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High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry

HighLite

HighLite- Deliverable report

D3.10- IBC cell with a top efficiency ≥24.5% (full-size) and ≥24.3% (cut-cells).

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About HighLite

The HighLite project aims to substantially improve the competitiveness of the EU PV manufacturing industry by developing knowledge-based manufacturing solutions for high-performance low-cost modules with excellent environmental profiles (low CO_2 footprint, enhanced durability, improved recyclability). In HighLite, a unique consortium of experienced industrial actors and leading institutes will work collectively to develop, optimize, and bring to high technology readiness levels (TRL 6-7) innovative solutions at both cell and module levels.

HighLite consortium members

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Publishable summary

The major goal in the HighLite project in Task 3.4 was to develop an IBC cell with a top efficiency ≥24.5% (full-size) and ≥24.3% (cut-cells). The consortium followed two major development routes: the polyZEBRA concept, a solar cell process exclusively developed within the project, and the POLO IBC solar cell concept.

The polyZEBRA concept featured a both polarities passivating contact n-type IBC solar cell using an innovative laser treatment to obtain the p-poly-silicon passivating layer. It was designed to be an upgrade of the ZEBRA technology, which already has entered mass production.

The second promising approach was the POLO concept, a p-type IBC cell with a passivating contact emitter structure. It featured a mainly PERC-based process and a very lean process flow.

Both approaches have reached well over 23% efficiency and we are presenting an easy to follow roadmap to reach the final efficiency goals. To follow further this roadmap and to reach pilot production TRL levels, the Horizon Europe Project (No. 101084259) "IBC4EU" was started in November 2022.

Principal studies have been conducted to quantify and minimize edge recombination on IBC structures. We present the most promising approaches that are expected to reach the losses as anticipated at the beginning of the project.

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List of acronyms, abbreviations and definitions

Abbreviation	Definitions
AlO_x	Aluminum Oxide
FFE	Front floating emitter
IBC	Interdigitated back contact
iV_{oc}	Implied open circuit voltage
$J_{0,\ldots}$	Recombination current (at given location (…) in the device)
n^+ poly-Si	Highly n-dope polysilicon
p^+ poly-Si	Highly p-dope polysilicon
PECVD	Plasma enhanced chemical vapour deposition
POLO	Polysilicon on oxide
SiN_y	Silicon nitride
SiO_x	Silicon oxide
TOPCon	Tunnel oxide passivating contact
V_{oc}	Open circuit voltage

1. Introduction

Several of the main objectives of this work package were to

- demonstrate a best IBC cell with efficiency ≥24.5% (full-size) and ≥24.3% on ¼ (or smaller) cut-cells
- develop innovative cutting and edge re-passivation processes to minimize cut-edge recombination losses.

For IBC cells, the target was to drastically improve the efficiency from <23% currently to ≥24.5% (full-size) by introducing high-temperature passivating contacts. In order to fast-track developments, industrial approaches for the patterning of the high-temperature passivating contacts had to be developed before finally being implemented in IBC cells to reach the efficiency targets.

In order to achieve such efficiencies, the most suitable methods for poly-Si deposition and metallization were selected from T3.3. Compared to nPERT cells optimized in T3.3, IBC cells required structuring of the passivating contact layers. Several industrial approaches were studied by the partners: (i) patterned ion implantation (ISFH, CEA-INES, IBS), (ii) laser structuring (ISC, ISFH).

Table 1: Overview of deliverable D3.10.

Deliverable Number	Short deliverable name	Lead beneficiary	Type	Dissemination level	Due date
D3.10	IBC cell with a top efficiency ≥24.5% (full-size) and ≥24.3% (cut-cells)	ISC	R	PU	M42

2. Work performed for deliverable

2.1. Approach

2.1.1. polyZEBRA

The polyZEBRA concept was developed by ISC Konstanz in the HighLite project as an upgrade of the well-established ZEBRA process towards both polarity poly-Si based passivating contacts[3]. It featured flat regions of n^+ poly-Si and p^+ poly-Si, separated by a textured and p-diffused gap, which had the same structure as the front side with floating emitter (Figure 1). Key processes were laser-based patterning of the poly-Si layer, a p-diffused gap, and the metallization of both polarities in one single screen-printing step.

Patterning of the base region followed the ZEBRA process with mask deposition and laser-induced mask ablation of the non-base regions. In contrast, the patterning of the emitter region was newly developed within the HighLite project: by fine-tuning the laser fluence it was possible to increase the amount of activated boron within the p^+ poly-Si by roughly one order of magnitude without destroying the tunnel oxide below. This higher activation made the p^+ poly-Si to be etch resistant in alkaline solution with an etch selectivity of ~500 compared to the surrounding not laser-treated p^+ poly-Si, enabling texturing of the front side and gap region without additional mask[4].

