Progress of plated metallization for industrial bifacial TOPCon silicon solar cells

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Abstract
Industrial tunnel oxide and passivated contact (i-TOPCon) solar cells were metallized at Fraunhofer ISE using ultrashort pulse laser ablation of the passivation layers for the subsequent Ni/Cu/Ag plating process. The solar cells feature a tunnel SiOx and n-type doped polysilicon layer covered by a SiNx at the rear side, whereas the front side is made of a boron emitter passivated with a AlOx/SiNx stack. The reference i-TOPCon solar cells screen-printed at the supplier reach an efficiency of 23.46% measured by Fraunhofer ISE CalLab. The impact of the laser process on the implied open circuit voltage ($V_{oc}$) is characterized showing minor impact on the TOPCon side, while the emitter side reveals an increased $V_{oc}$ loss due to laser damage. Loss analysis by simulating the plated solar cells points out the benefit of reducing the laser contact opening (LCO) area in terms of shading and contact recombination. Optimization of laser ablation and hydrofluoric acid (HF) pretreatment process result in $V_{oc} > 700$ mV and $FF > 82\%$ leading to a mean efficiency 23.6% measured in-house and a champion efficiency of 23.84% measured at Fraunhofer ISE CalLab thus outperforming the references by 0.4%abs.

KEYWORDS
laser ablation, metallization, passivated contacts, plating, TOPCon

1 | INTRODUCTION
Silicon solar cells featuring passivating and carrier selective contacts are considered to be a viable candidate for future industrial mass production.1 Passivating contacts using hydrogenated amorphous silicon (a-Si:H)2 or polysilicon layers (poly-Si)3–5 enable to significantly reduce the metal contact recombination allowing high open circuit voltages well above 700 mV. One implementation concept is the use of an ultrathin SiOx layer and a highly doped poly-Si layer referred to as tunnel oxide passivating contact (TOPCon).3 Laboratory-type implementation of this concept has already demonstrated 26.0%6 on a both-sides-contacted cell on small area ($2 \times 2$ cm$^2$) and 26.1%6 on an inter-digitated back contact solar cell on small area ($2 \times 2$ cm$^2$). Industrial adoption of this technology on large area shows promising results.7,8

A key challenge in industrially upscaling the TOPCon solar cell concept is the metal contacting of the solar cells. Especially the metallization on the TOPCon side reveals to be challenging as the tunnel oxide should not be damaged to guarantee its full functionality as carrier selective contact,9 as state-of-the-art metallization technique of industrial tunnel oxide and passivated contact (i-TOPCon) solar cells screen-printing of Ag/Al is used on the front and Ag on the rear side, respectively. Recent publications point out that the limitation in silver...
supply and increasing raw material costs are a critical factor for an increasing photovoltaic (PV) market heading towards terawatt scale within the next decade.\textsuperscript{10,11} Conventional technology evolution (as expected according to the ITRPV\textsuperscript{12}) is not sufficient to overcome these limitations especially for solar cell designs with silver contacts on both sides.\textsuperscript{10,11}

Electroplating of Ni/Cu/Ag contacts was found to be a suitable candidate to metallize bifacial TOPCon solar cells.\textsuperscript{13,14} Plating is a lead-free metallization technique which allows narrow contact geometries (<25 μm) and low contact resistivities ($\rho_c < 1 \, \text{mΩcm}^2$).\textsuperscript{13,15} A recent publication by Kluska\textsuperscript{16} presented module manufacturing of fully plated TOPCon solar cells with reliable and sufficient contact adhesion of fingers and soldered busbars (BB). Further, using mainly Cu as the main conductive component a significant cost reduction is accessible resulting in cost-of-ownership (CoO) advantage of around 45% compared with screen-printing.\textsuperscript{14,17}

In this paper, industrial TOPCon precursors were laser ablated and plated. The laser ablation process and the hydrofluoric acid (HF) pretreatment prior to the plating process were optimized to contact opening width <14 μm and $\rho_c < 0.6 \, \text{mΩcm}^2$. The optimized processes resulted in a champion efficiency of 23.84% measured by Fraunhofer ISE CalLab in Germany showing an 0.4%\textsubscript{lab} compared with the reference.

