DEVELOPMENT AND PROCESS OPTIMIZATION OF A P-IBC SOLAR CELL WITH PECVD DEPOSITED PASSIVATED CONTACTS

L. Rachdi[1], J. Lossen[1], D. Rudolph[1], Y.P. Sharma[1], L.J. Koduvelikulathu[1]
J.I Polzin[2], S. Schmidt[2], A. Wolf[2] and T. Pernau[3]
[1]ISC Konstanz e.V., Rudolf-Diesel-Str. 15, 78467 Konstanz, Germany
[2]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
[3]Centrotherm International AG, Württemberger Str. 31, 89143 Blaubeuren, Germany

ABSTRACT: In this research, we present the design and optimization of an interdigitated back contact (IBC) solar cell. The cell utilizes a cost-effective, commonly used substrate material, a Cz-Si Ga-doped wafer. The proposed processing techniques are all well-known from high-volume Passivated Emitter and Rear Cell (PERC) production, allowing for efficient utilization of existing production tools. The solar cell design features a front floating emitter and rear passivated contacts, with an in-situ doped a-Si layer deposited by plasma enhanced chemical vapor deposition (PECVD). Our process optimization efforts presented in this work have resulted in a current champion cell with a conversion efficiency of 22.94%.

Keywords: interdigitated back contact, IBC, TOPCon, passivated contacts

1 INTRODUCTION

In recent years, the photovoltaic industry has seen a dominant use of Passivated Emitter and Rear Cell (PERC) technology in silicon solar cell production [1]. Despite this, Interdigitated Back Contact (IBC) solar cells have been shown to offer significant advantages, including better light management with higher Jsc values, compared to PERC cells [2]. However, the industry's reliance on PERC production equipment presents a challenge for a widespread adoption of the IBC technology.

One potential solution is to select an IBC technology with high tool reutilization, which would allow for a technology transition while maximizing usage of existing equipment [3]. Another key enabler for high efficiency is the use of passivating contacts, also known as tunnel oxide passivating contact (TOPCon)-technology [4]. The combination of a thin oxide and a polysilicon layer offers excellent passivation properties and simple process requirements, making them a key enabler for devices with high efficiency.

Currently, low pressure chemical vapor deposition (LPCVD) is the dominant technology used for polysilicon deposition in the PV industry. However, plasma enhanced chemical vapor deposition (PECVD) offers many advantages over LPCVD, including a higher deposition rate and the ability to deposit single sided, which enhances its industrial compatibility [4]. These benefits make PECVD a cost-effective alternative for depositing passivating contacts and a potential solution for high efficiency solar cells while minimizing the cost.

In this study, we present our advances in the development of a Front floating Emitter- Interdigitated Back Contact (FE-pIBC) solar cell architecture on p-type Ga-doped mono Cz-substrates with a-Si(n) deposited utilizing a Centrotherm cPlasma PECVD tool.

2 SAMPLE PREPARATION

2.1 Solar cells

The experiments are conducted on commercial M2-sized Ga-doped p-type Cz-Si wafers with a resistivity ranging from 1 to 2 Ω.cm. Figure 1 shows the applied process flow. The p-type wafers undergo an alkaline texturing process, followed by a single-side chemical etching and cleaning procedure. Subsequently, a thin interfacial oxide layer is thermally grown in a tube furnace and an in-situ doped a-Si(n) layer is deposited on the rear side using PECVD. The wafers are then subject to thermal annealing and phosphorous (n+) diffusion in a $POCl_3$-tube furnace to create the front floating emitter (FFE) region. The aforementioned processes are carried out at Fraunhofer ISE and the samples are then shipped to ISC Konstanz for further processing.

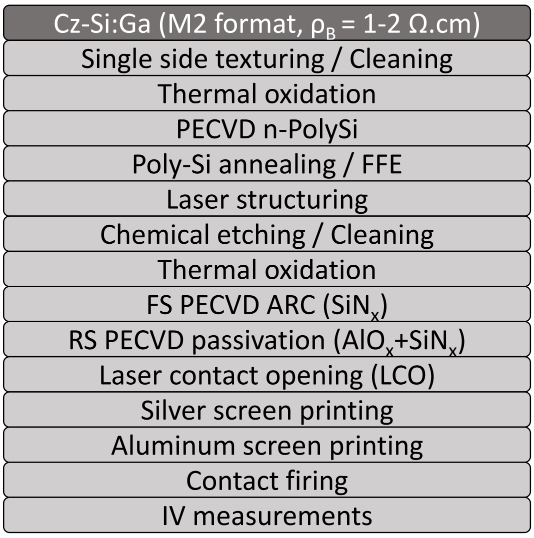

Figure 1: Schematic process sequence of the p-IBC base-line fabrication process at Fraunhofer ISE and ISC Konstanz

At ISC Konstanz, the interdigitated base and emitter region pattern is defined using laser ablation utilizing the phosphosilicate glass (PSG) layer as a mask, followed by a chemical removal of laser damage, PSG removal and wet chemical cleaning. After a thermal oxidation process, a passivation stack of AlO_x-SiN_y is deposited on the rear side and a SiN_x layer on the front side using PECVD.

