Presented at the 37th European PV Solar Energy Conference and Exhibition, 7-11 September 2020

PLATING ON TOPCON AS A WAY TO REDUCE THE FABRICATION COSTS OF I-TOPCON SOLAR CELLS

Bernd Steinhauser[1], Benjamin Grübel[1], Sebastian Nold[1], Varun Arya[1], Christian Schmiga[1], Sven Kluska[1], Andreas A. Brand[1], Frank Feldmann[1], Norbert Bay[2], Xavier Gay[2], Michael Passig[2], Markus Glatthaar[1]
[1]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany
[2]RENA Technologies, Höhenweg 1, 78148 Gütenbach, Germany

ABSTRACT: i-TOPCon solar cells commonly make use of a TOPCon/SiN_x stack at the rear side. For screen-printed contacts, a certain TOPCon layer thickness in the range of 110 to 150 nm is usually required to prevent spiking of the contacts. In this publication, it is shown that laser contact opening can be used in a thickness range of 60 to 90 nm with a $J_{0,\mathrm{met}}$ of around 50 fA/cm^2 for a thickness of 90 nm. The $J_{0,\mathrm{met}}$ of over 1000 fA/cm^2 for the screen-printed references indicates that in this thickness range screen-printing is not a viable technology with state-of-the-art pastes. However, the reduction in the TOPCon thickness can give a significant advantage in the cost of ownership for the TOPCon deposition due to the reduced deposition time. The variation of the TOPCon thickness is investigated on solar cells as well proving again that screen-printing on less than 100 nm thick TOPCon layers should be avoided. On the other hand, laser contact opening in combination with plated contacts is shown to work well reaching an efficiency of 22 % limited by the front side emitter passivation and contact.

Keywords: Passivating Contacts, TOPCon, Plating

1 INTRODUCTION

Passivating contacts realized by a thin interfacial oxide and a heavily doped poly-Si layer (hereafter referred to as TOPCon) are considered as the next-generation technology after PERC. Its huge efficiency potential has been underlined by both an IBC lab cell achieving 26.1% efficiency [1] and a 25.8%-efficient n-type lab cell featuring front and rear contacts [2]. The industrial implementation of this layout featuring a boron emitter passivated by Al_2O_3/SiN_x at the front side and a TOPCon/SiN_x passivation on the rear side is typically called i-TOPCon. Here the SiN_x is deposited on top of the poly-Si as an optical layer and hydrogen source. So far, the favored solution for i-TOPCon by research institutes and companies seems to be to contact the layers by screen-printing of silver pastes. However, other approaches are considered as well and in this work we are discussing the advantages of plating of nickel and copper on TOPCon as an alternative metallization technique. This approach makes use of laser contact opening (LCO) of the dielectric layer (SiN_x). The laser ablation of dielectrics on TOPCon (or poly-Si) layers was already successfully demonstrated by Haase et al. requiring a minimum of 60 nm poly-Si to avoid increased recombination due to the laser process [1]. The implementation of LCO/Plating for i-TOPCon cells was demonstrated by Grübel et al. [3]. For typical i-TOPCon precursors no influence of laser-damage was observed. Since the precursors were optimized for screen-printed contacts, this is attributed to the rather thick TOPCon layers that are used in these cases to prevent metal spiking [4].

In this work, we discuss the merits of LCO/Plating as an alternative metallization approach to screen-printing. These technologies are especially compared in a TOPCon thickness range well below the optimum for screen-printed contacts. This is motivated by the cost of ownership calculation for the TOPCon deposition. The impact of the metallization techniques is first investigated on dedicated lifetime test samples to gather information about the contact recombination and in a second step at the device level on i-TOPCon solar cells.

2 COST OF OWNERSHIP CALCULATIONS

Figure 1 shows cost of ownership (COO) results for fully screen-printed cells in comparison to plated cells [5]. For the plating on the TOPCon side (which is the focus of this work) a significant reduction in the fabrication cost could be achieved by switching to LCO/Plating at the rear due to the material cost of the silver paste in case of screen-printing.

