Inline Plating of Ni/Cu Contacts for Industrial TOPCon Si Solar Cells—Status and Outlook

Jonas Eckert, Sven Kluska, René Haberstroh, Christian Schmiga, Sebastian Mack, Mathias Kamp, Damian Brunner, Jan Nekarda, and Florian Clement

***Abstract*—This article explores an inline plating metallization technique aimed at reducing silver usage in the production of tunnel oxide passivated contact (TOPCon) silicon solar cells. Utilizing ultrashort-pulse UV laser patterning combined with electrochemical deposition of Ni, Cu, and Ag, this approach has successfully achieved efficiencies up to 24% with silver consumption reduced to 1.1 mg/Wp. The process has been applied using pilot line equipment developed by RENA Technologies GmbH. This work not only demonstrates the potential of inline plating for cost-effective solar cell manufacturing but also addresses industrially feasible mitigation strategies for challenges such as contact adhesion and process stability. These include strategies to avoid insufficient Ni nucleation and uneven plating current injection, which are critical for achieving low contact resistivity and high fill factors (FF). As a result, FF of (82.1 ± 0.3)% were demonstrated for a batch of 186 TOPCon solar cells (M10 wafer size). In addition, reliability tests on fabricated mini modules demonstrate promising resistance to degradation. This research advances TOPCon solar cell technology by providing deeper insights into the piloting of inline plating technology for cost-effective and silver-lean metallization of TOPCon solar cells.**

***Index Terms*—Copper, c-Si, laser ablation, metallization, plating, silver reduction, solar cell, tunnel oxide passivated contact (TOPCon).**

I. Introduction

THE ongoing demand for higher efficiency and lower production costs in silicon photovoltaics has driven the widespread adoption of advanced passivating contact technologies such as tunnel oxide passivated contact (TOPCon) solar cells [1]. TOPCon technology enables excellent surface passivation and high open-circuit voltages, establishing itself as a leading architecture for next-generation industrial silicon solar cells. However, one of the key challenges for large-scale TOPCon commercialization remains the high material costs and supply chain vulnerabilities associated with silver-based screen-printed metallization.

To address this issue, alternative metallization strategies that significantly reduce silver consumption while maintaining high electrical performance are being explored. Among these, electroplated nickel/copper/silver (Ni/Cu/Ag) contacts deposited through inline plating processes have emerged as a promising solution [2]. Inline plating offers the potential for both substantial silver savings and compatibility with industrial-scale, high-throughput manufacturing. In particular, the use of laser contact opening (LCO) to locally remove dielectric layers enables precise definition of contact areas, paving the way for reliable, low-resistivity metal-semiconductor interfaces.

Recent research has demonstrated that, with proper process optimization, inline-plated Ni/Cu/Ag contacts can achieve high fill factors (FF), low contact resistivity, and excellent adhesion, even when applied to large-area TOPCon cells [3], [4]. Moreover, the integration of inline plating with pilot line equipment and industrial cell designs has yielded cell efficiencies exceeding 24% while reducing silver consumption to as little as 1.1 mg/Wp [5]. In addition, initial module-level studies indicate that plated contacts are compatible with established interconnection technologies and can meet reliability standards under accelerated aging conditions [4].

Despite these advances, several technological and industrial challenges remain. Ensuring robust contact adhesion, achieving homogeneous plating current injection, and controlling process-induced recombination are critical for reliable and efficient cell fabrication. Furthermore, the transition from screen-printed to plated metallization requires careful consideration of process integration, cost implications, and supply chain factors.

This article presents a comprehensive study of inline plating for Ni/Cu/Ag metallization in industrial TOPCon silicon solar cells. We detail the process development on pilot line equipment, evaluate the electrical and reliability performance of both bifacially plated and hybrid-metallized (front side: screen-printed Ag contact, rear side: plated Ni/Cu/Ag contact) cells, and discuss key challenges and mitigation strategies relevant to large-scale adoption. By advancing understanding of inline plating technology, this work supports the pathway toward cost-effective, silver-lean, and high-efficiency TOPCon solar cell manufacturing.

