Laser Ablation and Ni/Cu Plating Approach for Tunnel Oxide Passivated Contacts Solar Cells with Variate Polysilicon Layer Thickness: Gains and Possibilities in Comparison to Screen Printing

Varun Arya,* Bernd Steinhauser, Benjamin Gruebel, Christian Schmiga, Norbert Bay, Damian Brunner, Michael Passig, Andreas A. Brand, Sven Kluska, and Jan Nekarda

Herein, an alternative approach of metallization on tunnel oxide passivated contacts (TOPCon) devices, through the method of localized laser ablation and nickel–copper plating, is presented. The method is demonstrated to be a viable and effective alternative, yielding better performance and results than the conventional screen-printed contacts. The laser ablation process, with a lower increase in recombination current as compared to screen printing, proves to be a far less damaging process than the latter. TOPCon solar cells, fabricated and compared using the two metallization approaches, show a substantial improvement in an absolute power efficiency of ≈1%. Due to the highly superficial nature of damage with the optimized laser parameters, it enables the reduction of the poly-Si layer thickness down to 70 nm in the TOPCon stack and also a high cell conversion efficiency of 22%. This allows for a substantial reduction in ownership costs of the final device without compromising on performance, making TOPCon cells with plated contacts an attractive technological upgrade for industrial-level production following the passivated emitter rear contact cell technology.

1. Introduction

Recombination of photo-generated charge carriers at metal–semiconductor junctions is a strong limiting factor in achieving high efficiencies for conventional c-Si solar cells [e.g., aluminum back scatter field, passivated emitter rear contact (PERC), etc.]\(^1\)–\(^3\)

This can be reduced by squeezing the metallized area fraction, but that results in an increase of fill-factor (FF) losses. A novel approach developed at Fraunhofer ISE, namely, tunnel oxide passivated contacts (TOPCon), attempts to counter this effect by implementing passivating contact structures to drastically reduce metal–semiconductor junction recombination.\(^1\)–\(^3\)\(^,\)\(^4\) Passivated contact layers, such as TOPCon, constitute an ultrathin (1–2 nm) silicon oxide (SiO\(_x\)) layer grown over the bulk c-Si, which is further deposited upon with a highly doped poly-Si layer and finally capped with SiN\(_x\). Together they provide excellent passivation, enabling high implied open circuit voltage \((iV_{oc})\)\(^2\) and carrier selectivity.\(^2\)\(^,\)\(^4\) Furthermore, the depletion zone field generated due to high doping of poly-Si also contributes to the passivation effect.

Passivating contacts are, therefore, considered to be the next major technological upgrade in the solar cell technology.\(^1\)–\(^4\) However, forming metal contacts on TOPCon is still a challenge that requires further investigation and improvements. Some commonly reported concerns pertaining to the conventional screen-printed metallization on TOPCon are 1) higher specific contact resistivity \((1.5–10 \Omega \text{cm})\) on thick (>150 nm) poly-Si passivated contacts\(^5\) and 2) increase of metal-induced recombination with decreasing thickness of poly-Si due to the metal spiking through the poly-Si and coming in contact with the bulk c-Si.\(^6\)

Spiking of the metal paste through the poly-Si layer drastically increases the \(J_{0,\text{sn}}\) (recombination current at metal–silicon junction) due to poor shielding of recombination at metal contacts, resulting in a low open circuit voltage \((iV_{oc})\).\(^6\) To prevent the penetration of fire-through metal pastes all the way through to the c-Si substrate, it becomes necessary either to keep the thickness of poly-Si above 120 nm or use low temperature metallization techniques.\(^7\)–\(^10\) However, a thicker poly-Si layer has two serious drawbacks—increased parasitic absorption and higher cost of ownership (COO). Parasitic absorption inflates with increasing poly-Si thickness, resulting in the loss of short circuit current \((J_{sc})\)\(^6\)\(^,\)\(^11\)\(^,\)\(^12\) whereas the COO calculations reveal a jump of around 75% if the poly-Si thickness is increased from 50 to 200 nm.\(^13\) Hence, to keep the parasitic absorption and the cost

**V. Arya, Dr. B. Steinhauser, B. Gruebel, C. Schmiga, A. A. Brand, Dr. S. Kluska, Dr. J. Nekarda
Fraunhofer ISE
Heidenhofstrasse 2, 79110 Freiburg im Breisgau, Germany
E-mail: varun.arya@ise.fraunhofer.de
N. Bay, D. Brunner, M. Passig
RENA Technologies GmbH
Hans-Bunte-Strasse 19, 79108 Freiburg im Breisgau, Germany
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of fabrication/ownership low, it becomes imperative and desirable that the thickness of the poly-Si layer be reduced.