The observations regarding the laser damage by Grübel et al. [3] hint that further cost reductions will be possible by reducing the requirement on the TOPCon layer thickness in the TOPCon/SiN_x stack. Figure 2 shows the normalized COO for the TOPCon process for a variation of the deposition time and hence the TOPCon layer thickness. Each 50 nm reduction results in a further 14 % reduction in the COO. Updated calculations by Kafle et al. [6] indicate that this effect is especially present for TOPCon deposition by APCVD and PECVD, but less pronounced in case of LPCVD. With thinner TOPCon layers an additional advantage is expected but not taken into account here: Thinner TOPCon lead to a higher efficiency due to reduced free-carrier absorption (FCA) and by that an increase in J_{SC} [7].

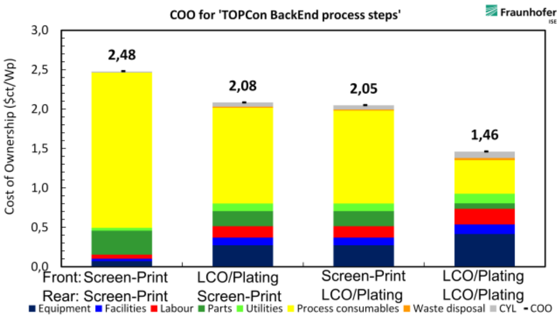

Figure 1: Cost of ownership calculations for the back-end processes. Taken from [5].

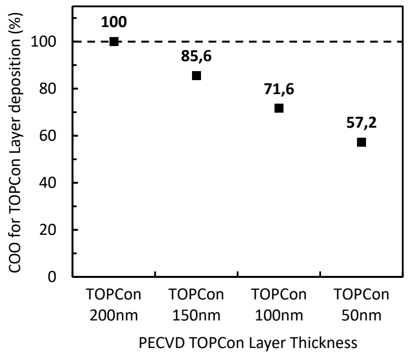

Figure 2: Normalized cost of ownership (COO) for the PECVD TOPCon process with decreasing TOPCon layer thickness. The typical thickness as used for screen-printing on TOPCon is in the range of 100 to 200 nm. Taken from [5].

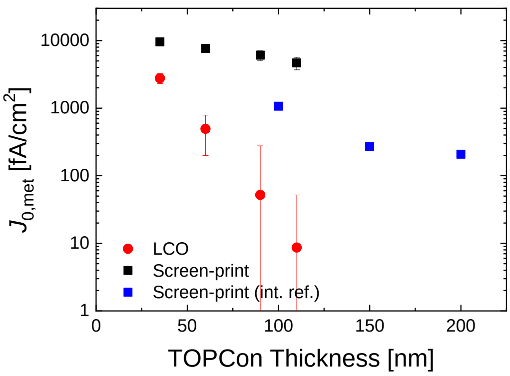

Figure 3: $J_{0,met}$ for LCO in comparison to screen-printed contacts for a variation of the TOPCon thickness in comparison to screen-printed references. In addition the values for screen-printed contacts for a second batch (internal reference) is given, for which the values were a bit lower but still significantly higher than for LCO.

3 TOPCON THICKNESS VARIATION

3.1 Experimental Details

TOPCon lifetime samples were prepared on M2-sized, *n*-type Cz wafers. After saw damage removal, the wafers were textured in KOH. On the rear side the texture was removed in a solution of HNO_3 and HF to achieve a surface topology similar to that of typical i-TOPCon solar cells. The wafers where then cleaned following the RCA procedure. Thereafter, an about 1.2 nm thin tunnel oxide layer was thermally grown in a tube furnace. In-situ Phosphorus-doped a-Si films were deposited on both sides by direct-plasma tube PECVD followed by a 10-minute anneal at 900 °C. SiN_x was deposited on top of the poly-Si on both sides as a hydrogen source. The samples were then processed by a UV-ps laser (355 nm, < 15 ps pulse duration) on the rear side to remove the SiN_x locally. The laser-processed areas were arranged in a chessboard-like field structure with varying pulse energy in the laser-treated fields and neighboring reference fields without laser treatment. Instead of the laser processing, for the reference samples silver was printed onto the samples in an equivalent layout by screen-printing. The samples were then fired in an in-line fast-firing furnace to activate the passivation, anneal possible laser damage and – for the reference samples – trigger the contact formation.

