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APPROACHES FOR REDUCING METALLIZATION-INDUCED LOSSES AND COST IN INDUSTRIAL TOPCON SOLAR CELLS

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ABSTRACT: Reducing carrier recombination in silicon solar cells is essential for enhancing conversion efficiency, as it influences both fill factor and open circuit voltage. Recombination occurring at metal-semiconductor interfaces is particularly significant; however, processing conditions that minimize recombination often lead to higher contact resistivities. This is overcome by the implementation of laser-enhanced contact optimization, which enables both high fill factors and elevated open circuit voltages. To maximize the gain in efficiency, front end processing has been optimized. We show an implied open circuit voltage limit of industrial cell precursors exceeding 740 mV, indicating the extremely high voltage potential of modern TOPCon solar cells. Ag based metallization pastes without Al are chosen for contacting, as they exhibit a lower metallization related recombination. Contact optimization leads to an increase in conversion efficiency by almost 24 % (absolute). Such treated samples feature a similar conversion efficiency as conventional AgAl pastes. Light induced plating of nickel, copper, and Ag on M10 cells leads to a higher conversion efficiency than screen-printed contacts, even without the additional need for contact treatment, while at the same time reducing Ag consumption by more than 90 % to only 1.1 mg/W_p, which lowers metallization related cost.

Keywords: TOPCon, metallization, screen-printing, plating

1 INTRODUCTION

The tunnel oxide passivating contact (TOPCon) structure has become widely accepted in industrial manufacturing. These solar cells are made from n-type silicon wafers and feature a tunnel oxide combined with an n-doped polysilicon layer on the rear side. The synergy between passivation from the interfacial oxide layer and a very shallow dopant profile beyond the oxide in the silicon wafer results in an exceptionally low recombination current density. Additionally, metal-induced recombination can be reduced significantly. Overall, the implementation of passivating contacts in industrial solar cells (*i*TOPCon) has led to conversion efficiencies surpassing 25% [1–5].

To further enhance solar cell efficiency, it is crucial to minimize other loss mechanisms in *i*TOPCon solar cells. Key factors include carrier recombination within the wafer itself, as well as on front and rear side of the sample, which encompasses dielectrically passivated areas and contacted regions. Front side recombination at the metal contacts $j_{0e,met}$ is influenced by the emitter dopant profile, as well as by the type of metallization technique used. In the case of flatbed screen printing technology this includes the composition of the metallization paste, the contact firing profile, and the metallization fraction, such as finger widths and pitch. For *i*TOPCon solar cells, metallization typically involves the use of Ag based pastes on both front and rear, which is a significant cost driver for this type of solar cell.

This paper describes approaches to address metallization-related carrier recombination in *i*TOPCon solar cells. First, the impact of laser-enhanced contact optimization (LECO) on cell parameters is described, on solar cells, which feature a front side metallization formed by either an AgAl paste or an Ag paste without any Al content. In a second section, screen-printing technology is compared to laser ablation of dielectrics in combination with light induced plating of a metallization stack of Ni/Cu/Ag. Here, a metallization approach based on plating strongly reduces Ag consumption and thus cost.

2 SAMPLE PREPARATION

2.1 Solar cells

The process sequence for *i*TOPCon solar cells, illustrated in Fig. 1, utilizes commercial n-type silicon wafers. Our lab is compatible with different wafer formats, and in the experiments described below, wafers with either M2 (156.75 mm edge length) or M10 (182 mm) size are being used. Following saw-damage removal, etching in an alkaline solution creates upright random pyramids. Gas-phase diffusion in an atmospheric tube furnace with boron tribromide (BBr_3) forms the emitter, which is then followed by inline glass etching and batch alkaline etching to eliminate the parasitic emitter doping on the rear side of the wafer, as well as on the edges. After growing an interfacial oxide layer of 1 nm to 1.5 nm thickness, a phosphorus-doped silicon layer is deposited on the rear using a chemical vapor deposition process, either low pressure (LPCVD) or plasma-enhanced (PECVD). Another inline etching step removes the wrap-around on the front side and the wafer edge, as well as the borosilicate glass (BSG) stack formed during diffusion. Following a cleaning step, thermal annealing drives phosphorus deeper into the silicon wafer and enhances the crystallinity of the deposited silicon layer. The passivation sequence includes another cleaning step, the deposition of an Al_2O_3 layer by means of atomic layer deposition, outgassing, and the deposition of SiN_x layers on both the front and rear sides via PECVD. For metallization, we employ established flatbed screen printing technology with silver-containing pastes, followed by contact firing in an inline conveyor belt furnace. Optionally, laser-enhanced contact optimization (LECO) [6, 7] is used to reduce contact resistivity ρ_c. An alternative metallization approach consists of laser ablation of front and rear side dielectrics, firing for thermal activation of passivation layers, and light induced plating of Ni, Cu, and Ag.