During p-diffusion of the front side, the unprotected gap region on the rear was also p-diffused. This was a key process as on the one hand the thermal budget was used to activate the poly-Si passivation on both polarities. On the other hand, the doped gap region ensured an early and soft breakdown in reverse bias, which could serve as a built-in bypass-diode.

Lastly, printing of both polarities in the same screen-printing step was of high interest for industrialization as a lean metallization sequence. In fact, the well-established ZEBRA metallization scheme was utilized apart from an optimized screen layout for finger print. The process and the resulting structures were part of a European patent application[5].

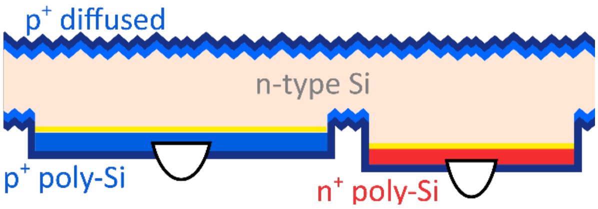

Figure 1: Schematic cross section of the polyZEBRA cell.

2.1.2. POLO-IBC

Figure 2 shows the schematic cross-section perpendicular to the fingers of the ISFH POLO-IBC cells. The process sequence started with the formation of a POLO junction using a wet-chemically grown interfacial oxide and a 200 nm-thick in-situ doped low-pressure chemical vapor-deposited poly-Si layer. A subsequent annealing step generated the pinholes in the interfacial oxide and formed a SiO_2 on top of

[3] J. Linke, F. Buchholz, C. Peter, J, Hoß, J, Lossen, V. Mihailetchi, R. Kopecek., Proc. of 8th WCPEC, 2022, 102-106

[4] Applied for patent (app. number: EP20201147.4)

[5] Applied for patent (app. number: EP21214033.9)

the poly-Si and thinned the poly-Si layer down to 120 nm. This was the only high temperature step in this process[6]. The oxide was ablated with a laser to form the base region and remove the poly-Si in the ablated regions by etching. Then, a plasma-enhanced chemical vapor deposited SiN_y layer was deposited to protect the non-textured rear side from the following texturization step. Thus, random pyramids were created only on the front side. After texturing the SiN_y layer was removed and a passivation layer stack of a 10 nm-thick AlO_x layer and an 80 nm (60 nm)-thick SiN_y layer was deposited on the front (rear) side. Laser contact opening (LCO) generated dashed lines in the base region. Subsequently, silver-paste fingers were printed to contact the POLO layer and aluminum-paste fingers to form the Al-doped p^+ base contact during a co-firing step. An M2-sized full and cut cells with busbars were developed.

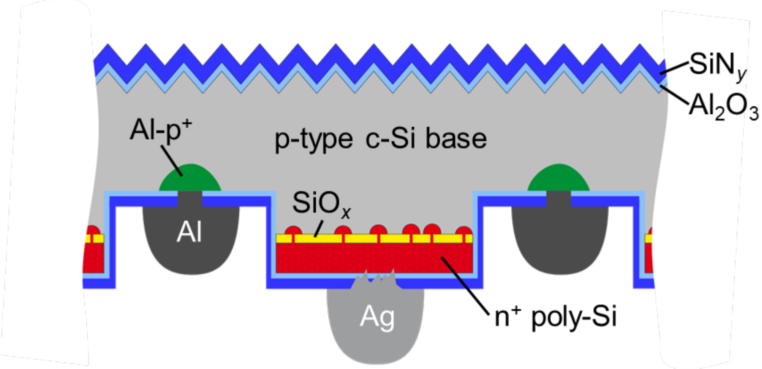

Figure 2: Schematic cross section of the POLO IBC cell.

2.2. Results obtained

2.2.1. polyZEBRA – learning curve

Applying the polyZEBRA process as sketched above, enabled a champion cell efficiency of 23.5% on G1[7] and 23.4% on M6 full wafer size. Figure 3 shows the learning curve from the first measurable cells (late 2020) to the mature process (late 2022). It is evident, that the efficiency was dominated by the fill factor. Passivation optimization on test structures in the second half of 2021 led to a V_{oc} gain of 35mV, but the fill factor dominated cell efficiency was not increased. Only later after a paste change and screen optimization, the fill factor approached 80% and thus cell efficiencies >23% were enabled. The most recent cell runs were limited by a V_{oc} of only about 700mV. Passivation was already enhanced on test wafers but could not yet be tested on cell level due to problems with the crucial laser tool at ISC Konstanz.