To bypass the metal paste spiking issue, we suggest the approach of locally laser ablating the top dielectric layer (laser contact opening (LCO) process). Using wavelength and pulse-duration optimized laser pulses, the laser damage is kept largely superficial, which is calibrated by following the principles of laser–silicon interaction. This is followed by nickel–copper (Ni/Cu) electroplating to form the metallic contact grid on the TOPCon surface. The Ni/Cu contacts are covered with a thin capping layer of silver (Ag) that is around 0.5 μm thick, which prevents corrosion of Cu and enables solder interconnections.

Initial attempts at contacting passivated contacts devices, such as polycrystalline silicon on oxide (POLO) interdigitated back contact cells through UV pulsed laser ablation by Haase et al.,\(^\text{[15]}\) show excellent results of 26.1% cell efficiency. Grübel et al.\(^\text{[16]}\) demonstrated very low resistive contacts ($\rho_{\text{res}} = 0.2 \pm 0.1 \text{ mΩ cm}^2$) on 150 nm thick TOPCon samples by the LCO – Ni/Cu/Au plating process, which is very promising. However, whether this allows for the reduction of the TOPCon layer thickness has not yet been investigated. Implementing Ni/Cu/Au-plated contacts instead of screen-printed silver paste contacts also drastically brings down the material costs by a factor of 100.\(^\text{[13]}\)

In this article, it is demonstrated that 60–70 nm poly-Si is sufficient to absorb most of the laser damage and prevent excessive and irreversible damage to the entire TOPCon stack. The laser ablated and plated contacts allow reduction of the thickness of the TOPCon stack without drastically increasing the $J_{\text{0,met}}$ on industrially relevant surface topology, thereby positioning LCO and Ni/Cu/Au plating as a viable alternative to screen-printed contacts on passivated contact structures.

2. Experiment Section

Topologically asymmetrical lifetime TOPCon samples with n-type bulk and a base resistivity of $1 \text{ Ω cm}$ were fabricated using Cz-Si wafers as a base material. The layer structure schematic of the lifetime samples is shown in Figure 1.

Both sides received alkaline etching to generate a random-pyramid (RP) texture. The processing sequence for the experiment is shown in Figure 2. The samples were then etched on one side in a HNO$_3$/HF etchant solution, as industrially used for single-sided emitter diffusion removal. Afterward, the wafers were cleaned in HNO$_3$ and HF before the passivation by the TOPCon process. For the TOPCon passivation, the interfacial oxide was formed in a tube furnace at 600 °C under nitrogen/oxygen atmosphere and coated with phosphorus-doped amorphous silicon on both sides, deposited using plasma-enhanced chemical vapor deposition.\(^\text{[17]}\)

The thickness of the poly silicon layer was varied in four steps: 35, 60, 90, and 110 nm. The transition from amorphous silicon to polycrystalline silicon was performed in a tube furnace at 900 °C under nitrogen atmosphere. The poly-Si was coated on both sides with amorphous silicon nitride using an in-line MeyerBurger MAiA tool.

The laser used in this experiment is a diode-pumped mode-locked laser, namely, HYPER RAPID from Coherent Inc. It produces UV (355 nm) picosecond pulsed laser with a pulse duration ($\tau$) of $<10$ ps. The laser beam was fed to an x-y translational galvo-scanner to scribe the laser beam, focused to a spot size of $\approx25$ μm through an F-theta lens that corrects for the focus plane curvature and flattens the focus plane. Each single pulse ablates open a single spot of a certain diameter, depending on the pulse energy. Hence, pulse pitch was adjusted, so that the ablated spots are adjacent and touch each other (i.e., pulse pitch = opening dia.), resulting in a continuous ablated line with opening width equal to the diameter.

In general, the lifetime samples, as well as the solar cells, were kept stable using a vacuum chuck during the lasering process runs to avoid misalignments and inhomogeneity. Laser test-fields pattern was created on samples where the laser fields (shown in red shade in Figure 3) contained singular ablated lines with a line-to-line pitch of 1.0 mm. The pulse energy was varied from field to field, and the lasered field were placed alternately with non-lasered “reference fields” (shown in green shade) as per the distribution shown in Figure 3.