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II. Material and Methods

A. Plating Approach, Tools, and Solar Cells Design

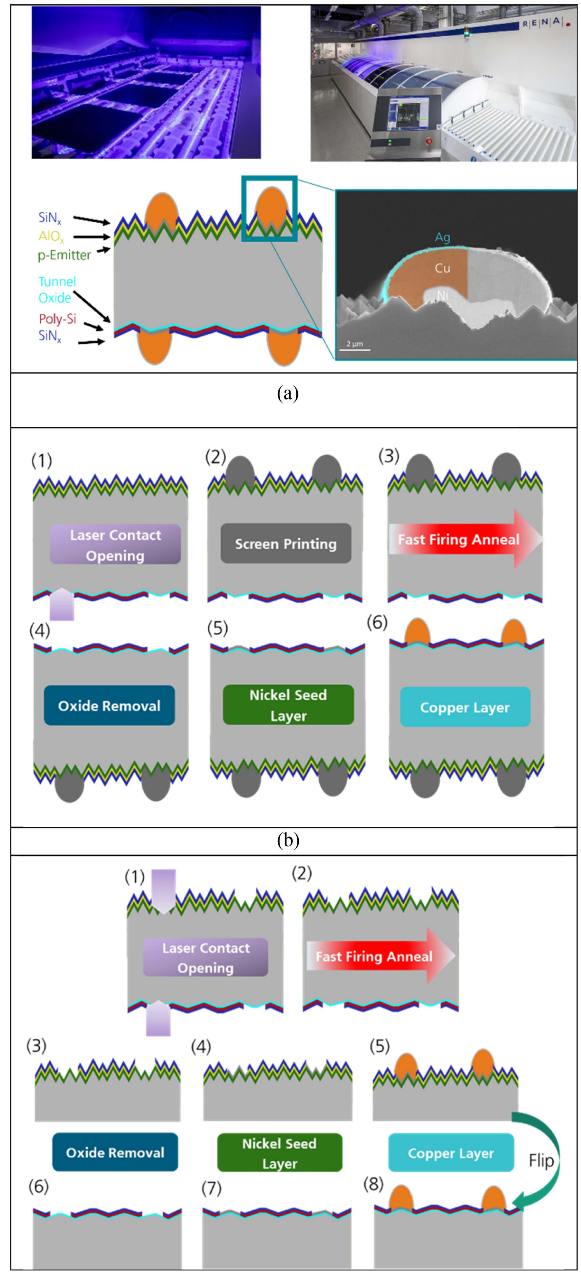
The plating approach in this work, based on Grübel et al. [2], forms Ni/Cu/Ag contacts by first patterning the dielectric masking layers (antireflection/passivation layers) using LCO. This is followed by single-side inline plating of a nickel seed layer (<1 μm), a copper conductive layer (3–10 μm), and a silver capping layer (<0.5 μm). Fig. 1 shows two variants of the inline plating approach used in this work to metallize TOPCon solar cells: a hybrid approach (with screen-printed front-side contacts and plated rear-side contacts), and a bifacial plating approach (with plated contacts on both the front and rear sides).

The single-side plating approach in this work deposits the nickel seed layer directly on the Si semiconductor interface. This requires a homogeneous plating current injection and low-stress plating electrolytes. The plating current injection is triggered by an electrical contact at the dry top side of the solar cell as shown for the case of bifacially laser patterned TOPCon solar cells in Fig. 2. In the case of TOPCon solar cells with plated contacts on both sides the application of a temporary metal contact (TMC) improves the current distribution and the contact resistance to the LCO. The TMC is manually placed on the solar cell top side during inline plating and is removed afterward.

The inline plating tool (RENA InCellPlate) used in this work is a pilot line tool, the basic concept is scalable to mass production. It features four parallel lines for inline plating with possible wafer sizes ranging from M6–G12 or any rectangular format within these limits.

B. Tape Test for Contact Adhesion Characterization

Contact adhesion reliability is tested in this work using tape test characterization (depicted in Fig. 3). Four stripes of adhesive tape are placed on a TOPCon solar cell with M10 wafer size. The analysis of the adhesion results after removing an adhesive tape in a 90° angle was conducted by counting the remaining fingers on the solar cell. Therefore, the solar cell is scanned in high quality and image processing techniques are applied. Fingers are detected and counted automatically. If there is a small region of the finger which has peeled off the whole finger is marked as failed. The four stripes are summarized and the percentual finger adhesion is measured. This method has proven to be efficient in terms of characterization time while still providing a semi-quantitative measure of overall contact adhesion reliability. Adhesion failure occurred exclusively at the Si-Ni interface. Further, the interface of peeled off fingers was analyzed using SEM characterization to evaluate possible reasons for adhesion loss.



(c)

Fig. 1. (a) Single-side inline plating tool (RENA InCellPlate) installed at Fraunhofer ISE and schematic design of a bifacially plated TOPCon solar cell with SEM cross-section of a plated Ni/Cu/Ag contact. (b) Metallization sequence of plated TOPCon solar cell in hybrid approach with screen printed front side and plated rear side contacts. (c) Metallization sequence of plated TOPCon solar cell with bifacial plated contacts in two consecutive single-side inline plating processes. (a) Tool & Contact Design. (b) Process sequence hybrid approach (FS: screen printing, RS: plating). (c) Process sequence double side plated contacts.

III. Results

A. Solar Cell and Module Results

1) Bifacially Plated Solar Cells: Bifacially plated solar cells refer, in this work, to TOPCon solar cells with plated contact on the front and rear side, which are metallized with the process sequence shown in Fig. 1(c). At Fraunhofer ISE TOPCon solar cells (M10 wafer format) were fabricated using n-type Si Cz wafers, a homogeneous front side boron emitter diffusion (no selective emitter) and a full area n-type TOPCon (no selective TOPCon) rear side. The processing sequence is similar to that used in Mack et al. [6]. Two types of metallization approaches were evaluated in this experiment. First, the plating approach depicted in Fig. 1(c), resulting in plated Ni/Cu/Ag contacts on the front and rear side. Second, an industrial type of screen

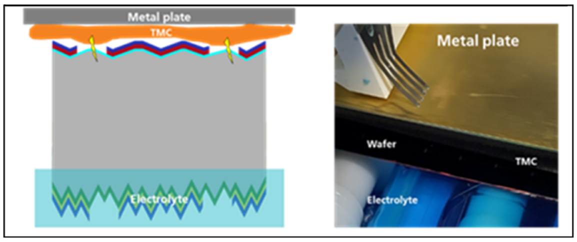


Fig. 2. Schematic design to ensure homogeneous current injection into the bifacial TOPCon solar cell during Plating and the implementation inside the InCellPlate Tool.