To characterize the influence of the laser ablation / contact formation we used calibrated photoluminescence imaging (PLI) at one sun illumination. The $J_{0,met}$ was extracted from the difference of the processed (laser or printed) and the corresponding reference fields normalized to the processed area.

3.2 $J_{0,met}$ Analysis

Figure 3 shows the $J_{0,met}$ after LCO and firing in comparison to the reference samples after screen-printing an firing. Here we only present the results for one laser pulse energy (suitable for the usage on solar cells). A broader variation is discussed in [8]. In addition to the screen-printed references within this experiment, we also show additional values that were determined in another experiment equivalently for higher TOPCon thicknesses. While there is a certain discrepancy between the two sets of screen-printed samples, the values for the LCO-processed samples were still significantly lower in any case. At a thickness of 110 nm, the $J_{0,met}$ is in the range of 10 fA/cm^2, which means that in solar cells the influence would be barely noticeable, since the metallized area fraction is usually below 10 %. This is in accordance with the observations by Grübel et al. who found little influence in a large range of laser intensities suitable to ablate SiN_x on typical TOPCon precursors, which have TOPCon thicknesses within this range [3]. At lower thicknesses we observe an exponential increase in $J_{0,met}$ with decreasing thickness, but even at 90 nm the $J_{0,met}$ is reasonably low with around 50 fA/cm^2. At 60 nm we determined a $J_{0,met}$ of approx. 500 fA/cm^2, which is similar to what we can achieve with screen-printed contacts at twice the TOPCon thickness or more. Thus, at around 60 nm the recombination at the rear contacts becomes noticeable. At first this seems to contradict the results determined by Haase et al. [1], who showed that recombination-free ablation is possible with a thickness of 60 nm or higher on planar surface. However, since the surface of our wafers is rougher, we expect an increased impact due to the laser processing [9] compared to planar surfaces meaning that a higher TOPCon thickness could be required for very low recombination after ablation.

4 TOPCON SOLAR CELLS

4.1 Experimental Details

TOPCon solar cells were realized on M2-sized, n-type 1 Ωcm wafers. The solar cells are discussed in more detail in [8]. The basic layout is shown in Figure 4. After saw damage removal the wafers were textured in KOH and cleaned according to the RCA procedure. The wafers were then diffused in a BBr_3 tube furnace. The emitter was etched-back on the rear side in a solution of HNO_3 and HF. The rear side was passivated by the TOPCon process as outlined in the previous section. After anneal about 10 nm of the poly-Si was etched-back on both sides using a solution of O_3 and HF to remove wrap-around. The front side was passivated using spatial atomic layer deposition of Al_2O_3, followed by an out-gassing step at 550 °C in nitrogen atmosphere and coating of both sides with SiN_x. The contacts at the rear were either realized with LCO or with screen-printing of silver. The contacts at the front were realized by screen-printing of silver-aluminum paste. After contact opening and screen-printing the samples were fired in a belt-driven firing furnace at a set temperature of 820 °C, which corresponds to an actual peak wafer temperature of approx. 720 °C. After firing the LCO/Plating samples received a Dip in 1 % HF for 30s to remove any oxide created by the laser ablation or firing. The contacts were then deposited by forward-bias plating of nickel, copper and capped by electro-less plating of silver.

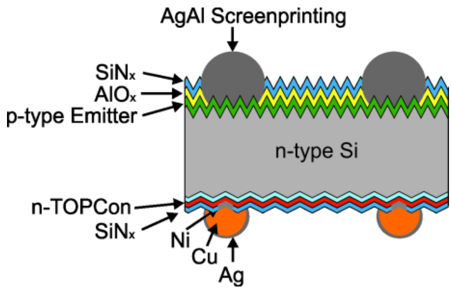

Figure 4: Sketch of the investigated cell design. The cell features a boron emitter at the front, passivated by an Al_2O_3/SiN_x stack. The rear is passivated by a TOPCon/SiN_x stack. The rear contacts are realized either by screen-printing or by NiCuAg plating. The front contacts are always realized by screen-printing.