The reference fields serve the purpose of providing information about the baseline recombination activity of the TOPCon stack (or $J_{\text{0,pass}}$ as in Figure 5b) and also for tracking possible changes or deteriorations, if any, in the passivation quality due to processes other than LCO. This also helps in identifying if the change in recombination current is solely due to the laser process or if there are other sources of degradation in the process chain. For the purpose of lifetime characterization, combination of modulated photoluminescence (Mod-PL) and photoluminescence imaging (PLI) was used as the primary method. Thorough information regarding the experimental setup and the data analysis method for the Mod-PL calibrated PLI is presented in extensive details by Höfler et al. in his recent work.\(^\text{[18]}\)

The algorithm also generates $J_0$ and $i_{\text{Voc}}$ images from the lifetime calibrated PL images of the samples, and hence, the methodology bypasses the need for calibration by photoconductance measurements. It is highly reproducible, and the results are comparable to those of photoconductance lifetime measurements to a great degree. Another major benefit of Mod-PL calibrated PLI is that Mod-PL can be used to measure lifetime of metallized samples.\(^\text{[19]}\) It was especially useful and straightforward for measuring the recombination current density at metal–silicon junction ($J_{\text{0,met}}$) of screen-printed contacts in our experiments.

Mod-PL calibrated PLI (henceforth, mentioned just as “calibrated PLI”) was performed at multiple stages. First, it was performed before the LCO process and then directly after the LCO process. The samples were, thereafter, subjected to a thermal annealing process in a fast-firing oven (termed “FFO”...
in Figure 2) at the set peak temperatures of 820 °C, as it has shown to reverse the laser damage and improve the lifetime of the cells. After the FFO, they were subjected to the final round of calibrated PL measurements.

The $J_0$ calibrated PLI images of the lasered samples were then subjected to field evaluation, using a custom built Python-based tool for automated analysis of multiple fields at the same time. It also performs automated calculations to deduce the change in $J_0$ of laser fields in comparison with the reference fields (or $\Delta J_0$). It works by recognizing and measuring all the reference fields and averages the $J_0$ of all of them, providing with baseline $J_0$, ref (or $J_{0\text{ref}}$ as in Equation (1)). It then does the same with the laser.
fields of all the pulse energies and generates the average \( J_{0e2} \) for each pulse energy (see Equation (2)). Subtracting the two values provides the increase/decrease in \( J_0 \) or \( \Delta J_0 \). Figure 4 shows the various stages of processing of automated analysis tool and also shows, pictorially, how the field evaluation method works.

The field evaluation process was done at two stages—first, after LCO and result is denoted by “\( \Delta J_{0,LCO} \)”, and second, after the FFO, denoted by “\( \Delta J_{0,LCO + FFO} \)”. The following equations show the working algorithm to extract these values.

\[
J_{0e1} = J_{0,ref} 
\]

\[
J_{0e2} = f(J_{0,MET-LCO}) + (1-f)J_{0,ref} 
\]

\[
\Delta J_{0,LCO} = J_{0e2} - J_{0e1} = f(J_{0,MET-LCO}) + (1-f)J_{0,ref} - J_{0,ref} 
\]

Similarly,

\[
\Delta J_{0,LCO + FFO} = J_{0e2} - J_{0e1} = f(J_{0,MET-LCO + FFO}) + (1-f)J_{0,ref} - J_{0,ref} 
\]

The entities \( \Delta J_{0,LCO} \) or \( \Delta J_{0,LCO + FFO} \) represent the absolute change in \( J_0 \) (after the LCO or LCO + FFO process) of an entire field and were, therefore, further normalized by the percentage of ablated area (area fraction “\( f \)”) generated by the used pulse energy in that field. For calculating the area fraction of a field, where each field was \( 2 \times 2 \text{cm}^2 \) in dimension, microscopy images were used to measure the finger width. The measured width of the finger was multiplied by the length of the finger (2 cm) and the total no. of fingers in a field, that gave the total ablated area which was then divided by the total field area (\( \approx 4 \text{cm}^2 \)).

This yielded \( J_{0,MET-LCO} \) and \( J_{0,MET-LCO + FFO} \), which are the area-fraction normalized values of \( \Delta J_{0,LCO} \) and \( \Delta J_{0,LCO + FFO} \), respectively. These terms are equivalent and comparable to the \( J_{0,ref} \) results of screen-printed samples. The derivations are shown in the following equations.