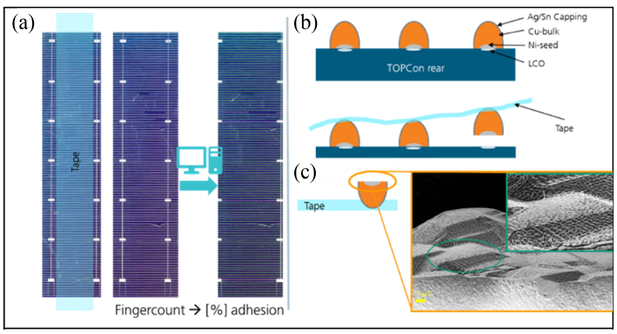


Fig. 3. Schematic of tape test approach for contact adhesion reliability testing. (a) / (b) Adhesive tape is placed perpendicular to the plated contact fingers along the full wafer length. The adhesive tape is removed in a 90° angle under constant force The cell is scanned and the total amount of fingers is counted. (c) In the case of contact failure the Ni-interface of the peeled of contacts is analyzed in the SEM in terms of surface morphology and Ni coverage.

TABLE I
Measured Champion IV Data of Internal M10 TOPCon Solar Cells With Either Plated Ni/Cu/Ag Metallization or Screen-Printed AgAl/Ag Metallization

M10 TOPCon solar cell (0 BB grid design)	η	V_{oc}	j_{sc}	FF
	[%]	[mV]	[mA/cm²]	[%]
Plated Ni/Cu/Ag	24.0	708	41.0	82.7
Screen-printed Ag	24.0	713	41.0	82.0

printing process described in Mack et al. [6], which features AgAl paste for contacting the emitter front side and pure Ag paste for contacting the TOPCon rear side.

The IV data of the fabricated TOPCon solar cells are summarized in Table I. Both metallization approaches achieved a maximum solar cell efficiency of 24.0% and a maximum FF of 82% and above.

By optimizing the process sequence for LCO formation and inline plating—particularly the contacting approach for plating current injection FF —we demonstrated that a narrow FF distribution can be achieved for bifacially plated TOPCon solar cells (see Fig. 4) with an average FF of 82.1%. The key factor for achieving a stable FF distribution was homogeneous plating current injection as described in Eckert et al. [7].

The main benefits of applying plated contacts on the rear and front side for TOPCon solar cells is the significant reduction in Ag consumption for plated Ni/Cu/Ag contacts compared

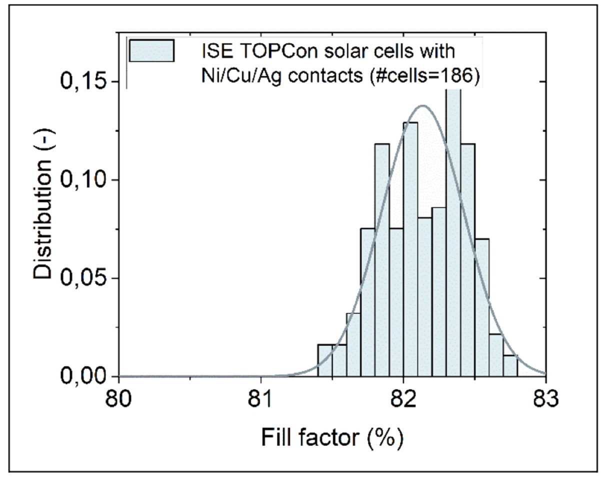


Fig. 4. Measured FF distribution of 186 bifacially plated TOPCon solar cells (M10 wafer format).

to screen-printed Ag or AgAl contacts. The plated solar cells in Table I had an Ag consumption of only 1 mg/Wp, which corresponds to an Ag reduction of 93% compared to the screen-printed solar cells. This enables significantly lower OPEX costs in industrial production and less dependency on volatile Ag prices. In addition, the global supply chain for plating electrolytes is geographically more diversified than that for silver pastes, which reduces the risk of supply chain dependencies due to geopolitical disruptions.

The main challenges regarding costs and tool design arise from increased CAPEX compared to screen printing, primarily due to the low maturity of plating technology in photovoltaics and by the resulting lack of scaling effects. Other technological challenges of bifacially plated TOPCon solar cells include increased contact recombination compared to screen-printed LECO contacts and challenging contact adhesion on the non-textured TOPCon rear side. Both technological challenges will be discussed in more detail in Section III-B.

2) Plated TOPCon Solar Cells in a Hybrid Design: The hybrid design refers, in this work, to a TOPCon solar cell with screen-printed front side contacts and plated rear side contacts shown in Fig. 1(b). This allows mitigation of some challenges in terms of front side contact recombination and still provides a significant silver reduction by substituting the silver rear side contacts with plated copper.