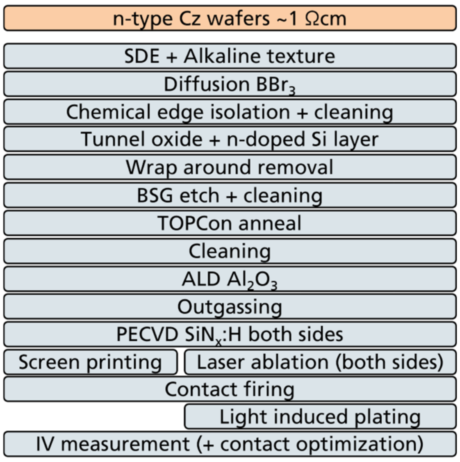

Figure 1: Process sequence for fabrication of industrial *i*TOPCon solar cells. The route with screen-printing technology is displayed on the left, whereas the right side represents the alternative with plated contacts.

2.2 Characterization

Throughout processing, samples are removed from processing and characterized. This includes measurement of the passivation quality by means of photoconductance decay in a Sinton lifetime tester WCT-120, the measurement of the emitter sheet resistance R_{sheet} by four-point-probe (4pp), and current-voltage (*I-V*) measurements of the fabricated solar cells in a lab-type cell tester. Additional transfer length method (TLM) analysis yields contact resistivity ρ_c on prepared samples.

3 RESULTS

3.1 Lifetime results

The passivation quality has been determined on asymmetric lifetime samples, *i.e.* solar cells without metallization. To determine the potential of our baseline, we process samples as depicted in Fig. 1, but leave out the processes screen printing, laser ablation, and plating. Next to our baseline emitter process with a R_{sheet} = 160 Ω/sq, as measured by 4pp on textured surfaces, we also include two other emitters with sheet resistances of 220 Ω/sq and 330 Ω/sq, respectively. In addition, we also include wafers of a second source. The samples have been fired for activation of the passivation layers at a set temperature of 800°C, which is a typical temperature also for *i*TOPCon solar cells in our laboratory.

Optimizations at Fraunhofer ISE show how a low level of minority carrier recombination can be achieved, as visible from Fig. 2, with the inset showing a schematic cross section of the investigated structure. The current baseline process with R_{sheet} = 160 Ω/sq (black) yields a median iV_{oc} = 727 mV and represents a starting point compared to current industrial standards. The implementation of an advanced emitter with R_{sheet} = 220 Ω/sq (red) increases this limit to over 730 mV, and 734 mV with another wafer stock. Replacing advanced emitter 1 with advanced emitter 2 with R_{sheet} = 330Ω/sq (blue) increases iV_{oc} to a remarkable level of 742 mV, closing the gap towards silicon hetero-junction (SHJ) solar cells. While advanced emitter 1 is still within range of what is compatible with screen-printed contacts today, emitter 2 currently requires either the use of a selective emitter structure at the contacts, due to low

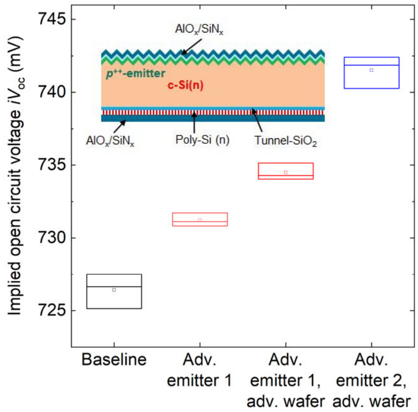

Figure 2: Implied open circuit voltage results for non-metallized *i*TOPCon precursors, measured after firing.

surface dopant concentration, which otherwise would make contacting with low contact resistivity challenging. Alternatively, a contact optimization such as LECO would be required for a low ρ_c. The demonstrated high iV_{oc} on TOPCon precursors illustrates that the reduction of metallization induced losses is key for closing the V_{oc} gap to SHJ cell technology.

3.2 Impact of front metallization paste

An experiment was conducted to compare the effects of two distinct metallization pastes for contacting the front side of the solar cell. The first paste is a pure Ag paste, whereas the second one includes additional Al. The *I-V* parameters are illustrated in Fig. 3.

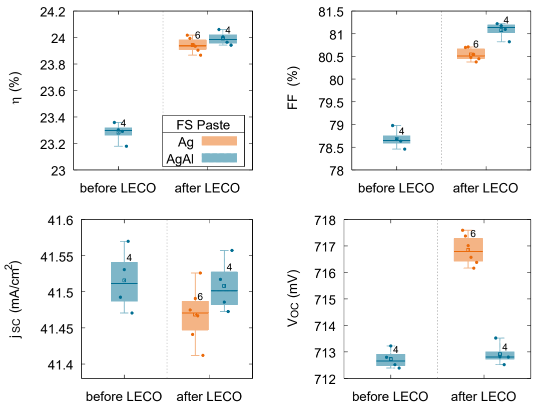

Figure 3: *I-V* parameters of *i*TOPCon solar cell results on M2 wafers, indicating the impact of LECO treatment, for samples with a front side metallization by either Ag or AgAl paste determined at an industrial cell tester.

