

A round Robin-Highlighting on the passivating contact technology

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Received: 1 July 2021 / Received in final form: 22 October 2021 / Accepted: 15 November 2021

Abstract. The aim of this work is to demonstrate the maturity of the TOPCon technology by conducting a round-robin on symmetrically processed lifetime samples in the leading European PV institutes EPFL, ISC, CEA-INES, ISFH, IMEC and Fraunhofer ISE within the H2020 funded project called HighLite. For all layers, dark saturation current-densities ranging between 2 and 10 fA/cm² can be reported. Simultaneously, no metal induced recombination for the two lower sintering temperatures have been observed pointing towards a true passivated contact. Furthermore, contact resistivities below 10 mΩcm² have been achieved. It seems that the industrial passivating contact matured to a fully passivated and conducting contact enabling full efficiency potential. The fact that this can be realized using either PECVD or LPCVD from various manufacturer is expected to drive costs down and contribute to the increased adoption of the TOPCon technology.

Keywords: Silicon solar cell / passivated contact / TOPCon / POLO / round robin

1 Introduction

The poly-Si based surface passivation using a thin tunnel oxide also known as “TOPCon” [1] or “POLO” [2] (for simplicity, in the following only the expression “TOPCon” is used) is subjected to an increasing interest from the industry. In the last years, increasing conversion efficiencies were reported ending so far in record values of 24.6% reached by Trinasolar [3] and recently of 25.25% reported by Jinkosolar both in lab scale production.

The aim of this work is to demonstrate the maturity of the TOPCon technology by conducting a round-robin in the leading European PV institutes EPFL, ISC, CEA-INES, ISFH, IMEC and Fraunhofer ISE within the H2020 funded project called HighLite. Deposition tools from various companies using plasma enhanced chemical vapour deposition PECVD and low-pressure chemical vapour deposition LPCVD were used. Properties of the layers and information of the tools are given in Table 1.