2 | EXPERIMENTAL

2.1 | Solar cell fabrication

In this work i-TOPCon solar cell precursors which are optimized for screen-printed metallization were supplied by an industrial partner. The precursors consist of an n-type doped silicon bulk material (2 Ω·cm assumed) with an industrial-type boron emitter on the textured front side passivated by an AlOx/SiNx stack. The rear side features a TOPCon layer with a tunneling oxide and a highly n-type doped poly-Si layer which is covered by a SiNx layer as presented in Figure 1. The solar cells were designed for screen-printed metallization. Screen-printed references were metallized and fired at the supplier with a finger width of 31 μm and characterized at Fraunhofer ISE. More information about the samples were presented by Zheng.\textsuperscript{18} The precursors for the plating group were in the status prior to the metallization process. At Fraunhofer ISE the antireflective coating was laser ablated on the front and rear sides using a frequency tripled UV (355 nm) pulsed laser with <15-ps pulse duration. With this laser system Bühler\textsuperscript{19} showed reliable contact adhesion by laser-induced nanoroughening. On the front side a variation of the laser contact opening (LCO) width of 5.5, 9, and 14 μm was performed by varying the spot size of the laser beam resulting in pulse spacings of 12.5 μm on the rear sides and 4.75, 9, and 13.5 μm on the front sides, respectively. Half of the samples were processed with an identical grid layout on both sides consisting of 9 BB and 106 fingers, while for the other half the number of fingers was increased to 163 on both sides. The precursors were fired in a fast-firing oven (FFO) at a set peak temperature of 820°C, corresponding to an actual wafer temperature of around 720°C. Such high temperature treatments have shown to recover the laser damage.\textsuperscript{20} Both sides were subjected to the plating process described by Grübel.\textsuperscript{13} The plating process combines two single side electroplating steps of a Ni/Cu/Ag stack subsequently on each side. The Ni and Cu were supplied by Atotech Group, whereas the Ag electrolyte is identical as presented by Grübel.\textsuperscript{13}

The rear TOPCon side is plated first by performing an HF pretreatment designed for removal of native and laser-induced oxide layers within the LCO.\textsuperscript{21} Subsequently, a Ni (~0.5 μm)/Cu (5–10 μm) stack is deposited by light-induced plating (LIP)\textsuperscript{22} finished by an Ag (<0.5 μm) immersion plated capping. The solar cell is flipped, and a similar process sequence is performed by forward bias plating (FBP).\textsuperscript{23}

To investigate the influence of the HF pretreatment, a variation of the HF concentrations of 1%–1.5% and process times of 30–60 s was performed. Depending on the composition of the oxide layer, an increase of the HF concentration from 1% to 1.5% can increase the etch rate up to three times.\textsuperscript{21,24} The solar cells finally processed were submitted to a HF pretreatment with a concentration of 1.5% for 30 s.

2.2 | Characterization

The plated and screen-printed TOPCon solar cells were then subjected to flash IV cell tester with a nonreflective conductive chuck using a busbarless contact unit due to the limited maximum number of contact rails in the setup. The contact resistivity of the plated and screen-printed contacts was characterized by transfer length method (TLM).\textsuperscript{25}

FIGURE 1 Schematic of plated (left) and screen-printed (right) industrial tunnel oxide and passivated contact (i-TOPCon) solar cell used in this work. The screen-printed samples and half of the plated samples have an identical grid layout with 9 busbar and 106 fingers on both sides, while for the other half of the plated samples the number of fingers was increased to 163 on both sides. Reproduced under terms of the CC-BY license\textsuperscript{12} Copyright 2020, The Authors, published by IEEE
The plated contacts were imaged by confocal laser microscopy, measuring the contact width \( w_{\text{Finger}} \) and height \( h \). From these measurements the aspect ratio \( AR_{h/w} \) of the plated contacts can be determined according to Equation 1 with respect to the LCO width \( w_{\text{LCO}} \). Subtracting the \( w_{\text{LCO}} \) from \( w_{\text{Finger}} \) allows to extract whether the deposition is isotropic independently of the LCO width. An isotropic deposition would correspond to a plating width twice as wide as the plated height with an aspect ratio \( AR_{h/w} \) of 1:2.

\[
AR_{h/w} = \frac{h}{\Delta w} = \frac{h}{(w_{\text{Finger}} - w_{\text{LCO}})}
\]

(1)

The resistive contribution of the fingers \( R_s,f \) to the series resistance \( R_s \) is determined by Equation 2. \( R_s,f \) is determined by characteristics of the finger with the conductivity \( \rho_f \), half of the length \( l_f \) between two BB, and cross-section area \( A_f \). The unit cell for the calculation consists of half of the BB width \( a \) and the finger pitch \( s \).26 For the plated contacts \( \rho_f \) of Cu is used, whereas for the screen-printed contacts \( \rho_f \) of bulk Ag is selected as ideal conductivity.

