photovoltaics* **3**, 1184 (2013). <https://doi.org/10.1109/JPHOTOV.2013.2270351>
9. S. Tepner, A. Lorenz, Printing technologies for silicon solar cell metallization: a comprehensive review, *Prog. Photovolt.: Res. Appl.* **31**, 557 (2023). <https://doi.org/10.1002/pip.3674>
10. A. Lorenz, M. Linse, H. Frintrup, M. Jeitler, A. Mette, M. Lehner, R. Greutmann, H. Brocker, M. König, D. Erath, F. Clement, Screen printed thick film metallization of silicon solar cells – recent developments and future perspectives, in *Proc. of the 35th Photovoltaic Solar Energy Conference (EUPVSEC)* (Brussels, Belgium, 2018), pp. 819–824
11. J. Schube, M. Jahn, S. Pingel, A. de Rose, A. Lorenz, R. Keding, F. Clement, FlexTrail printing as direct metallization with low silver consumption for silicon heterojunction solar cells: evaluation of solar cell and module performance, *Energy Technol.* **10**, 2200702 (2022). <https://doi.org/10.1002/ente.202200702>
12. J. Schube, M. Klawitter, M. Linse, J. Schleuniger, I. Kegel, S. Toguem Fokoua, D. Gurovich, S. Melamed, F. de La Vega, M. Mäser, O. Mürdter, L. Englisch, F. Clement, A. Lorenz, High-throughput indirect gravure printing applied to low-temperature metallization of silicon-based high-efficiency solar cells, *Energy Technol.* **12**, 2400066 (2024)

13. M. Pospischil, M. Kuchler, M. Klawitter, I. Lacmago Lontchi, S. Tepner, R. Efinger, M. Linse, D. Witt, S. Gutscher, A. Brand, M. König, L. Wende, F. Clement, D. Biro, High Speed Dispensing – A High-Throughput Metallization Technology for >21% PERC Type Solar Cells, in *Proc. of the 32nd Photovoltaic Solar Energy Conference (EUPVSEC)* (Munich, Germany, 2016), pp. 403–406
14. S. Pordan, M. Mosig, F. Heitmann, M. Palme, N. Heuser, M. Weil, R. Steffens, O. Zuaiter, M. Kuchler, M. Pospischil, Optimizing solar cell metallization by parallel dispensing, *Sol. Energy Mater. Sol. Cells* **266**, 112685 (2024). <https://doi.org/10.1016/j.solmat.2023.112685>
15. J. Specht, K. Zengerle, M. Pospischil, D. Erath, J. Haunschild, F. Clement, D. Biro, High aspect ratio front contacts by single step dispensing of metal pastes, in *Proc. of the 25th Photovoltaic Solar Energy Conference (EUPVSEC)* (Valencia, Spain, 2010), pp. 1867–1870
16. M. Pospischil, M. Klawitter, M. Kuchler, J. Specht, H. Gentischer, R. Efinger, C. Kroner, M. Luegmair, M. König, M. Hörteis, C. Mohr, L. Wende, J. Lossen, M. Weiß, O. Doll, I. Koehler, R. Zengerle, F. Clement, D. Biro, Process development for a high-throughput fine line metallization approach based on dispensing technology, *Energy Procedia* **43**, 111 (2013). <https://doi.org/10.1016/j.egypro.2014.02.001>
17. M. Pospischil, T. Riebe, A. Jimenez, M. Kuchler, S. Tepner, T. Geipel, D. Ourinson, T. Fellmeth, M. Breitenbücher, T. Buck, M. Dhamrin, F. Clement, Applications of parallel dispensing in PV metallization, *AIP Conf. Proc.* **2156**, 20005 (2019)
18. M. Pospischil, M. Kuchler, M. Klawitter, C. Rodríguez, M. Padilla, R. Efinger, M. Linse, A. Padilla, H. Gentischer, M. König, M. Hörteis, L. Wende, O. Doll, R. Zengerle, F. Clement, D. Biro, Dispensing technology on the route to an industrial metallization process, *Energy Procedia* **67**, 138 (2015). <https://doi.org/10.1016/j.egypro.2015.03.297>
19. K. Gensowski, M. Much, E. Bujnoch, S. Spahn, S. Tepner, F. Clement, Filament stretching during micro-extrusion of silver pastes enables an improved fine-line silicon solar cell metallization, *Sci. Rep.* **12**, 12318 (2022). <https://doi.org/10.1038/s41598-022-16249-5>
20. K. Gensowski, M. Much, M. Palme, A.M. Jimenez, E. Bujnoch, K. Muramatsu, S. Tepner, F. Clement, Filament stretching during parallel dispensing – a way to reduce silver consumption in SHJ metallization, *Sol. Energy Mater. Sol. Cells* **245**, 111871 (2022). <https://doi.org/10.1016/j.solmat.2022.111871>