Solving Equation (3) further yields

\[
J_{0e2} - J_{0e1} = f(J_{0,MET-LCO}) - f \cdot J_{0,ref} 
\]

\[
J_{0e2} - J_{0e1} + f \cdot J_{0,ref} = f(J_{0,MET-LCO}) 
\]

The above-mentioned equation can be re-written by replacing \( J_{0e1} \) with \( J_{0e1} \) as per Equation (1).

\[
J_{0e2} - J_{0e1} + f \cdot J_{0,ref} = f(J_{0,MET-LCO}) 
\]

\[
J_{0e2} - J_{0e1}(1-f) = f(J_{0,MET-LCO}) 
\]

As usually for laser fields, the ablated area fraction is very low \( \approx 1\% \) because of finger width in the range of 10–20 \( \mu \text{m} \), and the \( (1-f) \) term is approximated to 1, resulting in the following equation.

\[
J_{0e2} - J_{0e1} = f(J_{0,MET-LCO}) 
\]

\[
\frac{J_{0e2} - J_{0e1}}{J_{0,ref}} = f(J_{0,MET-LCO}) 
\]

Using Equation (3), we reach the final expression for \( J_{0,MET-LCO} \) and \( J_{0,MET-LCO + FFO} \).

\[
\frac{\Delta J_{0,LCO}}{J_{0,ref}} = J_{0,MET-LCO} 
\]

And similarly,

\[
\frac{\Delta J_{0,LCO + FFO}}{J_{0,ref}} = J_{0,MET-LCO + FFO} 
\]

For comparing the performance of laser ablated contacts to screen-printed contacts, some of the samples were subjected to the screen printing process using a standard fire through silver paste followed by FFO for contact formation. A test layout was used to print a chequered field pattern, similar to the one used for laser ablation (without any sort of variation). The printed fingers were \( \approx 50 \mu \text{m} \) wide, and the finger pitch was 1.0 mm. These samples were then subjected to the same evaluation sequence as the LCO samples.

2.1. TOPCon Solar Cell Batch

Another batch of samples with boron-doped p-type emitter on the front side and TOPCon stack on the rear side was fabricated to test the efficacy of LCO and Ni/Cu/Ag plating on solar cell devices and investigate the benefit this metallization approach can generate. Figure 5 shows the cross-sectional schematic of the precursors and an example of the final cell structure with plated contacts on TOPCon surface. The process chain to fabricate the solar cell precursors is also shown in Figure 2. The same base material, i.e., n-type Cz-Si wafers as bulk and a resistivity of \( 1 \Omega \text{cm} \), was used. After passing the wafers through the exactly similar process of alkaline etch on both sides to generate RPs, the samples were subjected to boron doping to form the p-type emitter. The rear side was then subjected to the HNO\(_3\)/HF etch back process to remove the emitter.

TOPCon passivation was performed as described in the previous section, but with the poly-Si thicknesses of 40, 60, 80, and 100 nm. After the TOPCon anneal at 900 °C the samples were subjected to an O\(_2\)/HF solution to remove TOPCon wrap-around, resulting in a TOPCon layer thickness reduced by about 10 nm; i.e., a final poly-Si thickness in cell devices was 30, 50, 70, and 90 nm. A stack of Al\(_2\)O\(_3\)/Si\(_3\)N\(_4\) then passivated the boron emitter (front side), and the TOPCon stack was coated with Si\(_3\)N\(_4\) acting as the hydrogen source.
Metal finger contacts were printed on the front, with a pitch of 1.3 mm were using commercially available AgAl paste. Hereon, two different metallization approaches for the TOPCon surface were taken to make the solar cells: 1) screen printed with Ag paste and fired at a peak temperature of 820 °C and 2) LCO followed by firing at 820 °C and subsequently plating. Finger pitch in both cases on rear side was kept to 0.8 mm. For the purpose of plating the ablated openings, the solar cells were subjected to the light-induced plating (LIP) process in an in-line plating tool “InCellPlate” from Rena Technologies GmbH.

To initiate the plating process, the TOPCon side was contacted with 1% HF solution for 30 s to remove the native and laser-induced oxide, formed at the laser openings. For the following Ni and Cu layer deposition, the laser ablated side of the cell was then immersed in the plating electrolyte while being illuminated by light emitting diodes. The light intensity could be adjusted to control the current generated by the solar cells, which, in turn, would control the plating rate and behavior. The front, screen-printed side, was contacted with a temporary metal plate, pressed against the printed fingers, to complete the galvanic circuit.