\[
R_s,f = \rho_f l_f \frac{a}{3A_f}
\]

(2)

To characterize the impact of the laser process onto the precursors, samples were submitted to a single side laser process either on the emitter or on the TOPCon side. A checkered laser pattern was selected with lasered and nonlasered (reference) fields similar to the characterization made by Arya.20 Within the laser pattern, a variation of the laser pulse energy was performed and randomly positioned onto the wafer resulting in different LCO widths. After the laser process, the precursors were fired together with the lasered solar cells mentioned above. Subsequently, modulated photoluminescence (Mod-PL) calibrated PL imaging (PLI) was performed and the implied open circuit \( (V_{\text{oc}}) \) was extracted.27,28 Comparing the \( V_{\text{oc}} \) from IV characterization and \( V_{\text{oc}} \) from PLI resulted in an estimated bulk doping of 2 \( \Omega \cdot \text{cm} \) used for the measurements.

A power loss analysis (PLA) is evaluated by using Quokka3 version 2 which involves the free energy loss analysis (FELA).29,30 For the simulation the plated champion solar cell with the highest efficiency is taken as reference. The losses are grouped into emitter, TOPCon, and bulk-related losses. Further, mainly optical loss paths such as light trapping and surface reflections are consolidated into a group other. Bulk, emitter, and TOPCon layer include their respective transport and recombination-induced losses. Optical losses originating from shading of the metal grid on the front side are included in the emitter losses.

### RESULTS AND DISCUSSION

#### 3.1 IV-results

Figure 2 shows the IV-results of the plated solar cells according to the LCO width and the number of fingers of the metal grid compared with the screen-printed reference solar cells. A maximum efficiency \( \eta \) of 23.7% was reached for a plated cell in the group with an average \( \eta \) of 23.6% with an LCO width of 5.5 \( \mu \text{m} \) and 163 fingers. The plated group with a LCO width of 14 \( \mu \text{m} \) matches the \( \eta \) of the references. For narrower LCO widths the plated groups achieve higher efficiencies. Furthermore, there was no indication that narrow LCO widths impacted the contact adhesion. The mean value of the best plated group outperforms the mean value of the reference group by about 0.6%\text{abs}. For the plated cells, the groups with fewer fingers (106) show higher open circuit voltages \( V_{\text{oc}} \) and short current densities \( J_{\text{sc}} \) than
their respective groups with 163 fingers due to a higher area coverage which increases the total contact recombination as well as the shaded area. Decreasing the LCO width leads to a reduction of the metal area coverage so that the $V_{oc}$ for the group with an LCO width of 5.5 $\mu$m exceeds the $V_{oc}$ of the references reaching nearly 710 mV. The $J_{sc}$ of the plated cells with an LCO width of 5.5 $\mu$m reaches a value of nearly 40.9 mA cm$^{-2}$ compared with around 40.4 mA cm$^{-2}$ for the references. The fill factor FF profits from the greater number of fingers stabilizing at 82% even though this impact gets lower for wider LCO widths outperforming the references FF of about 1% abs.

Some of the best plated with a LCO width of 5.5 $\mu$m and screen-printed solar cells taken from Figure 2 were transferred to Fraunhofer CalLab for certified IV measurements. The BB of the plated samples featured no specifically designed pads for contacting for IV characterization. Therefore, a busbarless contact system was used to contact the front side combined with a highly reflective and conductive gold chuck to contact the rear side.$^{31}$ Table 1 shows that the best screen-printed solar cell reached an efficiency of 23.46% yet outperformed by the plated solar cell achieving an efficiency of 23.84%. The plated cell profits from narrower fingers allowing higher $J_{sc}$ of 0.5 mA cm$^{-2}$ while reaching similar FF and $V_{oc}$. The full area (268 cm$^2$) measurements include the metal fingers and BB.