6 F. Haase, B. Min, C. Hollemann, J. Krügener, R. Brendel, R. Peibst, Prog Photovolt Res Appl., 2021, 1–8.
7 J. Linke, F. Buchholz, C. Peter, J, Hoß, J, Lossen, V. Mihailetchi, R. Kopecek., Proc. of 8th WCPEC, 2022, 102-106

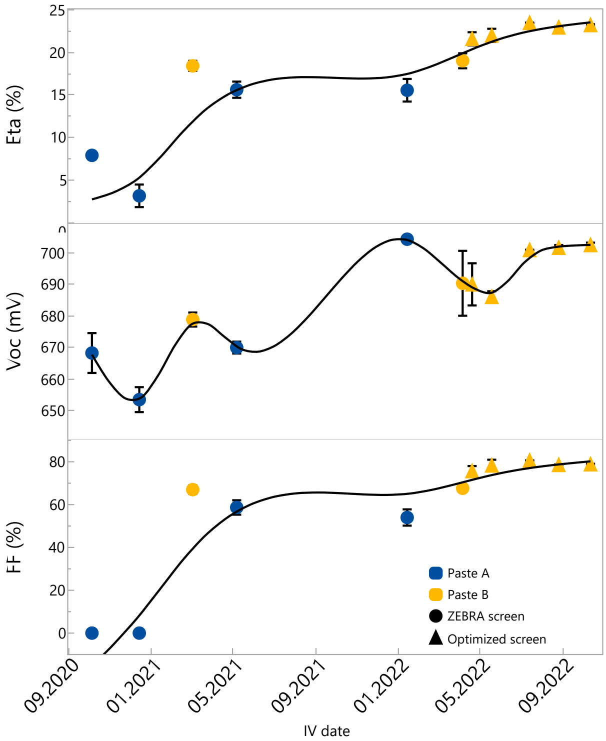

Figure 3: Learning curve of the newly introduced polyZEBRA concept from first measurable cells to mature process. Error bars indicate the standard deviation of the cell group.

2.2.2. polyZEBRA – Quokka3 simulation

In order to address the desired efficiency of 24.5% (the target of D3.10) in light of the unsolved problems with the laser tool, Quokka3 simulations were performed to estimate the expected gains from easy-to-implement improvements. Main input parameters are the rear geometry (emitter/base/gap width, pitch) and recombination/sheet resistance of emitter, base, gap and front side in metalized and metal-free areas. The baseline simulation was done with input values from experimental data from the current champion cell and corresponding test structures (see Table 2). It yields 23.2% cell efficiency, which is reasonably close to the measured value of 23.4%.

Table 2: Main experimentally determined input parameters for baseline simulation.

Parameter	Value
Bulk resistivity	20 Ωcm
Emitter width	240 µm
Base width	570 µm
Gap width	135 µm
Emitter recombination	5 fA/cm²
Base recombination	17 fA/cm²
Gap/font side recombination	17 fA/cm²
Emitter sheet resistance	50 Ω/sq
Base sheet resistance	170 Ω/sq
Gap/front side sheet resistance	460 Ω/sq

Figure 4 shows the evolution of the simulated cell efficiency by each easy-to-implement process modification. In a first step, a lower base resistivity increased the expected efficiency to 23.9%. Changing the dimensions of the IBC pattern, namely decreasing the width of the gap and the pitch, resulted in a slight gain to 24.1%. A significant reduction of the recombination on the front side, gap, and emitter region, as was previously demonstrated on test structures, would lead to an efficiency up to 24.8%, which would meet the requirements of D3.10. In particular the reduction of recombination in the front side and gap region has a huge impact due to its large surface fraction of 62% of the cell. Using the recently achieved recombination of 5 fA/cm² on test wafers as simulation input instead of the 17 fA/cm² from the baseline (see Table 2) increases the cell efficiency by +0.5%$_{abs}$.

As all simulated process modifications do either only change the rear geometry or were already experimentally demonstrated, **the 24.5% cell efficiency seems to be achievable** as soon as the laser problems will be solved.