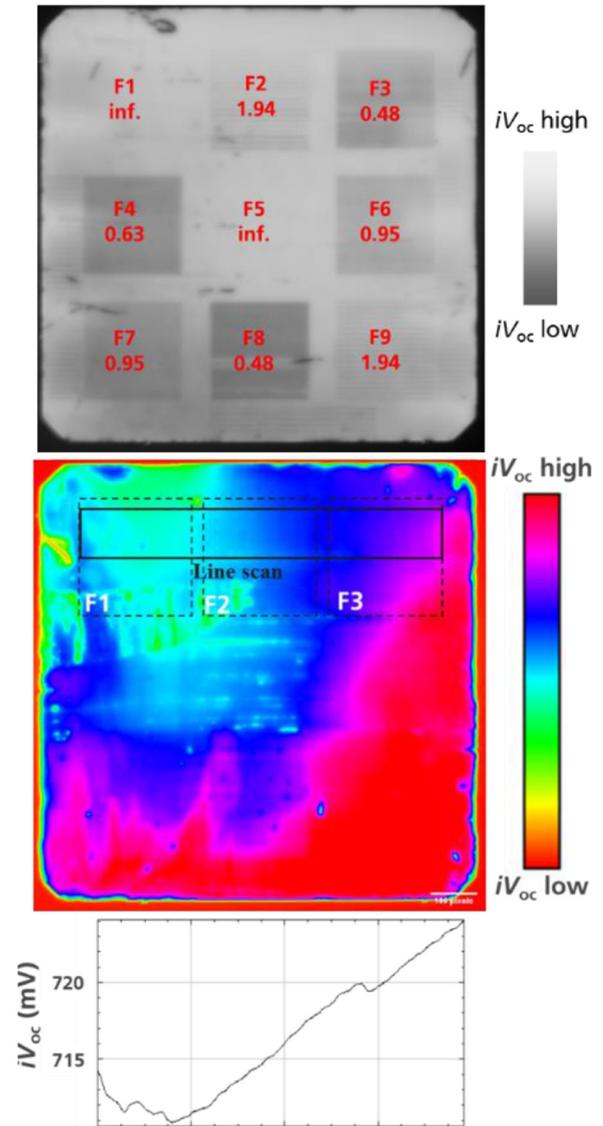
2 Approach

N-type Cz-Si wafers were saw damage etched by ISC Konstanz and distributed to the mentioned institutes to use their best-known deposition technology to create n-type TOPCon layers on both sides of the wafers. Despite the differences in the deposition technology, all layers consist of a thin tunnel oxide layer between the c-Si absorber and a phosphorus doped poly-Si layer, which was annealed or POCl₃-diffused to transform a- to poly-Si and subsequently capped with a hydrogen-rich SiN_x layer. Then, the samples were sent to Fraunhofer ISE for single side screen-printing of a parallel finger pattern with varying finger pitch consisting of nine individual fields (Fig. 1) [4], contact firing at varying temperatures and characterization. The dark saturation current-density for a single, unmetallized TOPCon layer J_{0T} and the total dark saturation current-density for the whole stack consisting of two TOPCon layers and bulk J_0 for metallized and unmetallized fields (Fig. 2) were extracted by a combination of the QSSPC [5] J_{0e} analysis from Kimmerle et al. [6] and the modulated photoluminescence Mod-PL [7]

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Table 1. Overview of the round-robin members, their technology and TOPCon layer properties.

Description	ISE	IMEC	ISFH	ISC Konstanz	INES
Technique	PECVD	LPCVD	LPCVD	LPCVD	LPCVD
Deposition tool	Centrotherm c.PLASMA	Tempress SPECTRUM	Centrotherm Europe 2000	Centrotherm	Semco Smartech
Deposition side	single	both	both	both	both
Doping process	in-situ	ex-situ, POCl ₃ diffusion	in-situ	in-situ	ex-situ (PIII)
Doping tool (only ex-situ)		Tempress SPECTRUM			IBS Pulsion Solar
Interfacial oxide	thermal	thermal	chemical	chemical	thermal
Poly-Si thickness	150 nm	160 nm	200 nm	150 nm	200 nm
Doping (cm ⁻³)	1.7×10^{20}	$2-3 \times 10^{20}$	2×10^{20}	2×10^{20}	$4-5 \times 10^{20}$
Anneal temperature	900 °C	860 °C	860 °C	825 °C	975 °C
Capping layer	SiN _x PECVD (75 nm)	SiN _x PECVD (85 nm)	AlO _x ALD, SiN _x PECVD (10 nm, 80 nm)	SiN _x PECVD (70 nm)	SiN _x PECVD (70 nm)

**Fig. 1.** TOP: A PL image of a over fired wafer, indicating nine individual fields F1-F9 with varying Finger pitches in “mm”. On the edges TLM structures are located. Middle: An implied iV_{oc} Mod-PL image of a selected sample showing no field pattern, but other significant inhomogeneities. The iV_{oc} as a result from the indicated line scan area is shown in the bottom graph.

method. Finally, transition line method TLM [8] line structures (equidistant lines) were cut off the wafers to obtain the contact resistivity ρ_c (Fig. 3).

All poly-Si layers investigated here exhibiting a thickness ranging from 150 to 200 nm being in a typical range for screen-printed contacts with sufficiently low parasitic absorption, if embodied as rear electrode [9].

In Table 1, an overview of the round robin members, their technology and layer properties are given. As can be seen, two CVD technologies from three different companies on five different tools are part of the round-robin.

