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TOPCon Solar Cells With Al-Free Ag and Cu Metallization

Strategies for Ag Reduction in Industrial Silicon Solar Cells

Jan Lossen[1], Pirmin Preis[1], Mertcan Comak[1], Joris Libal[1], Dominik Rudolph[1], Jan Hoß[1], and Lejo Joseph Koduvelikulathu[1]

[1] International Solar Energy Research Center (ISC) Konstanz e.V., Germany

*Correspondence: Jan Lossen, jan.lossen@isc-konstanz.de

Abstract. This work presents an approach to lower the silver consumption of screen printed TOPCon (Tunnel Oxide Passivated Contact) solar cells by reducing and partially replacing the silver by low cost copper metallization paste. On the solar cells front side an adapted process sequence enables the use of a pure Ag paste, which compared to the industrially established AgAl paste offers a better conductivity and respectively requires less laydown to enable similarly low grid resistance. On the solar cells rear side the conductivity of the metal grid is accomplished by a copper paste which is realized within a print-on-print step on top of the Ag contact layer with minimized laydown. A reduction in Ag paste consumption by 40% to less than 9 mg/ W_p without sacrificing conversion efficiency seems achievable and can enable a significant cost reduction for TOPCon solar cells.

Keywords: Ag-Reduction, Cu-Paste, Sustainability, TOPCon, Metallization

1. Introduction

Besides the silicon for the wafer itself, silver (Ag) used for the metal contacts is already the most expensive material of state-of-the-art industrial silicon solar cells. A growing demand by an increase of production volume is likely to lead to even higher prices. According to recently published market data [1], Ag-consumption of photovoltaic industry increased from 2022 to 2023 by 64% and accounted already for 16.2% of total global Ag demand in 2023. Various studies rightly pointed out that the Ag consumption of PERC solar cells of >10 mg/Wp would already be incompatible with a growth of the industry to an annual production capacity of several terawatts, as required to mitigate the climate crisis, as more Ag would be needed than can be mined annually worldwide [2], [3], [4], [5]. The ongoing rapid shift of the market to TOPCon and HJT solar cells further aggravates the situation, as both cell types feature higher consumption with Ag grids on front and rear side. A solution with leaner Ag consumption is needed.

For IBC solar cells, were contacts of both polarities are located on the rear side, metallization schemes using mainly copper (Cu) as conduction material have been common since the industrialization of Sunpower's first IBC cells, using a metallization approach based on PVD deposition and Cu plating [6], but the total costs for this metallization scheme are assumed to be rather high. D. Rudolph et al. [7] showed that the bus bars of screen printed IBC cells can be made from low temperature Cu paste without sacrificing efficiency and demonstrated good stability. N. Chen et al. [8] replaced also most part of the fingers by screen printed

Cu-paste keeping only a small contact layer from Ag-paste as electrical contact to the silicon and blocking layer against Cu-Diffusion.

For solar cells with double sided contacts, metallization schemes based on Cu plating have also been investigated since long. The companies BP Solar and later Suntech launched corresponding products on the market, but both were eventually outperformed by main stream products relying on Ag printing. For TOPCon cells, which are expected to be the dominant cell type for the next years, a metallization based on Cu-plating has been demonstrated, and showed a positive impact on efficiency [9], [10], but a wider adoption into industry could not been observed yet. A hindrance might be severe water contamination by existing industries using plating processes, which makes authorities reluctant permit plating in further industries. D. Ourinson et al. [11] followed for TOPCon a similar approach as N. Chen et al. for IBC and used a combination of high temperature Ag-paste for contacting and low temperature Cu-Paste for conduction. They presented TOPCon cells with a full area printed Cu-layer on the rear side featuring same efficiency as reference cells with Ag grid. Furthermore, repeated measurements over 124 days have shown that no Cu contamination of the silicon bulk could be detected during this time span. For the rear side, we follow the same idea and print a stack consisting of an Ag contact layer, and Cu layer for conduction. Other than Ourinson et al., we apply the Cu paste as H-grid rather than a full area print, in order to reduce Cu consumption and to achieve a bifacial device.