Through this process, a nickel seed layer of ~1 μm was deposited and subsequently covered by a thick layer of copper (~8 μm). Finally, the copper fingers were subjected to an electroless Ag bath to deposit a thin capping over the fingers. The complete plating parameters and information regarding the electrolytes can be found in Table 1.

**Figure 4.** The above-mentioned series of images showcases various stages of processing and graphs generated by the automated Python-based analysis tool. For example, PL image (top row) of a processed 60 nm thick poly-Si TOPCon sample, after Mod-PL calibration, was converted to an $iV_{oc}$ heat map (second row). Furthermore, heat-map graph of $\Delta J_0$ (third row) was generated at both stages of processing, and the last row illustrates how multiple region of interests are generated (indicated by the red colored boxes) to capture and evaluate each separate field.
levels for 60 nm samples at all pulse energies. Whereas after the FFO fi/
C0/C0 – LCO/C0 at a possible explanation þ at the device level. LCOþ Helios/C14 LCO10 0.5 – LCO/J have also observed a similar The 2/LCO– LCO show indicates (–2 μ/C.) increases because of LCO at almost all /C14/C0 LCO fi layer is extremely thin (1.2 μ/C.) at higher pulse energies, FFO. Furthermore, detailed information about the plating setup, plating conditions, and plating results on TOPCon surfaces can be found in the recent work of Grübel et al.[21] Cells created by the two metallization approaches were then subjected to I–V measurements, and their performances were compared.

3. Results and Discussion

The plots in Figure 6 show $J_{0,MET-LCO}$ and $J_{0,MET-LCO+FFO}$ against the pulse energies for samples of all thicknesses. Some clear trends that emerge are: first, with increasing thickness, there is a substantial drop in the $J_{0,MET-LCO}$ at almost all pulse energies.

For the TOPCon samples with thicker poly-Si layer (>90 nm), the drop in recombination current is more substantial as is apparent in the $J_{0,MET-LCO+FFO}$ levels. For 90 nm poly-Si TOPCon samples, the median of $J_{0,MET-LCO}$ stayed constantly above 1000 $\text{fA cm}^{-2}$ at all pulse energies. Whereas after the FFO process, the median levels of $J_{0,MET-LCO+FFO}$ dropped down to around 500 $\text{fA cm}^{-2}$ for lower pulse energies, and it decreased further down to below 100 $\text{fA cm}^{-2}$ at higher pulse energies, as the total ablated area percentage ($f$) increases because of larger openings. For the 110 nm poly-Si thickness samples, the laser damage has been annealed to a large extent, and especially, at higher pulse energies, the $J_{0,MET-LCO+FFO}$ indicates that the LCO does not result in a significantly increased recombination, as median levels drop below 10 $\text{fA cm}^{-2}$, whereas the 60 nm thick poly-Si TOPCon samples show stabilized $J_{0,MET-LCO+FFO}$ median levels of around 200–500 $\text{fA cm}^{-2}$ at high pulse energies, post thermal annealing (FFO). Despite the small irregularities and spread of data, even the 60 nm TOPCon should yield a good $V_{oc}$ at the device level.

The effect of the thermal annealing reverting the laser damage is in congruence with the experiments on PERC devices,[19] whereas similar effects have also been reported by Molto et al.[20] This phenomenon can be explained by the thermal anneal-assisted recrystallization[22–24] of the amorphous-type silicon material, which is generated around the ablated spot due to the nature of interaction of silicon and picosecond laser pulses.[25,26]

Raman scattering spectra performed by Marcins et al. reveal amorphous silicon transforming to nearly fully crystallized poly-Si film after subjecting to the temperatures of 700–1100°C.[24] Hence, it is understandable that a similar mechanism is working here as well.

Furthermore, the plots reveal that 35 nm samples show substantially more remaining damage and elevated levels of $J_{0,MET-LCO+FFO}$ when juxtaposed to the 60 nm samples. As the UV (355 nm) picosecond pulses, governed by the laws of optical absorption and thermal penetration, have a penetration depth of 50–60 nm on interaction with silicon,[14] a possible explanation can be drawn that with the decreasing poly-Si thickness, the interfacial oxide layer has also started seeing damage as it relatively closer (only 35 nm) to the surface where the laser pulse first strikes, and it falls in the range of the heat affected zone (HAZ) generated by the laser pulse.