### 3.2 Optical contact properties

In Figure 3 laser microscopy images of LCO, plated, and screen-printed contact fingers are shown on both sides with their respective heights and widths. For the plated contacts on the front side only LCO and plated finger are shown for the 5.5 $\mu$m LCO opening width, whereas on the rear side the LCO shows a width of about 12.5 $\mu$m. The small LCO widths on the front side allow to generate narrow contact finger widths of 12 $\mu$m and height of 5.5 $\mu$m on the front side resulting in a $AR_{h/w}$ of 1:1.2. The wider rear side LCO results in a plated width of 22 $\mu$m and a height of 7 $\mu$m with an $AR_{h/w}$ of 1:1.4. Both sides show an anisotropic deposition allowing to achieve the same finger cross-section area with smaller widths. In contrast, the screen-printed fingers feature widths of 31 and 40 $\mu$m on the front and rear sides, respectively, with widths above 10 $\mu$m. Even though the dimension of the plated fingers on the 5.5 $\mu$m LCO width is significantly smaller than the screen-printed fingers, the resistive contribution of the plated fingers $R_{s,f}$ to the series resistance $R_s$ is in the range of 0.02 $\Omega$ cm$^2$ for 163 fingers and 0.04 $\Omega$ cm$^2$ for 106 fingers for an $R_s$ of 0.44 $\Omega$ cm$^2$ compared with 0.01 $\Omega$ cm$^2$ of the screen-printed fingers (100% Ag content) on both sides for a mean $R_s$ of 0.6 $\Omega$ cm$^2$.

### Table 1 IV-results of full area (268 cm$^2$) champion bifacial i-TOPCon solar cells according to the metallization type measured by Fraunhofer ISE CalLab

| Metallization | Shading percentage on front side (%) | $V_{oc}$ (mV) | $J_{sc}$ (mA cm$^{-2}$) | FF (%) | $\eta$ (%) |
|---------------|-------------------------------------|---------------|------------------------|--------|------------|
| Plating       | 1.6                                 | 709           | 40.9                   | 82.2   | 23.84      |
| Screen-printing| 2.5                                 | 708           | 40.4                   | 82.0   | 23.46      |

Note: The screen-printed solar cell features the grid with 9 BB 106 fingers whereas the plated solar cell features 9 BB and 163 fingers with an LCO widths of 5.5 $\mu$m on the front side.

Abbreviations: BB, busbars; i-TOPCon, industrial tunnel oxide and passivated contact; LCO, laser contact opening.

### FIGURE 3 Laser microscopy images of laser contact opening (LCO), plated and screen-printed contacts on front and rear side
3.3 | Resistive properties of contacts

Low contact resistances of the metallization to the emitter and TOPCon are evident to limit $R_s$ and maximize $FF$. Figure 4 shows the contact resistivity $\rho_c$ as a function of the metallized side, $R_s$, and $FF$ according to the HF pretreatment concentration and time for the plated solar cells compared with the screen-printed references. Although the HF concentration was raised to 1.5%, no increased parasitic plating was observed. Independently of the pretreatment conditions, plated metallization reaches mean values below 1 m$\Omega$cm$^2$ outperforming screen-printing metallization which reaches mean $\rho_c > 2$ m$\Omega$cm$^2$. On the TOPCon side the increase of the HF concentration from 1% to 1.5% for the same process time leads to a decrease of $\rho_c$ of about 0.1 m$\Omega$cm$^2$. On the emitter both increasing the process time and increasing the HF concentration reduce $\rho_c$ to a similar level slightly above 0.5 m$\Omega$cm$^2$. The trend of $\rho_c$ is also visible in $R_s$ and $FF$. The increase of the process time from 30 to 60 s at a HF concentration of 1% allows to reduce $R_s$ from (0.74 ± 0.18) Ωcm$^2$ to (0.54 ± 0.07) Ωcm$^2$. An increase of the HF concentration to 1.5% with a process time of 30 s even further decreases $R_s$ to (0.44 ± 0.10) Ωcm$^2$. Both variations allow to reduce $R_s$ of the plated solar cells under $R_s$ of the screen-printed references thereby increasing the $FF$. For the higher HF concentration a mean $FF = (82.1 ± 0.6)$ % (HF 1.5%, 30 s) is achieved exceeding the screen-printed references which reach a $FF = (81.3 ± 0.4)$ %.

3.4 | Contact recombination

In Figure 5 the $iV_{oc}$ of the single side lasered TOPCon precursors is shown according to the LCO width and the laser treated side after FFO. Additionally, Quokka3 simulations of the $iV_{oc}$ depending on the LCO width on the front side and the contact recombination described by the saturation current density on the emitter side $J_{0,\text{met } p}\text{-}\text{emitter}$ are displayed between 1000 and 3000 fA/cm$^2$. As mentioned, the different LCO widths on the front side originate from variation in laser spot size, maintaining the optimal fluence. The nonlasered fields are used as reference fields representing the passivated wafer ($iV_{oc} = 714 ± 3$ mV). As no LCO variation was performed on the TOPCon side, only one value is shown which shows no significant loss in $iV_{oc}$ with respect to the standard deviation being consistent with earlier results. The laser impact on the emitter side reveals to be more significant. Decreasing the LCO width leads to a reduction of the $iV_{oc}$ loss. As contact opening losses originate predominantly from the emitter side, the trend in $iV_{oc}$ matches the trend of $V_{oc}$ values extracted from the $IV$-results from Figure 2. The trend of the measured $iV_{oc}$ on the emitter side is located between the simulated $iV_{oc}$ for $J_{0,\text{met } p}\text{-}\text{emitter}$ of 1500–3000 fA/cm$^2$. 