The established method for contacting the boron doped front side of TOPCon solar cells is screen printing of Al-containing Ag pastes. The recent introduction of LECO technology in TOPCon [12] opened a path for using Al-free Ag pastes, with reduced recombination and better line conductivity. Another possibility had been revealed much earlier by H. Chu et al. [13]. When only finger lines are printed, and kept electrically separated during fast firing, Al-free Ag-pastes can establish a low-ohmic contact to a boron emitter. The effect was explained by the suppression of charge carrier losses through earlier formed contacts, leaving more charge carriers for reduction of silver in the chemical reactions creating the contact between cell and Ag paste.

2. Approach

The aim is to reduce the metallization costs of TOPCon solar cells, without compromising the conversion efficiency. For reducing Ag on the front side we use an Al-free Ag paste, which is fired in bus bar less configuration for formation of good contacts to boron. Bus bars are printed afterwards using a low temperature paste, which in the final realization shall be Cu paste. On the rear side, only a minimized contact layer is printed with Ag paste, just enough to establish good contact to the silicon, while the major part of the finger and the bus bars are printed from Cu paste. We use a nano particle copper paste from the company Copprint, which contains a blend of Cu particles ranging from <100 nm to a few µm and a sintering agent which suppresses oxidation. Full conductivity is reached in a snap curing process at approx. 300°C. In the final realization both approaches should be combined on the same cell, as displayed in Fig. 1. However for simplicity in this work both approaches are tested only separately. The printing sequences for both experiments we realized are displayed schematically in Fig. 2.

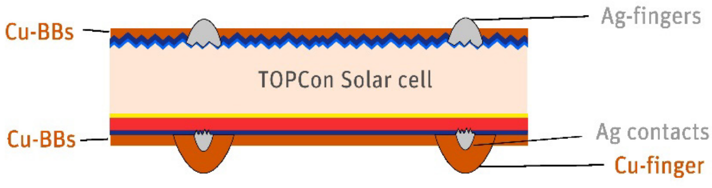

Figure 1. *Cross section of the Cu-TOPCon cell with Ag-reduction on front and rear side. Bus bars are displayed as a continuous layer, please note that that they have perpendicular to the picture plane a short dimension of only 50 – 200 µm.*