Prior to LECO treatment, the AgAl paste exhibits a median conversion efficiency η = 23.3%, while a low fill factor FF < 30% in case of the Ag paste (not shown) indicates that the front contact formation is incomplete, which results in a conversion efficiency of 0.0%. LECO processing strongly reduces the series resistance R_s for cells of both types, leading to similar FF and a η = 24%, with a slight advantage for the AgAl paste, while the short circuit current density j_{sc} is on the same level of 41.5 mA/cm². Thus, in case of the Ag paste, LECO treatment has to be considered as a contact forming process, which is in accordance with other work [5].

However, completely different behaviors are observed for *FF* and open circuit voltage V_{oc}. The Ag paste results in a 4 mV higher V_{oc} but a 0.6% lower *FF*, which is due to the absence of Al. The addition of Al leads to deeper contacts, as previously shown [8]. The emitter in this experiment features a depth of more than 1 µm. However, if metal penetrates too deep into the wafer and approaches the depth of the junction, a strongly increasing recombination current density $j_{0e,met}$ is the result [8], which needs to be prevented. On the other hand, the larger metallized area fraction due to deeper spikes [8] (i.e., the actual 3D contact area, which exceeds the 2D projection) and the Al doping from the paste itself lead to a lower series resistance R_s ($\rho_{c,AgAl} = 1$ mΩcm², compared to $\rho_{c,Ag} = 3$ mΩcm²). Thus, to exploit the higher V_{oc} in case of the Ag paste and to increase η even further, challenges have to be undertaken to decrease the final $\rho_{c,Ag}$ after LECO, either by changes to the emitter dopant profile, the use of an optimized metallization paste, or by modification to the LECO parameters.

Based on the results above and the described lower ρ_c, however, we chose to apply an AgAl paste for contacting of emitters with higher R_{sheet} and fabricated *i*TOPCon solar cells with the other processes as highlighted in Fig. 1. In the final *I-V* data, we did in fact find slightly higher V_{oc} and j_{sc} for advanced emitters 1 and 2, however, lower *FF* values originating again from higher R_s lead to slightly lower cell efficiencies, compared to our baseline process, even after LECO treatment. Therefore, at this point, the high V_{oc} potential previously identified could not be utilized effectively with the metallization process that we currently have at our disposal.

3.3 Screen printing vs. plating

For fabrication of M10-sized *i*TOPCon solar cells, LPCVD has been chosen as the technology for formation of the TOPCon stack. The *I-V* measurement results are depicted in Fig. 4, for both screen-printed (SP) metallization and plated contacts. Please note that here only an AgAl paste has been used for front side metallization. In addition, results are shown both directly after processing as well as after additional LECO treatment. For the solar cells with screen printed metallization, an additional firing set temperature variation (780°C to 820°C) has been performed.

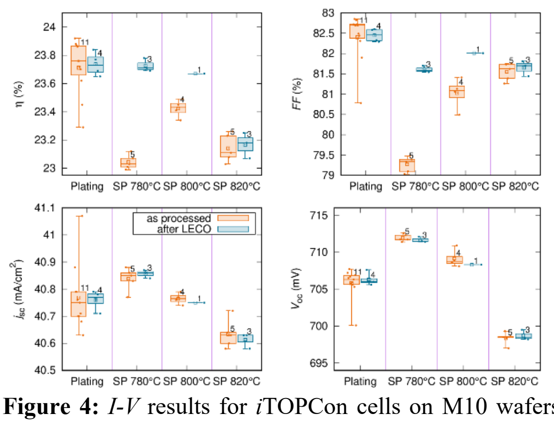

Figure 4: *I-V* results for *i*TOPCon cells on M10 wafers with either plated or screen printed metallization, measured with an industrial cell tester. In case of screen printing (SP), the experiment includes a variation in the firing set temperature (780°C to 820°C).

Directly after processing, which refers to the states "after plating", or "after contact firing", respectively, a considerably conversion efficiency up to $\eta = 23.9\%$ is found for plated contacts, while screen printed contacts allow for solar cells up to 23.5% at 800°C firing. Lower or higher firing set temperatures result in lower η, as an increasing *FF* for 820°C firing goes hand in hand with a decreasing V_{oc} due to increasing $j_{0,met}$, and vice versa for 780°C. This means, 800°C represents a trade-off between V_{oc} and *FF*. The comparison of plating and screen printing reveals a considerably higher *FF* and lower V_{oc} for plated contacts. The origin for this lies in the metallized area fraction, as laser ablation leads to a very efficient opening of the dielectrics on front and rear. This is especially detrimental on the front side, where typical $j_{0,met}$ values are in the range of 1000 fA/cm² [9, 10], compared to a $j_{0,met}$ in the estimated range of 10 to 50 fA/cm² on the rear side. In general, j_{sc} follows the trend visible in V_{oc}.