![FIGURE 4](image)

**FIGURE 4** Contact resistivity $\rho_c$ according to the metallized side, series resistance $R_s$, and fill factor $FF$ as a function of the HF pretreatment conditions concentration and time for solar cells with 106 fingers. Additionally, the results of the screen-printed references are shown.

![FIGURE 5](image)

**FIGURE 5** $iV_{oc}$ as a function of the laser contact opening (LCO) and the laser treated side after fast-firing oven (FFO) resulting from photoluminescence imaging (PLI) characterization. Additionally, the $V_{oc}$ values from the $IV$-results extracted from Figure 2 are displayed. The nonlasered fields are presented as reference fields and correspond to a LCO width of 0 μm. Additionally, Quokka3 simulation of $V_{oc}$ is shown as a function of the LCO width for a variation in $J_{0,\text{met } p}\text{-}\text{emitter}$.
4 | LOSS ANALYSIS

Figure 6 shows the PLA obtained from Quokka3 simulation as a function of the LCO width and for $J_{0,\text{met} \ p - \text{emitter}}$ between 1000 and 3000 fA/cm² including the simulated efficiency of the solar cells. As can be seen two thirds of the losses can be attributed to optical components referred as Other. From the remaining third the emitter and the emitter side metallization combine the main losses summing to a range between 20% and 25% with respect to the LCO width and $J_{0,\text{met} \ p - \text{emitter}}$. The losses from the emitter arise mainly due to recombination of the passivated areas and the lateral current transport to the metal contacts. The emitter side metallization losses are divided into optical losses originating from grid shading and electrical losses including all resistive components of the metal grid and the contact resistance to the emitter as well as the recombination losses of the contacted areas induced by the metal contacts. The TOPCon layer and the metallization on the TOPCon side together with the bulk represent about the remaining 9%–13% losses. The reduction of the LCO width reduces the contacted area thereby reducing the contacted recombination as well as the grid shading. Limiting $J_{0,\text{met} \ p - \text{emitter}}$ allows to further reduce the electrical losses on the emitter side. Both strategies lead to a substantial increase in the efficiency. Consequently, improving of the emitter side metallization results in the fact that the emitter constitutes the highest loss apart from the Others as it remains unaffected by the variations.

5 | CONCLUSION

The plating process developed at Fraunhofer ISE for metallizing bifacial i-TOPCon solar cells allowed to achieve a confirmed champion efficiency of 23.84% measured at Fraunhofer ISE CalLab. The reported efficiency was measured on a full area (268 cm²) illuminated solar cell including metal finger and BB and with a screen-printed reference solar cell provided by the industrial supplier of the precursors with a maximum efficiency of 23.46%. Reducing the LCO width and adapting the number fingers, the plated contacts benefit from narrower contact widths down to 5.5 μm allowing a $J_{SC}$ gain of nearly up to 0.5 mA/cm². There were no indications of the LCO width impacting the contact adhesion. Optimization of the HF pretreatment prior to the plating process showed an improvement of the contact resistivity allowing to stabilize the FF above 82% despite smaller contact geometries than the screen-printed references. Analysis of the laser process showed that the laser impact on the TOPCon side is negligibly low, whereas the laser impact on the front side emitter is identified as main source of $iV_{oc}$ loss bearing a large potential for further improvements. The reduction of the LCO width allowed to reach voltages close to 710 mV surpassing the screen-printed reference. Industrial implementation of such narrow LCO structures requires larger effective optical apertures as well as parallelization of the laser process to enable the throughput. PLA with Quokka3 simulation discloses the emitter side including the metallization and shading as main loss contributor. Reducing the $J_{0,\text{met} \ p - \text{emitter}}$ and decreasing the LCO width combined with $\rho_c < 0.4 \, \text{m} \Omega \text{cm}^2$ allows to diminish the losses. Plating metallization reveals to be a suitable candidate to metallize i-TOPCon solar cells with high efficiencies exceeding the screen-printed baseline metallization.

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DATA AVAILABILITY STATEMENT

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