TOPCon solar cells using industrial precursors (M10 wafer format, processed up to front and rear side passivation "blue wafer") were fabricated with a hybrid metallization approach and compared to the bifacial plating approach. The IV data of these solar cells are shown in Table II.

The TOPCon solar cells with hybrid design achieved maximum solar cell efficiencies of up to 24.0% and 24.3% depending on the choice of silver paste. The bifacial plated TOPCon solar cells achieved a solar cell efficiency of up to 22.7%. The bifacial plated solar cells in Table II featured an LCO width of (~12 μm) compared to the solar cell in Table I (LCO width ~5 μm), which resulted in a drop in open circuit voltage (V_{oc}) due to larger front

TABLE II
MEASURED CHAMPION IV DATA OF INDUSTRIAL M10 TOPCON SOLAR CELLS WITH EITHER A HYBRID METALLIZATION SCREEN-PRINTED FRONT AND PLATED REAR SIDE CONTACTS OR BIFACIALLY PLATED CONTACTS

M10 TOPCon solar cell	η	V_{oc}	j_{sc}	FF	Ag layd.	Ag cons.
	[%]	[mV]	[mA/cm^2]	[%]	[mg]	[mg/Wp]
Hybrid 1	24.0	718	41.3	81.1	62.7	7.9
Hybrid 2	24.3	721	41.5	81.3	64.8	8.1
Bifacial Plating	22.7	700	41.0	79.3	14.5	1.9

Printed front side contacts also split in two cases: Hybrid 1 featuring pure Ag paste and Hybrid 2 featuring an AgAl paste. All solar cells were treated with a LECO post-treatment process.

side contact recombination losses. This further highlights the advantage of state-of-the-art screen-printed contacts in terms of V_{oc}/front side contact recombination compared to plated front side contacts. The reason for this is the difference in the ratio of contacted area to passivated area underneath the front side metal contact. Plated contacts feature a complete removal of the passivation layer within the LCO, which means that the whole LCO width has a nonpassivated surface with a surface recombination velocity close to the thermal velocity limit of 107 cm/s. Screen-printed contacts—especially LECO post-treated contacts—feature only a very local contact formation of the printed contact to the silicon surface, which results in a significant area fraction still passivated under the contact. This has enabled the impressive V_{oc} of up to 730 mV and beyond in the recent years for screen-printed TOPCon solar cells [8].

The quantification of Ag consumption in the solar cells is based on weight measurements. For screen-printed contacts, the reported Ag mass refers to the "wet" Ag paste applied before drying. The application of the hybrid concept already enables Ag consumption below 10 mg/Wp for both hybrid 1 and hybrid 2, compared to literature values of approximately 12 mg/Wp in industry (ITPV, [9] and 17 mg/Wp for double-sided printed TOPCon solar cells with similar grid designs and screens produced at ISE [5]. Bifacial plated solar cells further reduce Ag consumption to below 2 mg/Wp, with the potential to become completely Ag-free by substituting the Ag capping layer with Sn.

3) Plated TOPCon Solar Modules: Recent publications have demonstrated that bifacially plated TOPCon modules are compatible with state-of-the-art interconnection technology (IR soldering) and allow superior performance in damp heat and thermal cycling tests [4]. These findings were reproduced at Fraunhofer ISE. A full area module (see Fig. 5) was fabricated from the bifacial plated TOPCon solar cells from Fig. 4 using conventional IR soldering interconnection technology.

For reliability investigations, mini modules (2 half cells) of TOPCon solar cells (M10) with plated Ni/Cu/Ag metallization were fabricated using state-of-the-art soldering interconnection technology. The champion module (see Fig. 6) with plated metallization demonstrated maximum power point degradations of less than 1% rel. after pressure cooker test (140 h, PC140), less than 2.3% rel. after damp heat (2000 h, DH2000) and less than 2% rel. after temperature cycle (400 h, TC400). The key aspect

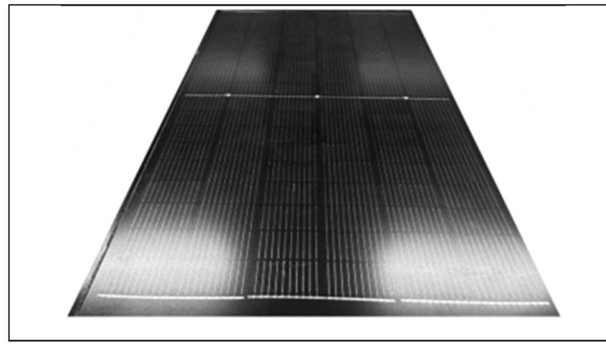


Fig. 5. TOPCon solar module featuring bifacially plated TOPCon solar cells fabricated at Fraunhofer ISE. The solar cells feature M10 half cells with 108 half cells in a butterfly design.