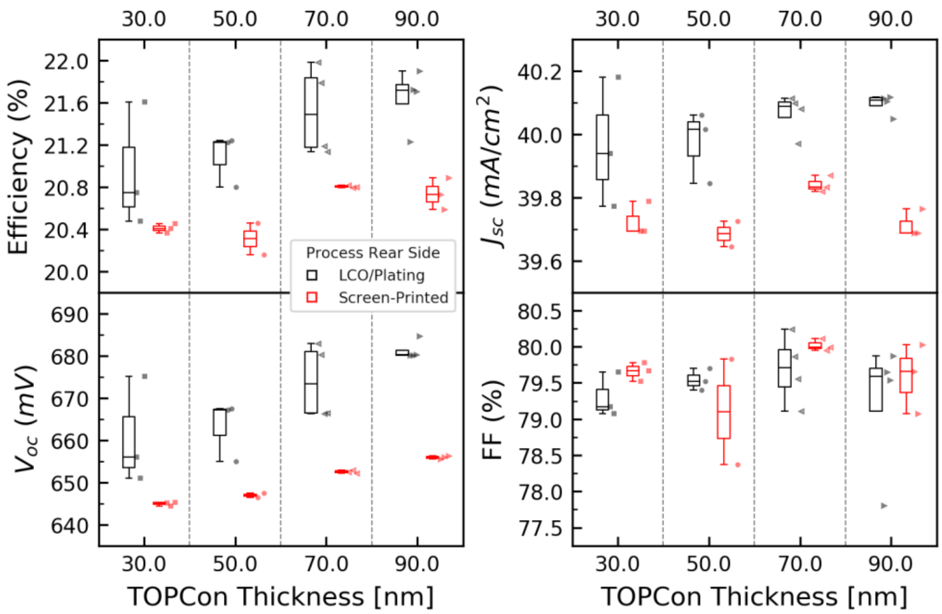

Figure 5: Results of the IV measurements for the TOPCon thickness variation.

4.2 Solar Cell Results

The IV measurements for the solar cells are shown in Figure 5. Good cell efficiencies close to 22 % were achieved with LCO/Plating. Clearly, the LCO/Plating groups deliver a better cell efficiency than their respective screen-printed references. For both LCO/Plating as well as screen-printing a tendency towards higher efficiency with higher TOPCon thickness was observed. This tendency is mainly present in the open circuit voltage V_{OC}, which is in accordance with the results determined on the lifetime samples shown in the previous section. While for screen-printing the increase is still present in the last step from 70 to 90 nm, for LCO/Plating this is where V_{OC} seems to settle, meaning that the V_{OC} limitation (around 685 to 690 mV for these specific cells) of the front side sets in. Nevertheless, even for the lowest TOPCon thickness of 30 nm, the mean V_{OC} determined for LCO/Plating is still higher than the mean V_{OC} determined for the highest TOPCon thickness of 90 nm and screen-printed rear contacts. The recombination for the screen-printed groups is actually so high that even J_{SC} is clearly affected, since the LCO/Plating groups indicate an increase in the range of 0.3 to 0.4 mA/cm^2 in comparison to their respective screen-printed references. While an advantage due to LCO/Plating is commonly observed this is usually an optical effect, since it is easier to generate narrow contacts using this technique in comparison to screen-printing. However, in this case the differences in J_{SC} are mainly caused by the increased recombination for the screen-printed contacts instead. This is supported by the tendency towards lower J_{SC} for lower TOPCon thickness for the LCO/Plating groups, since here the recombination at the rear contacts increased with decreasing thickness as well.

In principle an increase in J_{SC} with decreasing TOPCon thickness would be expected since the loss by FCA is reduced [7]. This could be present for our cells as well and might compensate for some of the J_{SC} loss due to recombination, but overall recombination seems to be the stronger influence on J_{SC}.