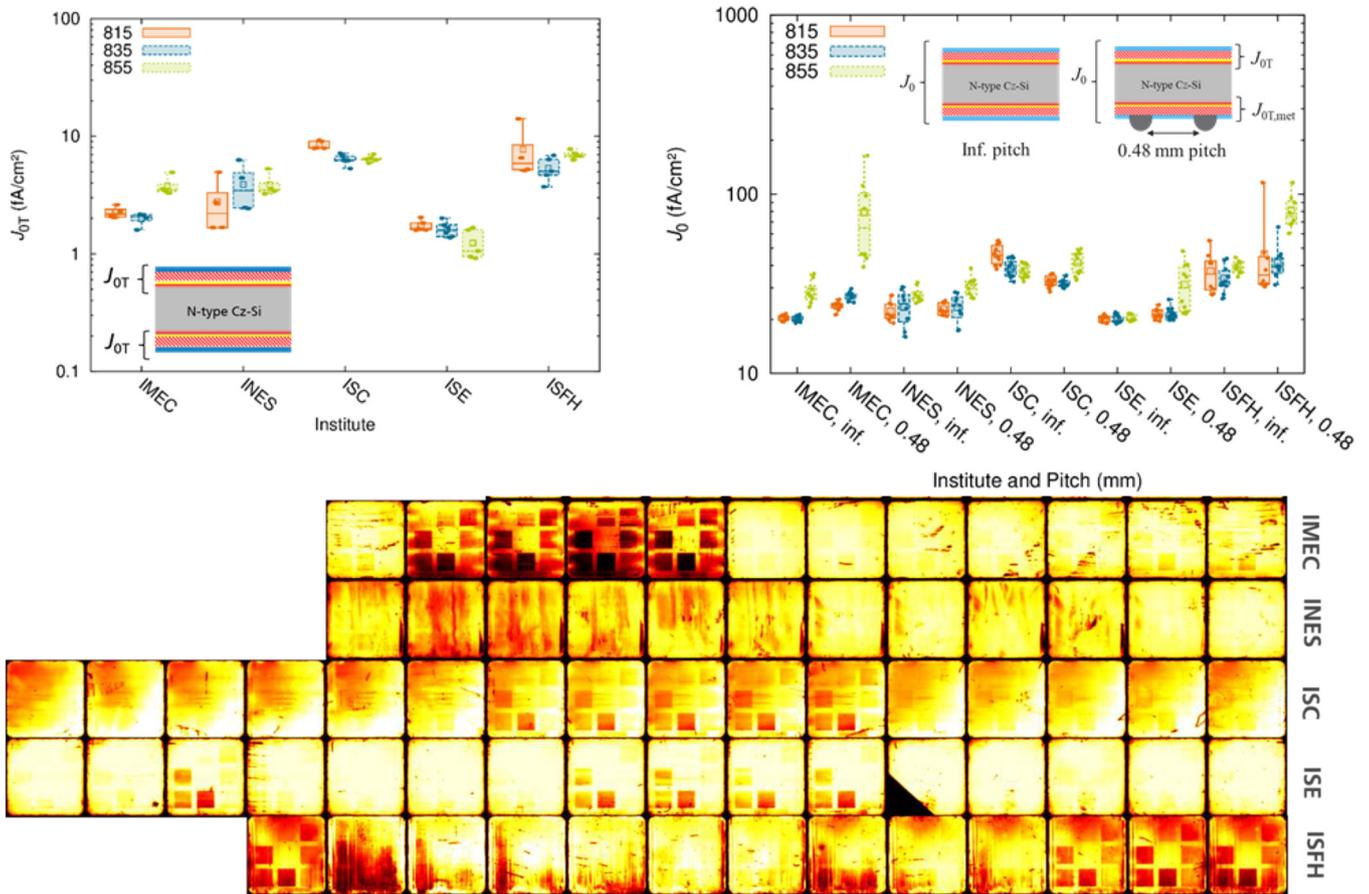


Fig. 2. Upper left graph: Dark saturation density J_{0T} from one single TOPCon layer extracted from field F5. Upper right graph: Total dark recombination current-density J_0 either consisting of a bulk and two unmetallized TOPCon layers “inf.” (average F1 & F5) or a bulk and two TOPCon layers of which one side is being metallized (0.48 mm pitch, average F3 & F8). Lower part: PL images of all specimens from all institutes showing partly no increased recombination or significant inhomogeneities of which both preventing a local $J_{0T,met}$ analysis.

In [Figure 1](#), a PL image is shown at the top exhibiting nine individual fields F1-F9 [4]. The fields F1 and F5 serve as reference without metallization, their size being compatible to allow QSSPC measurements. The remaining fields exhibit a parallel allocated finger pattern with nominal finger width of $40\ \mu\text{m}$ and as indicated varying finger pitch in “mm”.

The middle image of [Figure 1](#) shows a selected iV_{oc} calibrated PL image to visualize a challenge the authors observed for some samples during the characterization process. At the bottom, a line scan as indicated in the middle image show an increasing iV_{oc} from field F1 to F3. However, one expects a decreasing iV_{oc} considering the increasing metallized area potentially inducing additional recombination. That seems not to be the case, which points toward a vanishing contact recombination leading to other contrast drivers such as process inhomogeneities.