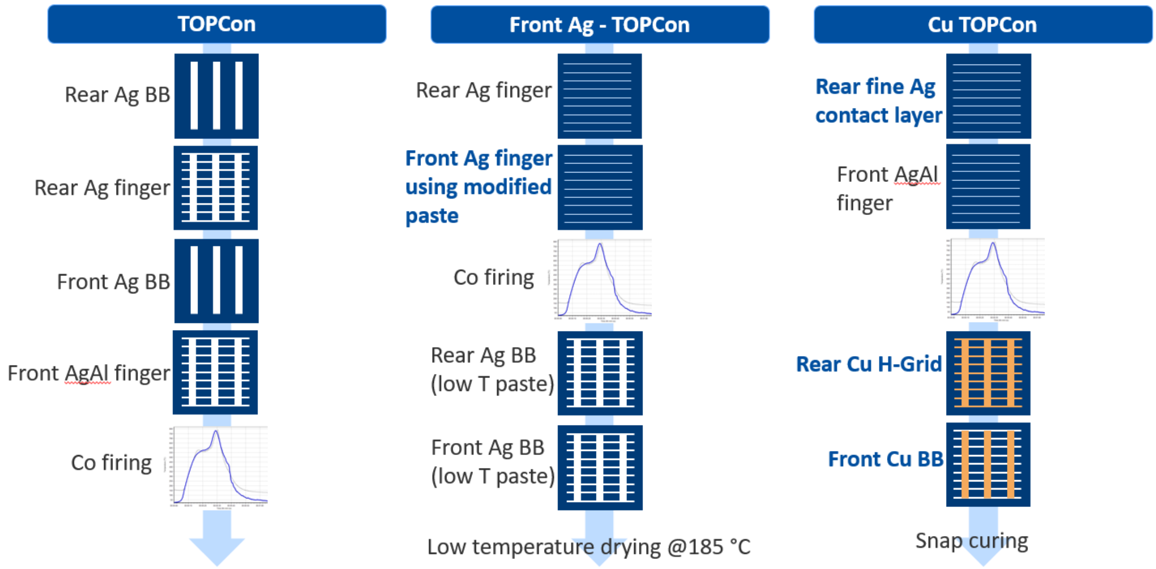

Figure 2. *Printing sequences for the two experiments compared to the reference process for TOPCon*

3. Experimental details and results of front side experiment

The first experiment on Ag-reduction on the front side is conducted on TOPCon precursors in G1 format from an industrial production line, they feature a homogeneous boron emitter with sheet resistance of approx. 165 Ohm/sq. We compare the use of a special Al-free Ag paste with an industry standard AgAl reference paste. The actual silver content of both pastes is similar according to information by the supplier, as only comparatively few Al particle are added. Both pastes are printed through a knotless screen with mesh 440-013, EOM 12µm and opening width of 18 µm in a M2-Layout with 135 fingers. As the wafers are full area G1 format, but the print layout has only M2 format, the corners of the cells remain unprinted. Laydown is 40 mg for Al-free Ag paste and 67 mg for the AgAl reference paste. Rear side metallization is printed from n+ poly contacting Ag paste. After fast firing in a belt firing furnace, the bus bars on front and rear side are printed from a low temperature Ag paste which is cured at the temperature of 185°C. Please note that in the final concept Cu paste shall be used for the bus bars.

The IV parameters in Fig. 3 show a loss in short circuit current (Jsc) for the Al-free Ag paste on the front side, while Voc and FF are increased. Laser scanning microscopy images displayed in Fig. 4, show that the fingers printed from the AgAl reference paste are much finer and higher, while the Al-free Ag pastes leads to wider finger of reduced height, which explains the loss in Jsc. Notable on the other hand is the increase in Voc although the contact area is wider, indicating a lower J0met. At the same time, also FF is increased although the paste laydown is much lower. This increase in FF is already reflected in a comparably higher pseudo-FF of the cells. It can be assumed to be also correlated to lower metal-induced recombination, with no Al particles spiking into the emitter region.