This influence of the recombination is not as present in the fill factor *FF* and the pseudo-fill-factor *PFF* shown in Figure 6. Here only at the higher thicknesses of 70 and 90 nm TOPCon thickness LCO/Plating exhibited an advantage.

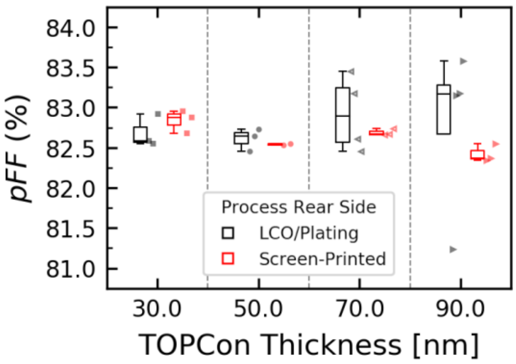

Figure 6: Pseudo-fill-factor *pFF* measured for the cells.

From the comparison of *FF* and *pFF*, it seems that LCO/Plating is influenced by a higher series resistance, since the screen-printed cells with 70 and 90 nm have a lower mean *pFF*, but similar or slightly higher *FF*. However, the measurements of the contact resistivity shown in Figure 7 indicate that this is not due an increase in the contact resistivity. While it is currently not quite clear where the advantage of screen-printing in the FF originates from it is thought to be a problem with contacting the plated fingers in the cell tester rather than a problem with the contacts themselves.

The measurements of the contact resistivity shown in Figure 7 indicate an additional trend with the TOPCon thickness. Overall, excellent specific contact resistivities were determined for LCO/Plating with mean values of 1 mΩcm^2 or lower. For both LCO/Plating and screen-printing a decrease in the contact resistivity with increasing TOPCon thickness was observed. The values for LCO/Plating were lower than their respective references by a factor of 3 to 4. The trend with the TOPCon thickness is thought to be caused by spiking or ablation of the TOPCon layer. In such a case, part of the metal would locally contact the base instead of the TOPCon layer, which is in-line with the observations regarding the recombination at the rear surface. Since the doping in the base is low both metallization types would not expect to form an ohmic contact with low contact resistivity in these local areas. However, the specific contact resistivity is normalized to the total metallization area (or ablated area in case of laser ablation) the actual contacted area TOPCon/metal is over-estimated as the TOPCon layer was partly removed or damaged. With decreasing TOPCon thickness, a larger portion of the area is affected. This leads to an increase in the calculated specific contact resistivity. The actual specific contact resistivity between the TOPCon layer and the metal would be expected to be constant with changing TOPCon thickness, as long as the doping in the layer does not change significantly. Thus, the measurements of the specific contact resistivity for LCO/Plating at 70 to 90 nm can be seen as being representative for the process, values below are over-estimated due to the damage to the layer.

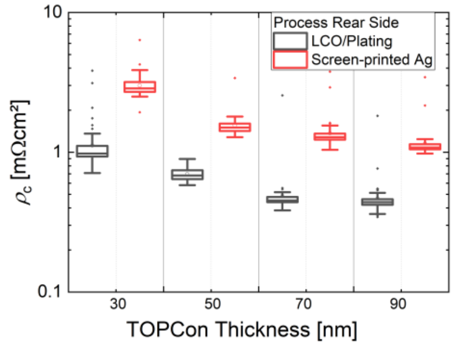

Figure 7: Specific contact resistivity for LCO/Plating in comparison to screen-printed silver.

Overall, the results indicate that in the investigated TOPCon thickness range the LCO/Plating approach is clearly superior. At 90 nm the cells are mostly limited by the front side emitter profile, passivation and contacts, the rear side would certainly be capable for efficiencies higher than 22 %. However, even at 70 nm the influence of the rear side is still low and comparable to what screen-printing at 110 to 150 nm TOPCon thickness would be able to achieve. Thus LCO/Plating as an alternative would allow for significantly lower TOPCon thicknesses within a range where screen-printing – as shown in our experiment – is completely failing.