Although SiO$_x$ is transparent to the 355 nm wavelength radiation, but at sufficiently higher energies, some amount of interaction with the oxide layer can happen by the mechanism of multiphoton absorption. Though this is highly unlikely as the SiO$_x$ layer is extremely thin (1.2–1.3 μm) but considering for sake of postulation, this can lead to creation of pinholes or even delamination of the SiO$_x$, meaning drastic drop in passivation quality, which would translate to high recombination activity. Interestingly, Rana and Zhang[27] have also observed a similar interactional behavior of SiO$_x$ with UV ultrashort laser pulses.

Another, more probable, working theory reported by Hermann et al. attempting to explain the damage to SiO$_x$ is that laser irradiation is absorbed by the silicon substrate underneath, and the delamination of the oxide is consequently initiated by the vaporization of the silicon substrate, a mechanism also known as spallation or liftoff.[28]

The understanding of the heat affected depth might also explain the drastic drop in the $J_{0,MET-LCO+FFO}$ levels for 60 nm samples as compared with 35 nm samples. It could be postulated that oxide layer is largely protected from the energy deposited by the laser pulses in the 60 nm samples, and the overlying poly-Si layer absorbs maximum of the energy. Any damage to the poly-Si (or amorphization) is reversed by the thermal annealing step, and what remains is, perhaps, very little damage to negligible damage to the SiO$_x$ as it is just at the border of the HAZ. Hence, a drop
to very low levels of $J_{0,MET-C0,LCO}$ is visible. This postulation would also explain why the change in $J_{0,MET-C0,LCO+FFO}$ from 90 to 110 nm samples is negligible as compared with the stronger shift in $J_{0,MET-C0,LCO+FFO}$ for 35–60 nm samples.

Figure 7 shows the $J_{0,met}$ (denoted by $J_{0,MET-SP}$ on the y-axis) for the screen-printed contacts, and in comparison, it shows excessive lifetime damage than laser ablation. The increase in $J_0$ after the screen-printing was the highest for, as expected, the thinnest 35 nm TOPCon samples. Although the thicker 110 nm samples show less damage, yet they still surpass laser ablation figures by a factor of 10–20. This further justifies the search for better approaches to metallization of passivated contacts.[6]

3.1. Cell Results

Solar cells fabricated by two metallization techniques were processed through an $I–V$ cell tester. The $I–V$ performance of the cells is shown in Figure 8. The former approach is termed “Screen-Printed,” and the latter is termed “LCO/Plating” in the legend of Figure 8 to maintain easy nomenclature.

Comparison of efficiencies shows that plating out performs screen-printed cells for all thicknesses of poly-Si in TOPCon. Even for the thickest 90 nm samples, the gap in the efficiencies between plated and printed cells is almost 1% (absolute).

The damage from the screen-printing process is so thorough that even the plated 30 nm cells perform better than 90 nm screen-printed cells. The primary damage of screen-printed cells is visible in $V_{oc}$ and short circuit current $J_{sc}$. The metal paste spiking through poly-Si, damaging the intermediate oxide layer and contacting the c-Si, resulting in high recombination,[6] can explain the drop in $V_{oc}$ and $J_{sc}$.

The FF remained largely constant in both cases and over all thicknesses, as shown in Figure 8, which indicates that plated contacts, although with higher $iV_{oc}$ and pseudo-FF (pFF) in comparison with printed contacts, are more resistive and, hence, pull down their FF. The slightly higher series resistance ($R_s$) values of plated contacts also corroborate with the same line of explanation. Eventually, even for 30 nm thick TOPCon cells, a high efficiency of 21.6% was achieved, and the best cell performance was 22% efficiency on 70 nm TOPCon cells.
4. Conclusion

Pulsed laser ablation with an optimized wavelength of 355 nm and picosecond pulses followed by nickel–copper plating can generate contacts that are less damaging to the TOPCon stack than conventional fire-through paste-based screen-printed contacts. Laser ablation also allows to drastically reduce the thickness of the poly-Si layer, as the damage is largely superficial and,
mostly importantly, is reversible by thermal annealing. Applying LCO and Ni/Cu/Ag plating on TOPCon cells enabled an efficiency of 22% with 70 nm thick poly-Si layer. Thereby, it enables to reduce production, material, and ownership costs, making it a viable, efficient, and an economical approach for metallization of large-scale, high-throughput industrial-level manufacturing of TOPCon solar cells.

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Conflict of Interest
The authors declare no conflict of interest.

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