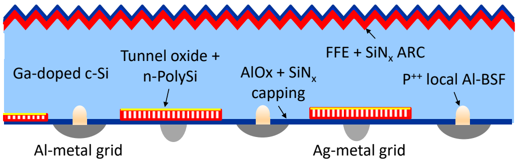

Figure 2: Schematic cross section of the p-IBC solar cell

Laser contact openings of the AlO_x-SiN_y passivation in the base region are carried out and subsequently aluminum base contacts are printed, similarly to the PERC process base contact formation. Silver contacts are established on the poly-Si emitter region using screen printing, followed by a standard co-firing process. The contacts are realized using a metallization pattern with 9 busbars per polarity. A schematic cross section of the finalized solar cell is shown in Figure 2.

2.2 Lifetime samples

In addition to the fabrication of solar cells, a set of carrier lifetime samples is prepared to assess the passivation quality across distinct regions. For the evaluation of the n-poly and base regions passivation, symmetrical flat samples are produced. These samples incorporated n-poly on both sides and were subject to laser ablation following a test structure configuration, with large area ablated test fields. After removal of the laser damage, PSG removal and wet chemical cleaning, thermal oxidation and PECVD AlO_x+SiN_y deposition on both sides forms the passivation layer stack.

Furthermore, cell precursors are generated, following the same laser ablation pattern, with the intention of assessing cells implied open circuit voltage (iV_{oc}) potential without metallization.

Both lifetime structures are subjected to fast firing in a conveyor belt furnace using the same temperature profile as the p-IBC solar cells. Subsequently, the samples underwent characterization using quasi-steady-state photo conductance (QSSPC) and photoluminescence imaging (PL).

3 OPTIMIZATION OF VARIOUS PARAMETERS

Several process parameter optimizations were carried out at various steps in the fabrication process. This paper will showcase a selection of optimization instances, without aiming to provide an exhaustive list.

3.1 Rear side surface morphology

Initially, the FE-pIBC cells featured a textured front side and a flat rear side, achieved by a first alkaline texturing batch process and subsequent single sided etching in acidic solution to remove the rear side texture. However, the diminished popularity of the latter method in numerous modern factories due to the HNO_3 wastewater and nitrogen oxides produced, has led us to explore substitute surface etching techniques for the rear side. In the current process flow, a sacrificial layer enables a single sided texturing process with a saw damage etched (SDE) rear side.

In Figure 3, fill factor (FF) values obtained by current voltage (IV) measurements are compared for groups with different rear side surface morphologies. The first reference group features the initial structure with an acidic polished rear surface. The second group features an SDE rear side and textured front side, as described above. Finally, the third group features a textured front and rear side. Additionally, two variants of silver finger pastes were subjected to testing.

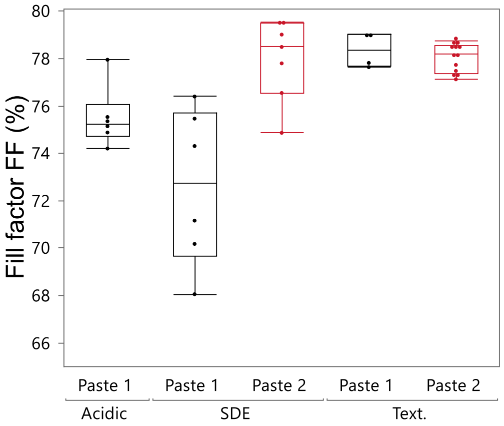

Figure 3: Fill factor results of FE-pIBC solar cells with different silver finger pastes and rear side morphology

In Figure 3, we can see that the FF values highly depend on the rear side surface morphology. Using the Ag paste 1, the FF improves when transitioning from an acidic polished rear side to a textured one, whereas for an SDE surface a lower FF is observed, which we attribute to differences in contact formation. The initial FF drop on SDE surface could be recovered with a new paste (Paste 2 in Figure 3) and highest efficiencies are obtained by combining the latter to SDE rear surface.

3.2 Laser structuring

Laser patterning experiments are conducted testing different sets of laser parameters both on test structures and on solar cells. Planar test structures with an equivalent PSG thickness are fabricated by the deposition of poly-Si(n) layers and subsequent $POCl_3$-diffusion. After laser ablation, the samples were chemically etched in alkaline solution and characterized by laser scanning microscopy (LSM). An example for such laser parameters variations, in this case different power settings, is depicted in Figure 4.