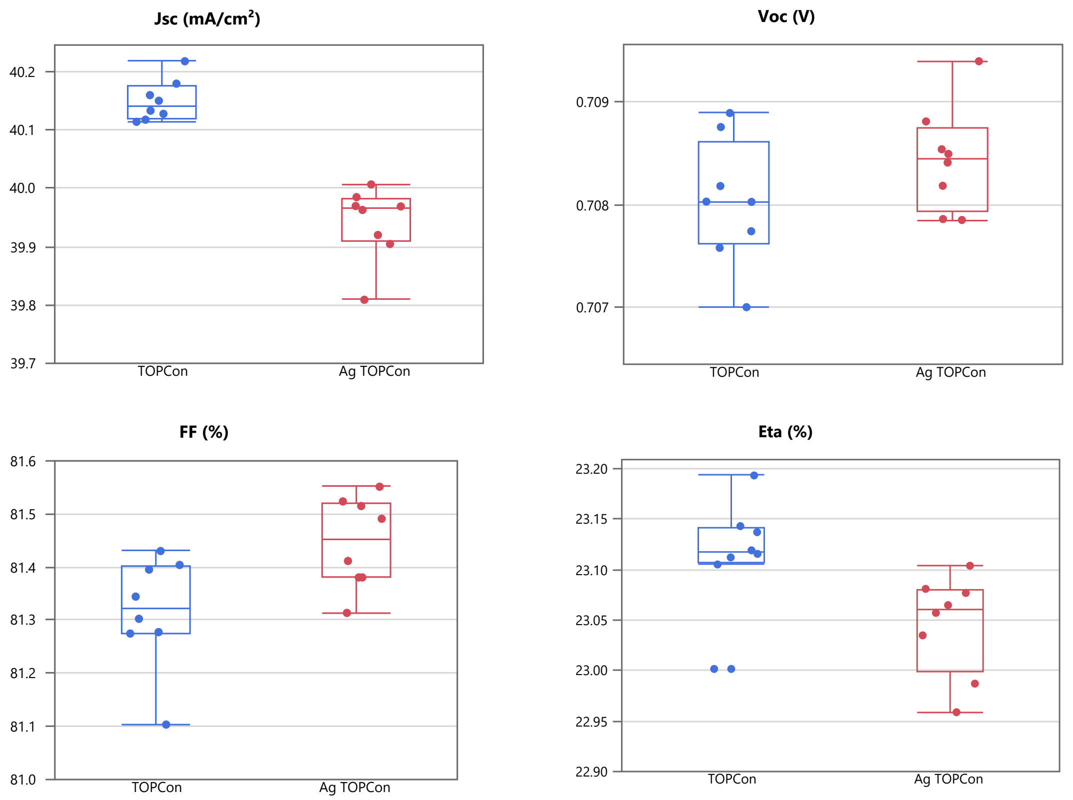

Figure 3. *IV parameters of TOPCon solar cells printed with two different front side pastes: the reference AgAl paste and a novel Al-free Ag paste*

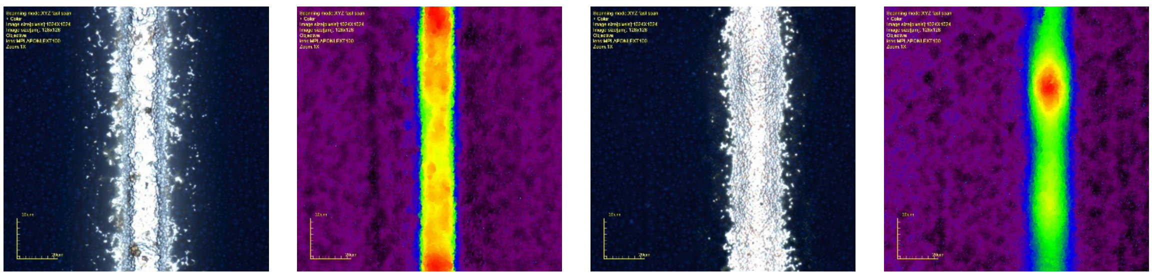

Figure 4. *Laser scanning microscope images of fingers printed from the two front side pastes. Image (a) shows the light microscope image of a finger printed from the AgAl reference paste and image (b) the corresponding height profile as heat map. Images (c) and (d) the light image and the height profile of a finger printed from the novel Al-free Ag paste. The latter features has much strong mesh marks, visible as significant variations of the finger height and a reduced average height.*

Table 1. *Paste laydown, extracted resistance values and effective bulk resistivity*

Paste	*width* (µm)	*height* (µm)	ρ_c (mΩcm²)	*laydown* (mg)	*R_line* (Ω/cm)	ρ_{bulk_eff} (µΩcm)
Reference AgAl paste	24	17	1.8	67	1.66	5.09
Al-free Ag paste	28	9	1.3	40	2.24	4.05

Table 1 lists average width and height, specific contact resistances extracted from TLM, wet paste laydown and line resistance extracted from BB-to-BB measurements. The Al-free Ag paste not only has a lower contact resistivity, but regardless its much lower laydown also still features a relatively low line resistance. We calculated an effective bulk resistivity based on wet laydown and the line resistance, which should only be seen as a broad approximation. The determined effective bulk resistivity of the Al-free Ag paste is much lower most likely due to the absence of aluminum particles in this paste. The silver hence is used more effectively. If fine line printability of this paste can be improved, an increase in efficiency at reduced Ag laydown can be expected.