21. M. Pospischil, J. Meda, M. Mosig, N. Heuser, F. Heitmann, S. Molinero, C. Djimegou, M. Weil, E. Milione, I. Lacmago, T. Müller, K. Gensowski, E. Bujnoch, A. Jimenez, S. Pingel, S. Tepner, F. Clement, M. Kuchler, M. Breitenbücher, Fully automated intermittent parallel dispensing, in *10th Metallization and Interconnection Workshop* (Genk, Belgium, 2021)
22. J. Buddgård, T. Lagerstedt, A. Machirant, Tape Interconnection for Silicon Solar Cells with Extended Long-Term-Stability (2018), Source: <https://jbecotech.se/wordpress/wp-content/uploads/2018/04/Article-Tape-interconnection-for-silicon-solar-cells-with-long-term-stability.pdf>, [Accessed: 6.01.2024]
23. StickySolarPower, The Tape Solution, 2024. <https://www.stickysolarpower.com/the-tape-solution/> (accessed 20 June 2024)
24. J. Buddgård, T. Lagerstedt, A. Machirant, Tape interconnection for silicon solar cells with extended long-term stability, in *Proc. of the 33rd Photovoltaic Solar Energy Conference (EUPVSEC)* (Amsterdam, Netherlands, 2017)
25. J.R. Davis, Aluminum and Aluminum Alloys, in *ASM Specially Handbook* (ASM International, 1993)
26. T. Söderström, P. Papet, Y. Yao, J. Ufheil, SmartWire Connection Technology (2014)
27. T. Geipel, U. Eitner, Electrically conductive adhesives: An emerging interconnection technology for high-efficiency solar modules, *Photovolt. Int.* **21**, 27 (2013)
28. T. Geipel, V. Nikitina, L. Pitta Bauermann, E. Fokuhl, E. Schnabel, D. Erath, A. Krieg, A. Kraft, T. Fischer, R. Lorenz, D. Breitenbücher, Industrialization of ribbon interconnection for silicon heterojunction solar cells with electrically conductive adhesives, in *Proc. of the 36th Photovoltaic Solar Energy Conference (EUPVSEC)* (Marseille, France 2019)
29. H.J. Lewis, F.M. Coughlan, An overview of the use of electrically conductive adhesives (ECAs) as a solder replacement, *J. Adhes. Sci. Technol.* **22**, 801 (2008). <https://doi.org/10.1163/156856108X305543>
30. Fraunhofer ISE, SmartCalc[®]. <https://www.cell-to-module.com/> (accessed 19 January 2024).
31. M. Pospischil, M. Klawitter, M. Kuchler, J. Specht, H. Gentischer, R. Efinger, M. König, M. Hörteis, C. Mohr, L. Wende, J. Lossen, M. Weiss, O. Doll, I. Kohler, R. Zengerle, F. Clement, D. Biro, Development of a high-throughput fine line metallization process using CFD-simulation, in *Conference Records of 39th IEEE Photovoltaic Specialists Conference (PVSC)* (Tampa, FL, USA, IEEE, 2013), pp. 2250–2253
32. R. Mayberry, K. Myers, V. Chandrasekaran, A. Henning, H. Zhao, U.E. Hofmueller, Laser enhanced contact optimization (LECO) and LECO-Specific pastes: a novel technology for improved cell efficiency, in *Proc. of the 36th Photovoltaic Solar Energy Conference (EUPVSEC)* (Marseille, France, 2019)
33. T. Wenzel, A. Lorenz, E. Lohmüller, S. Auerbach, K. Masuri, Y.C. Lau, S. Tepner, F. Clement, Progress with screen printed metallization of silicon solar cells – towards 20 µm line width and 20 mg silver laydown for PERC front side contacts, *Sol. Energy Mater. Sol. Cells* **244**, 111804 (2022). <https://doi.org/10.1016/j.solmat.2022.111804>
34. G. Yang, B. van de Loo, M. Stodolny, G. Limodio, J. Melskens, B. Macco, P. Bronsveld, O. Isabella, A. Weeber, M. Zeman, W.M.M. Kessels, Passivation enhancement of poly-Si carrier-selective contacts by applying ALD Al₂O₃ capping layers, *IEEE J. Photovolt.* **12**, 259 (2022). <https://doi.org/10.1109/JPHOTOV.2021.3119595>

Cite this article as: Andreas Lorenz, Jörg Schube, Veronika Nikitina, Sebastian Mack, Sebastian Schweigert, Jonas Buddgard, Jonas Albrecht, Maximilian Pospischil, Achim Kraft, Andreas Wolf, Martin Hermle, Florian Clement, Project “BUSSARD” – a holistic development of high-efficiency solar cells covering innovative front-end, metallization and interconnection approaches, *EPJ Photovolt.* **16**, 6 (2025)