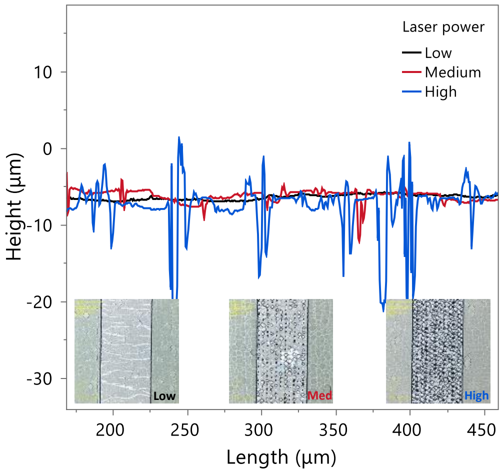

Figure 4: Height profile after laser ablation using different laser powers and subsequent alkaline etching measured by LSM

It is interesting to see, that when increasing the laser power to a certain extent, overlap spikes begin to appear. An optimum of laser parameters should be found to be able to etch the n-poly layer while mitigating the formation of these overlap spikes, which have the risk to introduce both passivation and contact-related defects.

3.3 FFE formation and poly-Si annealing

The $POCl_3$ tube furnace process following the a-Si deposition plays an important role by serving dual purposes: First, the high temperature facilitates the crystallization of the n-poly layer, and second, engendering the formation of a lightly doped front floating emitter on the front surface of the FE-pIBC solar cell. The developed $POCl_3$ process recipes enable the formation of lightly doped FFE profiles with high sheet resistance values of $R_{sh} \approx 1000$ Ω/sq., despite the high temperature required for fully crystallizing the silicon layer in the same process. A test diffusion with a full load of 500 HF-dipped wafers shows a uniform doping result over the process boat and wafer surface, confirming the industrial feasibility of the process. Figure 5 depicts doping profiles of the FFE observed for different process parameters.

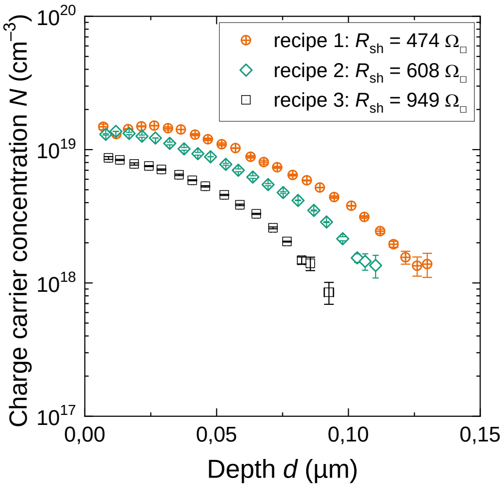

Figure 5: FFE doping profiles of different diffusion recipes determined by electrochemical capacitance voltage (ECV) measurements on alkaline textured surfaces. The profiles are scaled to match the local sheet resistance determined by eddy current measurements.

For two different diffusion recipes investigations are conducted on both lifetime samples and solar cells. The results shown in Figure 6 demonstrate that a FFE with a higher sheet resistance notably enhances the implied open-circuit voltage iV_{oc} of test structures that feature a FFE front side and a poly-Si passivated rear side. This improved implied iV_{oc} subsequently contributes to an overall elevation in the V_{oc} at the solar cell level, as evident in Figure 6.

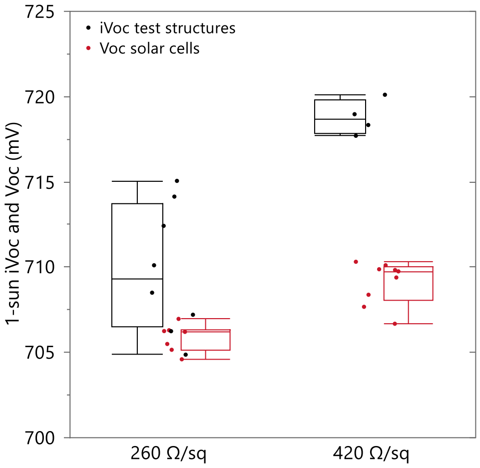

Figure 6: Influence of the front floating emitter diffusion process on iV_{oc} and V_{oc} obtained by quasi steady state photoconductance (QSSPC) and IV measurements, respectively.

3.4 Laser contact opening

In pursuit of enhancing the fill factor, experimentation is conducted involving two distinct laser contact opening geometries. Other printing parameters, including the specific aluminum paste employed and the fast firing temperature profile, are maintained constant.