4. Experimental details and results of rear side experiment

The experiment for Ag reduction on the rear side was conducted on TOPCon precursors in M6 format manufactured in our laboratory at ISC Konstanz. We used the Toucan-PECVD sequence, consisting of: SDE etching, texturing, cleaning, boron diffusion, single side etching in cluster process, PECVD n+ poly deposition, annealing, single-side etching of poly wrap around, PECVD AlO_x passivation and SiN_x capping, and screen printing of contacts. The reference group features AgAl fingers on the front and Ag-fingers on the rear as well as Ag bus bars (BB) on both sides and were fired after concluding all printing steps. In the Cu-TOPCon group AgAl fingers were printed on the front side, and a contact layer of Ag paste was printed on the rear side before firing the cells with same settings as the reference cells. Afterwards Cu fingers and bus bars were printed on the rear side as well as Cu bus bars on the front side, and cured at approx. 300°C, compare Fig. 2. Table 2 lists the wet paste laydown of the different printing steps. The screens in this experiment were not optimized for low laydown, leading to much higher laydown in all printing steps, as it would be used in an industrial production. Although not yet optimized, a strong reduction of Ag consumption can be seen for Cu-TOPCon group as the rear fingers are printed with much lower Ag laydown and the both bus bar prints are done by Cu paste.

The IV parameters of the solar cells are displayed Fig. 5. The Cu-TOPCon cells in mean have a slightly lower J_{sc} and a slightly higher V_{oc}. The first we attribute to a different internal reflection, the second to reduced recombination on the rear side with reduced contact area, although the contact is formed to the TOPCon passivation side. The cells from both groups have similar FF and efficiency, demonstrating that replacing the Ag paste metallization partly by Cu paste does not lead to a sacrifice in cell efficiency.

Table 2. *Wet paste laydown in the different print steps of the second experiment*

Group	*Rear Ag Fingers (mg)*	*Rear Ag BB (mg)*	*Rear Cu H-Grid (mg)*	*Front AgAl Fingers (mg)*	*Front Ag BB (mg)*	*Front Cu BB (mg)*	*Total Ag paste (mg)*	*Total Cu paste (mg)*
Reference	133	44	-	43	44	-	264	-
Cu-TOPCon	30	-	351	43	-	35	73	396