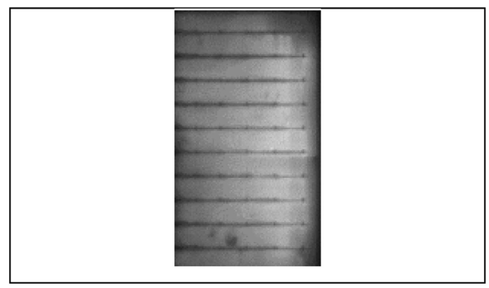


Fig. 6. EL image of half cell with plated metallization in minimodule after DH 2000 test.

for passing the reliability tests—especially the TC tests—was reliable contact adhesion of the plated contacts.

B. Technological Challenges and Mitigation Strategies

1) Contact Adhesion and Nickel Nucleation: Reliable contact adhesion is a key aspect for industrial implementation of plated contacts in TOPCon solar cells. There are typically three approaches to achieve reliable contact adhesion of plated contacts on silicon surfaces. First, the use of seed layers, which already provide reliable contact adhesion to silicon. Typical choices for seed layers in PV are PVD metal layers such as Ti, Pd, Ag, Ni, Cu, etc. [10], [11] or screen-printed seeds such as Ag pastes [12], [13]. Second, silicidation of the Ni-Si interface has also been shown to result in reliable contact adhesion of plated contacts on silicon surfaces [14]. Third, introducing nanoroughness at the Si interface can mechanically interlock the plated contacts at the surface [15].

The plating developments for TOPCon solar cells have focused mostly on the last approach to achieve reliable contact adhesion by laser-induced nanoroughness. This approach can be successfully applied on textured Si surfaces as it is the case for the TOPCon front side. The nontextured TOPCon rear side is more challenging since it has much lower surface roughness and less interlocking structures after LCO formation.

Our recent developments indicate that three key aspects are crucial to achieve reliable contact adhesion with the plating approach depicted in Fig. 1.

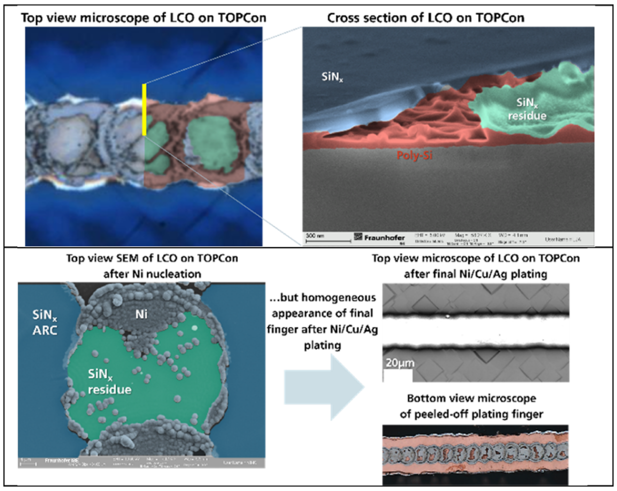


Fig. 7. Microscopy study of SiNx residue layer within LCO and its impact on the plated finger structure.

1) Proper LCO formation resulting in full area ablation of the dielectric layers on top of the silicon;
2) Proper Ni seed layer formation resulting in dense Ni nuclei;
3) Careful evaluation of laser and rear-side interplay.

Fig. 7 illustrates a case where an LCO process led to inhomogeneous SiNx ablation, resulting in a residual layer (thickness∼17 nm) within the LCO area. The presence of the residual layer leads to inhomogeneous Ni nucleation within the LCO (only Ni deposition on bare Si-interface, no deposition on residual layer interface) but subsequently to a homogeneously looking plated contact. Even though no Si-Ni interface is present at sites with residual layer, the Ni layer overgrows the residual layer and results in a homogeneously looking plated contact for plating heights in the range of 5–10 μm in top view microscope analysis. Inspection of the peeled-off finger reveals the insufficient Ni layer where the residual layer is present.

Further investigations were performed on the appearance of this kind of residual layer in the center of LCO on TOPCon solar cells. In summary, this layer appeared during UV-ps laser ablation depending on the choice of solar cell precursor in a reproducible manner on nontextured TOPCon rear sides with either SiNx or AlOx-SiNx ARC layer stacks for laser pulse energies at the ablation threshold and all tested pulse energies above the ablation threshold (Ep,max $\sim 3\times$ Ep,abl. thresh.). The appearance of this layer and its impact on Ni nucleation is strongly dependent on the choice of TOPCon solar cell precursor supplier. Fig. 8 shows the residual layer-induced differences in Ni nucleation for three TOPCon solar cell precursors. The general appearance of Ni nucleation was reproducible for each precursor but varied between the type of precursors.