Additionally, in the cases of over fired samples (see also [Fig. 2](#), PL montage), fields with nominal equal finger count appear different in terms of contrast. That is linked to a slightly inhomogeneous lateral temperature distribution during firing. At set peak temperature of $855\ \text{°C}$, metal

induced recombination is on-setting showing an exponential sensitivity on incremental changes in local temperature. This can be seen also in [Figure 2](#) upper right graph where an increasing J_0 comes along with an increasing spread in data.

3 Results

In [Figure 2](#) upper left, the J_{0T} extracted by QSSPC from field F5 (see [Fig. 1](#)) is displayed showing excellent values ranging from 2 to $10\ \text{fA/cm}^2$, indicating a wide spectrum of tools and manufacturers being capable of producing high quality layers and therefore excellent surface passivation. The extraction method used by Kimmerle et al. [6] is based on the Kane and Swanson method by fitting the lifetime in high-level injection and additionally taking into account finite carrier diffusion length and band gap narrowing.

It must be noted that such low absolute values as measured by ISE and others are significantly prone to uncertainties or inhomogeneities such as systematic errors from the measurement tool (WCT-120 from Sinton

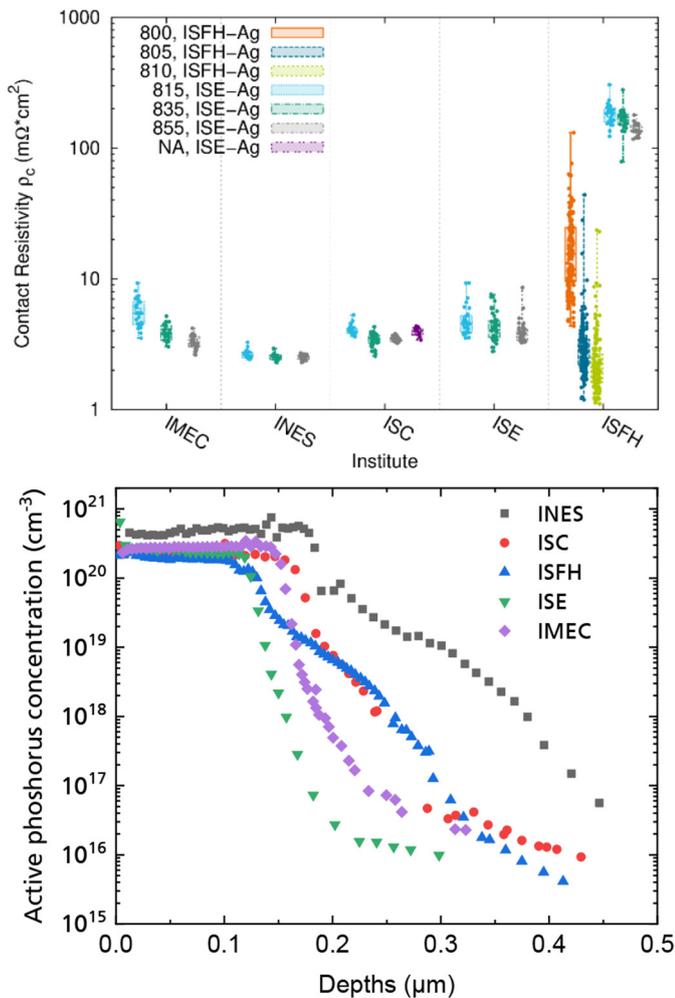


Fig. 3. The top graph shows the specific contact resistance ρ_c measured with a TLM-Scan+ device from PV-Tools for varying peak set temperature in “°C”. The bottom graph shows the corresponding ECV profiles for each TOPCon layer including both the phosphorus in the poly-Si (constant part) and the c-Si tail (strongly decreasing part).

Instruments). Therefore, on the upper right side the corresponding J_0 from the unmetallized reference fields F1 and F5 (infinite pitch) are shown, indicating more realistic values between 20 and 50 fA/cm². Also, the J_0 from the metallized fields F3 and F8 for up to 835 °C show comparable values to the unmetallized fields, pointing towards a true passivating contact for industrial relevant deposition and metallization technologies.

Eventually, at highest set peak temperature of 855 °C, the contact starts to depassivate, due to significant etching by the Ag paste, which is confirmed by SEM analysis. The peak set temperature range was determined with a thermal element in a way that the specimens see the same temperature profile as the final solar cells would experience.