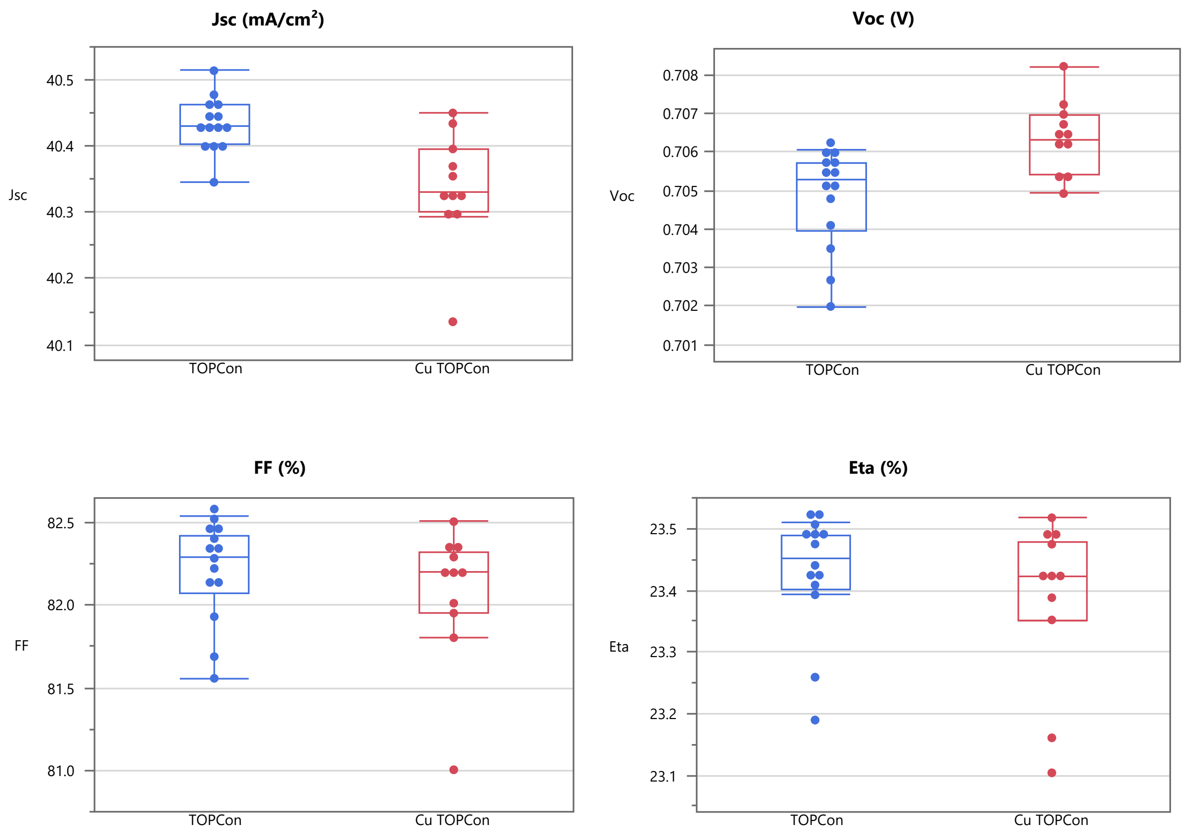

Figure 5. *IV parameters of solar cells from the second experiment on Ag reduction on the rear side*

5. Discussion

Two strategies for reduction of Ag content in industrial TOPCon solar cells were experimentally tested. On the front side AgAl paste was replaced by Al-free Ag paste and BB-less firing was used to maintain low contact resistance. An alternative option would be to use the LECO technology, which additionally was reported to enable very low J_{0met} values, but is protected by IP rights. In both cases, the higher conductivity of Ag pastes compared to AgAl paste allows for reduction of paste laydown. On the rear side, we demonstrated that a print-on-print finger composed of a minimized Ag contact layer and a Cu-bulk layer can achieve comparable efficiency at strongly reduced Ag laydown. Further, it was shown that bus bars on front and rear side can be printed by Cu paste. In the experiment, Ag usage was reduced by more than 2/3 but this value is not very meaningful as laydown was unrealistic high. We estimate that for a commercial TOPCon cell in M10 format the laydown on the front side can be reduce from currently around 60mg (for AgAl fingers and Ag bus bars) to about 45 mg (for Al-free Ag fingers), while on the rear side current laydown of 65 mg (for Ag fingers and bus bars) can be reduced to 28 mg or less (for the Ag contact layer). So in total a reduction from currently 125 mg to about 73 mg seems realistic. To replace the saved Ag paste, about 94 – 132 mg Cu-Paste would be needed as well as an additional process step for snap curing of the Cu paste. Assuming an efficiency of 24.5%, the Ag consumption TOPCon can be reduced from around 15 mg/W_p to around 9 mg/W_p, enabling a significant cost reduction potential. This potential might be even higher for rising Ag paste prices due to the higher demand of the PV industry in the coming years.

Data availability statement

Data is stored on the server of ISC, and can be supplied on request.

Author contributions

Jan Lossen: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – Original draft, Visualization, Project administration, Funding acquisition; **Pirmin Preis:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – Review& Editing, Visualization, Project administration; **Mertcan Comak:** Investigation, Resources; **Joris Libal:** Formal analysis; **Dominik Rudolph:** Conceptualization, Methodology, Investigation, Resources; **Jan Hoß:** Conceptualization, Writing Review& Editing; **Lejo Joseph Koduvelikulathu:** Writing Review& Editing, Supervision.

Competing interests

The authors declare that they have no competing interests.

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