5 SUMMARY AND OUTLOOK

The performance of LCO/Plating on TOPCon/SiN_x stacks with varying TOPCon thickness was investigated in a thickness range where screen-printing with state-of-the-art pastes is not viable anymore. It was shown that there is a clear trend in $J_{0,met}$ with the thickness and that about 60-70 nm is required for an acceptable level of damage after the laser process and firing. The influence of the thickness variation was further investigated at the device level. The observed trends in V_{OC} and J_{SC} confirmed the results previously obtained for the $J_{0,met}$ samples. While the efficiencies were limited by the front side, close to 22 % cell efficiency was obtained for a TOPCon thickness of 70 to 90 nm, thus demonstrating that such thicknesses are possible with industrially viable metallization techniques.

While a TOPCon thickness of around 70 nm would be a good progress in comparison to the thicknesses that are typically used for screen-printed contacts, it would be desirable to achieve equivalent performance on even thinner TOPCon layers. Thus, a goal for the future is to allow for TOPCon layers in the range of 30-50 nm. Such thin layers can be fabricated at significantly lower cost and result in negligible FCA losses in case of front-side illumination. In case of bifacial application (meaning rear side illumination) the performance gains would be even higher due to the reduced parasitic absorption in the TOPCon layer. In addition, thinner TOPCon depositions also reduce the amount of wrap-around making it easier to avoid complications due to edge shunting.

6 ACKNOWLEDGEMENTS

The authors would like to thank Gisela Cimiotti, Leonard Kraus, Antonio Leimenstoll, Michael Linse, Anamaria Moldovan, Henning Nagel, Rainer Neubauer, Marc Retzlaff, Bernd-Uwe Sanders, Stefan Schellinger, Harald Steidl and Tran Thien Thanh Nguyen for their support with processing.

This work was funded by the German Federal Ministry for Economic Affairs and Energy under contract number 0324274C (Project GENESIS) and the European Union under contract number 857793 (Project Highlite).

7 REFERENCES

References

[1] F. Haase *et al.*, "Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells," *Sol. Energy Mater. Sol. Cells*, vol. 186, pp. 184–193, 2018, doi: 10.1016/j.solmat.2018.06.020.

[2] A. Richter, J. Benick, F. Feldmann, A. Fell, M. Hermle, and S. W. Glunz, "n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation," *Sol. Energy Mater. Sol. Cells*, vol. 173, pp. 96–105, 2017, doi: 10.1016/j.solmat.2017.05.042.

[3] B. Grübel *et al.*, "Plated Ni/Cu/Ag for TOPCon Solar Cell Metallization," in *36th EU PVSEC*, Marseille, 2019, pp. 167–171.

[4] P. Padhamnath *et al.*, "Development of thin polysilicon layers for application in monoPoly™ cells with screen-printed and fired metallization," *Sol. Energy Mater. Sol. Cells*, vol. 207, p. 110358, 2020, doi: 10.1016/j.solmat.2019.110358.

[5] S. Kluska *et al.*, "Plating for passivated-contact solar cells," *Photovoltaics International*, vol. 44, 2020.

[6] B. Kafle, *submitted for publication*.

[7] F. Feldmann, M. Nicolai, R. Müller, C. Reichel, and M. Hermle, "Optical and electrical characterization of poly-Si/SiOx contacts and their implications on solar cell design," *Energy Proced.*, vol. 124, pp. 31–37, 2017, doi: 10.1016/j.egypro.2017.09.336.

[8] V. Arya *et al.*, "Laser Ablation and Ni/Cu Plating Approach for i-TOPCon Solar Cells with Variate Polysilicon Layer Thickness: Gains and Possibilities in Comparison to Screen Printing," *submitted for publication*.

[9] A. Knorz, M. Peters, A. Grohe, C. Harmel, and R. Preu, "Selective laser ablation of SiN x layers on textured surfaces for low temperature front side metallizations," *Prog Photovolt Res Appl*, vol. 17, no. 2, pp. 127–136, 2009, doi: 10.1002/pip.856.