Due to the vanishing contact recombination and frequently occurring inhomogeneities, no meaningful local $J_{0T,met}$ can be determined.

Finally, **Figure 3** completes the picture indicating a conducting contact for most of the samples with specific contact ρ_c below 10 mΩcm². The ISFH samples feature an additional AlO_x layer tremendously increasing ρ_c , if metallized with the ISE paste (“ISE-Ag”). Obviously, that paste is not optimized for an AlO_x layer. Considering this by using a different Ag paste (ISFH-Ag), excellent mean values for the best group of 2 mΩcm² is reached. The ISFH values are obtained on-site from a different experiment on comparable layers [10].

ISC Konstanz completely finalized a part of the round-robin samples internally, and the results are in good agreement to the ones obtained from ISE although different firing conditions are used.

Note: All TLM specimens exhibit a n⁺nn⁺-structure, hence current flow may extend in the n-bulk and the opposing unmetallized n⁺-layer. Depending on the tunnel resistance this might lead to an underestimation of the “real” contact resistivity on solar cell level. However, all layers are used in real solar cell devices showing high FF indicating a low tunnel contact.

Additionally, the electrochemical voltage (ECV) measured profiles for each TOPCon layer are shown. The profiles were recorded individually by each institute and provided to the main author. The doping levels are in good agreement to the contact resistivities and behave as expected. INES samples reach the lowest resistivities being also the one with the highest doping level, whereas ISE samples reach higher values due to the lower poly-Si doping.

4 Conclusions

J_{0T} ranging from 2 to 10 fA/cm² for a single n-type TOPCon layer and J_0 ranging from 20 to 50 fA/cm² for the total symmetrical device were reported. Also, for the contacted area similar J_0 -values are shown pointing towards a true passivated contact. Simultaneously, low specific contact resistance well below 10 mΩcm² allow a high fill factor potential, if applied as rear side electrode.

All this is realized on a wide technology base using PECVD and LPCVD technology with tools from various leading equipment manufacturers such as Centrotherm, Tempres, and Semco being available in the participating institutes EPFL, CEA-INES, ISC, ISFH, IMEC and ISE. This, together with a general trend towards higher efficient solar cells considering TOPCon, clearly underlines its relevance for the PV community and industry.

It seems that the industrial passivating contact matured to a fully passivating and conducting contact enabling full efficiency potential. The fact that this can be realized using either PECVD or LPCVD from various manufacturer is expected to drive costs down and contribute to the increased adoption of TOPCon technology. This comparable to what happened earlier with the PERC technology with capital expenditures for new production lines coming down by a factor of 5 in less than 10 years due to increased competition between equipment vendors [11].

The authors would like to thank all people from all institutes not mentioned as authors who have been involved in the process of assembling and characterization, as well as the logistic. This work was funded by the European Union's Horizon2020 program for research, technological development and demonstration under grant agreement no. 857793.

Author contribution statement

Tobias Fellmeth, main author: conducting experiment at ISE, coordination between institutes, writer of paper and person in charge. Frank Feldmann: coordination between institutes, helped with details in the experimental setup, proof reading. Bernd Steinhauser: a-Si deposition expert, proof reading. Henning Nagel: wetchemical expert, proof reading. Sebastian Mack; front end expert, proof reading. Martin Hermle: department leader, financial support. Frank Torregrosa: support in round robin, proof reading. Andrea Ingenito, Franz-Josef Haug, Audrey Morisset: experimental support round robin EPFL part, proof reading. Florian Buchholz, Aditya Chaudhary; experimental support round robin ISC part, proof reading. Thibaut Desrues: experimental support round robin INES part, proof reading- Felix Haase, Byungsul Min, Robby Peibst: experimental support round robin ISFH part, proof reading. Loic Tous: experimental support round robin ISFH part, proof reading, project leader HighLite

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Cite this article as: Tobias Fellmeth, Frank Feldmann, Bernd Steinhauser, Henning Nagel, Sebastian Mack, Martin Hermle, Frank Torregrosa, Andrea Ingenito, Franz-Josef Haug, Audrey Morisset, Florian Buchholz, Aditya Chaudhary, Thibaut Desrues, Felix Haase, Byungsul Min, Robby Peibst, Loic Tous, A round Robin-HighLighting on the passivating contact technology, EPJ Photovoltaics **12**, 12 (2021)