Looking at values after LECO, it becomes apparent that LECO has no positive effect in case of the plated contacts here, whereas screen printed metallization strongly benefits, with a significant increase of *FF* by 2.6% to 81.6%, which boosts efficiency to 23.8%, close to the initial value of plated metallization. The reason for this different behavior during LECO treatment is most probably linked to the actual contact area for plated contacts, where a larger Si area is in direct contact to the Ni contact material. Further work has to be underdone to investigate this in more detail.

Table 1 shows the *I-V* parameters of our champion M10 solar cell with screen-printed metallization. The calibrated measurement on a highly reflective chuck has been independently performed at ISFH CalTec, neglecting grid resistances on both front and rear. A conversion efficiency of 24% is found, with especially V_{oc} indicating significant room for improvement. Thus, future work needs to focus on decreasing minority carrier recombination on front and rear side, as well as minimizing metallization related recombination, while keeping *FF* on a high level. Please note that so far, the cell with plated metallization has not been subjected to a calibrated measurement.

Table 1: *I-V* data of our champion M10 *i*TOPCon solar cell. Independent, calibrated measurement at ISFH CalTec, measurement condition grid resistance neglected (grn) on both sides, measurement on highly reflective chuck (hrc) "grn | grn, hrc" [11].

***i*TOPCon**	**η (%)**	**V_{oc} (mV)**	**j_{sc} (mA/cm²)**	***FF* (%)**
M10	24.0	712	41.1	82.1

In terms of silver consumption and processing cost the implementation of Ni/Cu/Ag plating has the potential to significantly lower both. The fabricated solar cells feature a silver consumption of about 15 mg/W for screen printed metallization and down to 1.1 mg/W for plated metallization. This lies even below the targeted silver consumption of 2 mg/W [12] for a sustainable silver consumption in a multi TW PV production market. A direct comparison of the cost of ownership of screen printed vs. plated metallization of M10 TOPCon solar cells shown in Fig. 5 reveals a main difference in the cost structure of the two metallization approaches. The COO screen printing approach is mainly driven by process consumable costs (silver paste). The plating approach on the other hand is due to its low supply chain maturity mainly driven by equipment costs. Overall, the plating approach shows potential to significantly reduce processing cost especially in times of volatile and increasing silver prices.

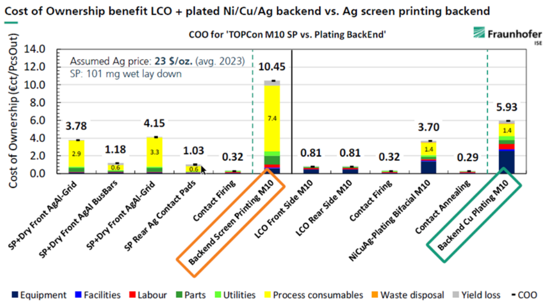

Figure 5: Cost of ownership calculations of the screen printing and plating metallization approach for M10 TOPCon solar cells.

SUMMARY

This study investigated the passivation quality and performance of *i*TOPCon solar cells using various emitter configurations and metallization techniques. Asymmetric lifetime samples with an emitter sheet resistance of $R_{\mathrm{sheet}} = 330\ \Omega/\mathrm{sq}$ achieve a remarkable $iV_{\mathrm{oc}} = 742$ mV, demonstrating the potential to close the voltage gap to SHJ cells. The investigation of Ag and AgAl front side pastes reveals a significantly different η directly after processing, but LECO treatment changes this to an absolute minimum, with a similar η in the 24% range. Nevertheless, *I-V* parameter strongly differ in terms of V_{oc} and *FF*. Quite similarly, also screen-printed metallization using an AgAl paste achieves a similar efficiency as cells with plated Ni/Cu/Ag metallization, with plated contacts achieving higher *FF*, but lower V_{oc}. The development culminates in a champion M10 cell with an independently measured conversion efficiency of 24 %. While cells with plated contacts are not affected by LECO treatment, plating technology represents a promising approach to reduce metallization related cost in *i*TOPCon solar cells, as it reduces Ag consumption by over 90%, to a level of only 1.1 mg/W_p, which is also relevant for reasons of sustainability.

However, challenges still remain to achieve lowest contact resistivities in order to fully exploit the high iV_{oc} potential of our optimized frontend process.

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