Sample S1 shows a ring-shaped Ni nucleation with an insulating residual layer in the LCO center. Sample S2 shows an inverted behavior with a nearly homogeneous Ni nucleation in the LCO center but hindered Ni nucleation at the LCO edges. S3 shows homogeneous Ni seeding across the whole LCO area. Nonhomogeneous Ni nucleation can be avoided with large laser

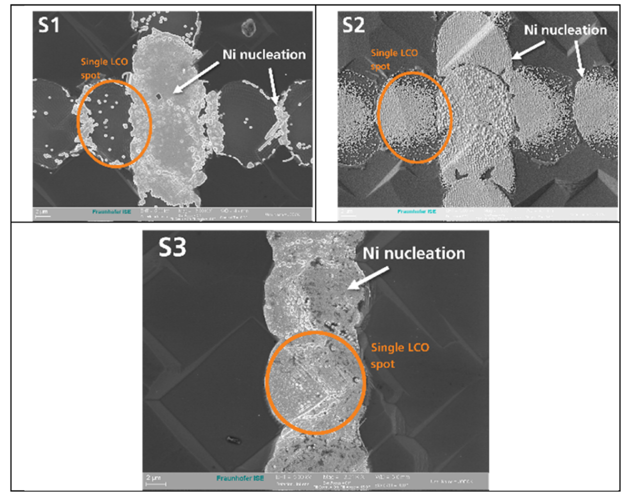


Fig. 8. Secondary electron microscopy (SEM) images of TOPCon solar cell rear sides after LCO and Ni-nucleation to visualize the residual layer within the LCO (nonplated area within LCO) for three different TOPCon solar cell precursors (S1–S3). The LCO processing of S1 and S2 featured two perpendicular lines with an intersection (overlapping LCOs) in the center of the SEM image. S3 features only a single LCO line.

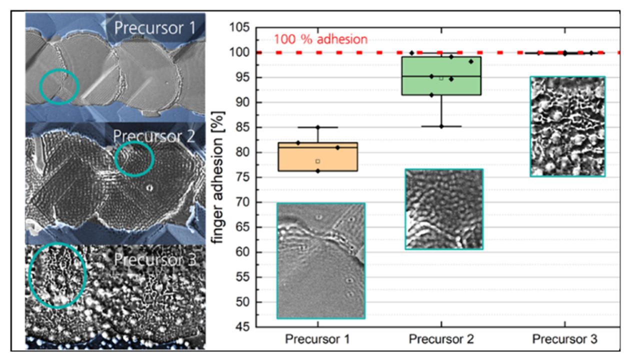


Fig. 9. Combination of measured contact adhesion in tape test in combination with SEM analysis of the TOPCon surface after LCO/before plating.

pulse overlap (multiple laser pulses per position, see LCO intersection for S1 and S2), LCO processes on textured surfaces and harsher wet-chemical pretreatments before plating (increased HF concentration or duration). All these mitigation strategies require careful optimization since they can affect the rear side contact recombination by either damaging the poly-Si layer and the underlying tunnel oxide.

Even in the case of proper laser ablation (without residual layer) and proper Ni nucleation at the TOPCon surface morphology can impact the resulting contact adhesion of plated contacts. Fig. 9 illustrates three examples of different industrial TOPCon rear side morphologies: precursor 1 (longer etching duration during emitter etch back resulting in smooth surface morphology), precursor 2 (medium etching duration during emitter etch back resulting in surface morphology with remaining subμm step size) and precursor 3 (medium etching duration during emitter etch back with subsequent short texturing resulting in surface morphology with remaining subμm step size and sporadically pyramids). After LCO formation precursor 1 shows only minor

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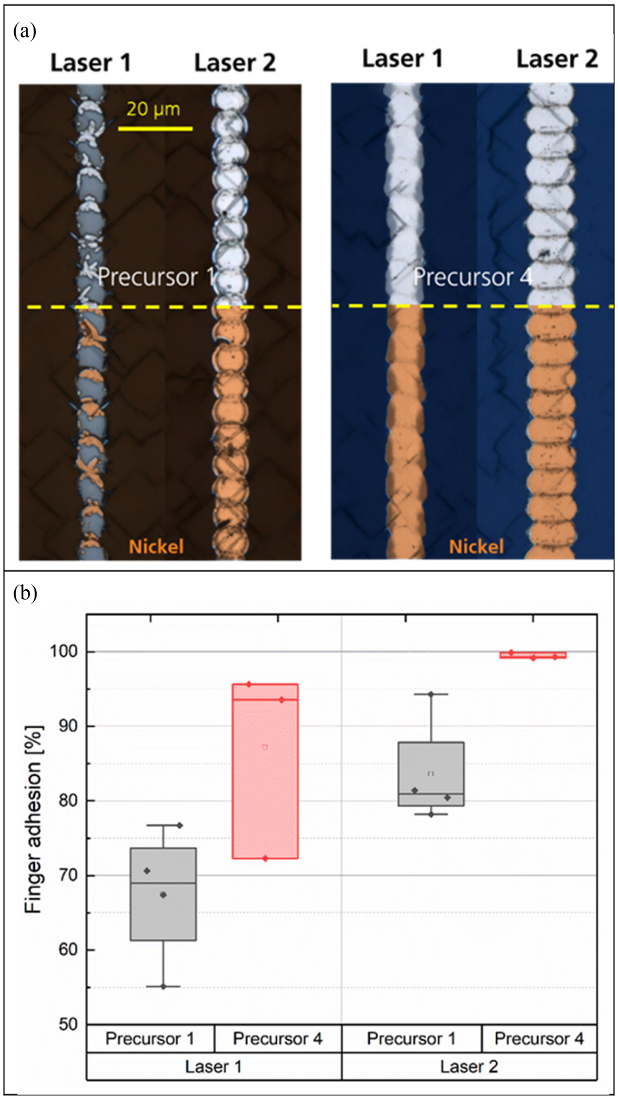