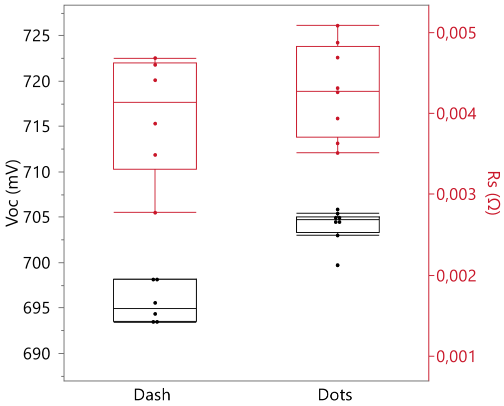

Figure 7: Open-circuit voltage V_{oc} (black, left scale) and series resistance R_s (red right scale) results obtained by IV measurements on solar cells with dash and dots shaped laser contact openings

While the implementation of dash openings succeeds in slightly diminishing the series resistance, a higher fraction of metallization results in a significant reduction in V_{oc}, a trend visualized in Figure 7. This decrease in V_{oc} leads to a decline in efficiency, not compensated by higher FF

4 RESULTS

4.1 Lifetime results

Lifetime samples prior to metallization are fabricated in order to evaluate the iV_{oc} potential within distinct regions of the solar cell. Two lifetime sample configurations are fabricated:

- Symmetrical flat samples with n-poly on both sides and laser ablated squares on one side following the PL image in Figure 8. The n-poly and the ablated area are passivated by thermal oxide + PECVD AlO_x+SiN_x layers
- Asymmetrical samples (cell precursors) following the same FE-pIBC architecture prior to the metallization printing.

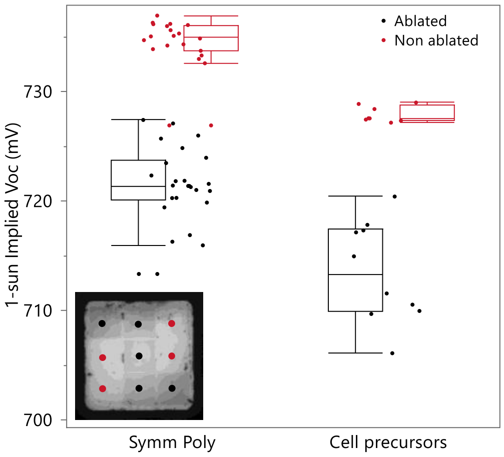

Figure 8: Implied open-circuit voltage iV_{oc} results obtained by QSSPC on different samples architectures. The PL image in the corner shows a typical result for the symmetrical n-poly-sample structure with ablated (black data) and non-ablated (red-data) regions

Apparent from Figure 8, the poly-Si passivation (non ablated area) yields a higher passivation quality compared to the ablated and dielectrically passivated regions. This is confirmed on cell precursers, where

We obtained an iV_{oc} of 715mV and 730mV in the ablated and non-ablated area, respectively.

4.2 Champion cell

After implementing the learnings from a series of optimization procedures, the current-voltage (IV) characteristics of our most exemplary solar cell are succinctly outlined in Figure 9.

The champion solar cell achieves an efficiency of 22.94%, as ascertained through measurements conducted at Fraunhofer ISE CalLab PV Cells. We are currently in the process of planning further optimization strategies with the objective of further efficiency increase.

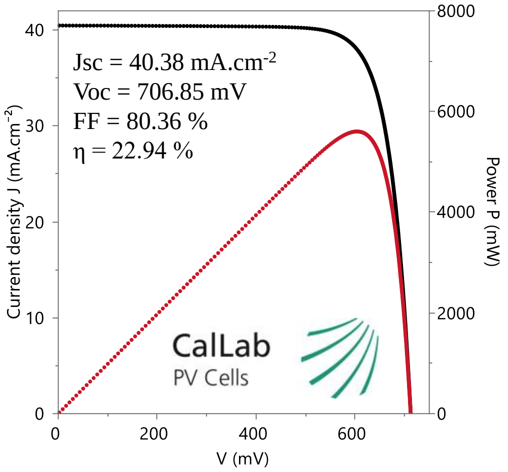

Figure 9: IV curves and characteristics of our champion p-IBC cell measured by Fraunhofer ISE CalLab PV Cells

5 SUMMARY

This manuscript summarizes our efforts concerning the design and optimization of a p-type front floating emitter- interdigitated back contact (FE-pIBC) solar cell, employing passivation through plasma-enhanced chemical vapor deposition (PECVD) n-poly Si layers. The study showcases the feasibility of fabricating FE-pIBC passivated contacts, guided by a process flow emphasizing high reusability of PERC related equipment. Notably, the process sequence harmonizes seamlessly with prevalent high-temperature processing utilized in solar cell fabrication. The front-side floating emitter and poly annealing are merged into a single step. Systematic optimization allowed us to reach an efficiency of 22.94%. Ongoing refinements and adjustments fuel our optimism in achieving further increase in efficiency.

ACKNOWLEDGMENTS

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