Fig. 10. Influence of used laser tool on (a) nickel nucleation characterized by optical microscopy and (b) corresponding finger adhesion.

changes in surface morphology, precursor 2 shows the formation of nanoripple features within the LCO due to self-interference at the surface steps and precursor 3 shows increased laser-induced surface roughness. Tape test characterization indicates increased contact adhesion. The precursors originate from different industrial sources. When reproducing the different rear side morphologies on one precursor type no such trend was visible. Finger adhesion values ranged between 80%–95%. This indicates that rear-side laser ablation is a complex interplay of precursor and laser.

To confirm this an experiment was designed where two different laser sources were used on two precursor types. The already known precursor 1 which forms a residual layer inhibiting Ni-nucleation and a commercially available industrial TOPCon precursor 4. The previously used laser tool (laser 1) operated at 343 nm and pulse duration of 3 ps and an industrial tool (laser 2) operated at 355 nm and 10 ps pulse duration. The microscope images of nickel nucleation in Fig. 10(a) demonstrate enhanced

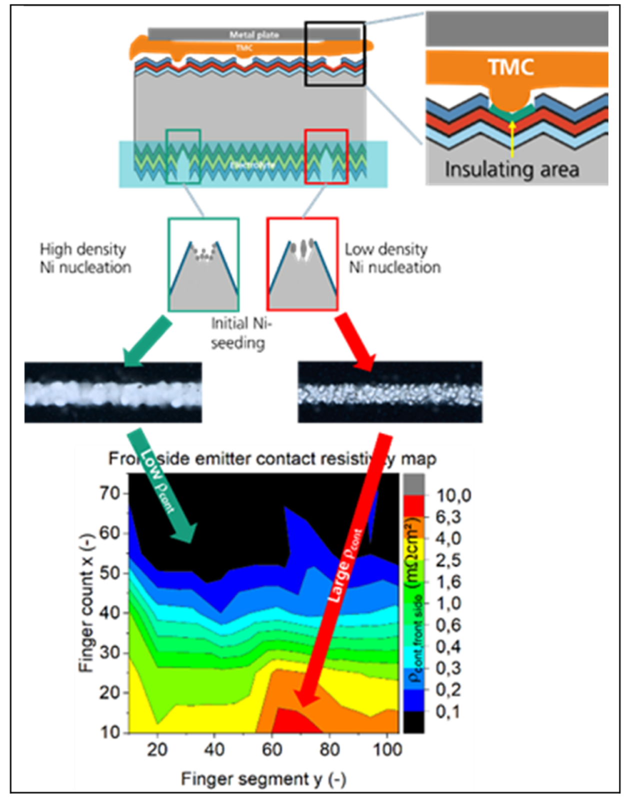

Fig. 11. Schematic of low-quality Ni nucleation due to insufficient plating current injection and its impact on the front side contact resistance.

seeding for precursor 1 which leads to improved adhesion values in Fig. 10(b). Precursor 4 passed the tape test with LCO performed by laser 2. Generally, increasing the Si-Ni interface surface area by enhancing nickel seeding results in improved adhesion for both precursor types. Up to now the authors have not been able to develop a hypothesis that matches the experimental results. Characterization of the different TOPCon solar cell precursors did not show a correlation of ARC properties such as (dielectric constant, layer thickness, layer stack (SiNx versus AlOx) or reflectivity) on the appearance of the residual layer or the Ni nucleation behavior. Further investigations on this are ongoing. The interplay of laser and precursor is crucial for adhesion and module integration and therefore needs to be re-evaluated if either is altered.

2) Low Emitter Contact Resistivity by Reliable Plating Current Injection: The inline plating approach depicted in Fig. 2 requires a homogeneous plating current injection of the temporary metal contact in the LCO structures to realize a well-defined plating deposition on the immersed solar cell surface. The appearance of a residual layer within the LCO on the TOPCon rear side would further hinder the plating current injection and lead to an inhomogeneous Ni plating on the opposite side (boron emitter front side), which has a detrimental impact on the front side contact resistance as portrayed in Fig. 11. Fig. 7 illustrates the impact of inhomogeneous plating current injection (e.g., due to residual layer or nonconformal TMC contact to the LCO [16]) on the Ni deposition and the measured contact resistivity of the plated front side contacts. Our investigations showed that especially the boron emitter front side is sensitive to that effect, which can lead to local contact resistivity inhomogeneities in a range of 1 – 20 mΩcm² over a single M10 solar cell.

Mitigation strategies to avoid this effect include optimization of the TMC material and contacting scheme to achieve conformal contacting of the LCO (e.g., by using elastic conductive fabrics and increased contact pressure [7]) and providing clean LCO Si interfaces (e.g., by avoiding residual layer in the LCO and/or precleaning of the plated and contacted side).

3) Contact Recombination: There are two origins for contact recombination of laser defined plated contacts. First, laser-induced crystal damage during LCO formation. UV-ps lasers typically induce near-surface damage at a depth of 40–60 nm [17] from the surface. This phenomenon becomes relevant for shallow emitter profiles (<300 nm) but becomes less significant for typical industrial boron emitter profiles with pn-junction depth of 1 μm and above.

Second, the LCO formation leads to removal of the passivating dielectric/ARC layer. As discussed in Section III-A the full area ablation of the dielectric/ARC layer leads to significantly larger nonpassivated contact areas for plated contacts than for screen-printed contacts with LECO post-treatment. This effect has only minor impact on the TOPCon rear side—since the passivating interface is at the TOPCon tunnel oxide instead of the ARC layer interface—but major impact on the boron emitter front side. Any damage or removal of the dielectric/ARC layer results in increased recombination leading to lower V_{oc}. This seems to be an intrinsic disadvantage of plated contacts, compared to screen printing on diffused surfaces.

Possible mitigation strategies are as follows:

1) Reducing the LCO area on the front side to a level comparable to LECO contacts;
2) Implementing a hybrid approach of front side screen printing contact and rear side plated contact;
3) Implementing a selective emitter structure on the front side either by local diffusion or local p-type TOPCon.

Reducing the LCO area on the front side seems to be possible by reducing the laser spot size. On the lab scale LCO width down to 3–5 μm were already demonstrated. In terms of maximizing solar cells efficiency simulation results performed at Fraunhofer ISE suggest that the minimum LCO width is in the range of 2–3 μm limited by the contact resistance of the front side contacts for narrower LCO widths.

As demonstrated in Table II the hybrid approach seems to be the easiest approach on how to implement plated contacts in industrial production. This allows to already reduce Ag consumption by up to 50% and still maintain low front side contact recombination.

The authors expect the local p-type TOPCon selective emitter approach to be the most promising for future implementation. Especially, if combined with a laser-based patterning approach for local TOPCon formation [18]. This laser-on-laser approach would allow low alignment tolerances between local TOPCon formation and LCO leading to low parasitic absorption of the local TOPCon structures. First investigations already demonstrated successful implementation of plated contacts on local TOPCon structures leading to V_{oc} up to 718 mV (see Fig. 12). The solar cells were manufactured at ISC Konstanz and plated at Fraunhofer ISE.

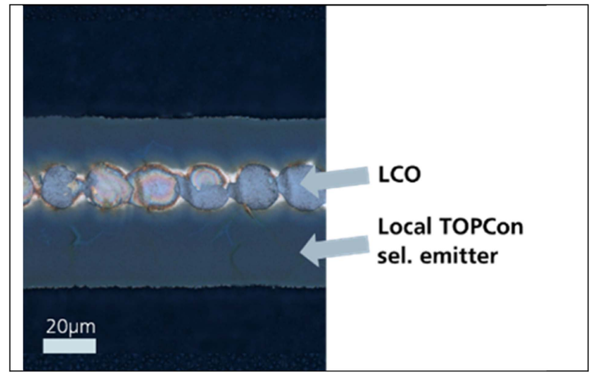

Fig. 12. Microscope image of LCO on local TOPCon structure.

IV. Conclusion

This work demonstrates that inline plating of Ni/Cu/Ag contacts is a viable and industrially scalable approach for metallizing TOPCon silicon solar cells. Using pilot line equipment and optimized process sequences, we achieved high-efficiency TOPCon cells (up to 24.3%) with silver consumption reduced to as low as 1.1 mg/Wp and FF above 82% for large batch sizes. Module integration studies confirm that plated contacts are compatible with existing interconnection technologies such as IR soldering, and mini-module reliability tests show power degradation below 2.3% after accelerated stress testing, provided that reliable contact adhesion is ensured.

From an industrial perspective, the hybrid metallization design—combining screen-printed contacts on the front and plated contacts on the rear—currently offers the most pragmatic pathway for integrating plating into mass production. This approach enables significant silver savings, leverages mature screen-printing technology for the front side, and avoids open-circuit voltage (V_{oc}) losses related to increased front-side contact recombination observed in bifacially plated cells.

Key technological challenges, such as achieving robust contact adhesion and ensuring homogeneous plating current injection—especially on the nontextured TOPCon rear side—have been systematically investigated. The main mitigation strategies include optimization of LCO processes, careful control of Ni seed layer nucleation, and engineering of surface morphology to generate mechanical interlocking features. In addition, minimizing front-side recombination losses remains critical; future improvements should target the implementation of local selective emitter or local p-type TOPCon structures, which could enable front-side plating without V_{oc} penalties.

Our results indicate that there are no intrinsic technological showstoppers for inline plating of TOPCon cells. However, the current market environment, dominated by highly matured screen-printing processes, poses challenges for large-scale adoption of plating. To accelerate market entry and close remaining gaps, continued collaborative R&D and technology transfer activities are required.

In summary, inline plating offers a promising route toward cost-effective, silver-lean metallization for TOPCon solar cells. With ongoing process optimization and strategic integration steps—starting with hybrid approaches and advancing toward fully plated structures—inline plating can play a key role in the next generation of high-efficiency silicon photovoltaics.

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