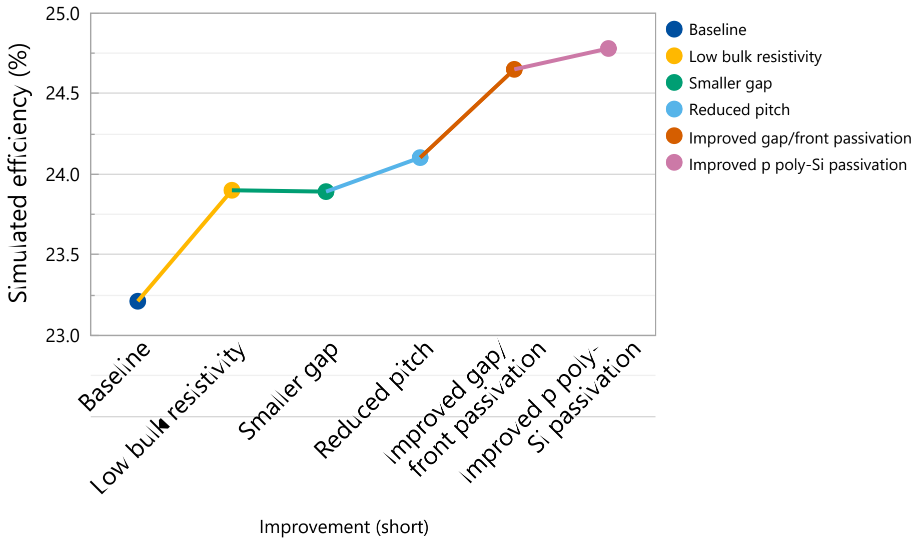

Figure 4: Quokka3 simulations of modifications to the process flow that will enable the desired >24.5% efficiency.

2.2.3. POLO-IBC

Figure 5 shows the IV parameters of the POLO IBC cells before and after cutting in half. Since the results scattered a lot due to process instabilities, we only show the results of the best 6 POLO IBC cells. The best efficiency before cutting the cells was 22.5%. However, these cells suffered from poor Al-p$^+$ contacts formation. Another major limitation of the batch was the insufficient passivation of the surfaces due to issues with the AlO_x/SiN_y deposition. In a batch with small area cells processed on a M2 wafer, an efficiency of 23.92% was independently confirmed by ISFH CalTec. The best V_{oc} values are above 718 mV. These high achieved V_{oc} values moreover show the overall good passivation quality, which was confirmed by lifetime measurements on cell precursor structures that yielded values of $J_{0\,\mathrm{front}}$ = (4.5 ± 1.5) fA/cm^2, $J_{0,\mathrm{rear,\,n+POLO}}$ = (0.75 ± 0.55) fA/cm^2 and $J_{0\,\mathrm{rear,\,base}}$ = (1.5 ± 0.5) fA/cm^2. By varying the Al-p$^+$ contact fraction we analysed an $J_{0,\mathrm{Al-p+}}$ of 1500 fA/cm^2 indicating a significant deterioration of the Al-p$^+$ quality compared to previous batches in which a $J_{0,\mathrm{Al-p+}}$ of 600 fA/cm^2 was determined using the same method. Unfortunately, the surface passivation was worse in the previous batch and thus the efficiency lower. A simulation showed that a combination of the good passivation of the last batch and the good Al-p^+ contacts could increase the efficiency by about $0.4\%_{abs.}$ In combination with shorter fingers on the large cell, the FF would increase additionally by about $1\%_{abs.}$ and thus the efficiency would increase to 24.6%. With this, the aim of 24.5% would be reached.

Figure 5: IV parameters of the POLO IBC cells before and after cutting in half.

2.2.4. Cutting of ZEBRA cells

Table 3 shows experimental data of optimized cutting for ZEBRA solar cells. The advantage of IBC cells is that cutting through emitter regions can be avoided. When using TLS it has been demonstrated that the losses can substantially be reduced. The edge recombination in Table 3 refers to slices cut at one side ("North") and two sides ("North&South").

Table 3: Cut-edge recombination losses of different cell sizes and cut edge scenarios.

Cell size	Aspect ratio (cm^{-1})	Edge diffusion	Edge recombination	V_{oc} loss (mV)	J_{sc} loss (mA/cm²)	FF loss ($\%_{sb}$)	η loss ($\%_{abs}$)
1/4	0.26	n+	North	-0.84	-0.17	-0.16	**-0.17**
	0.52		North&South	-1.68	-0.33	-0.32	**-0.33**

In the case of 1/4 cut cells cutting through BSF, the efficiency loss is on average only $-0.25\%_{abs}$, as of course one will obtain edge stripes and middle stripes. Thus, by only optimizing the cutting, the losses in efficiency can be quite close to the target value. That the same is true for polyZEBRA solar cells in the anticipated efficiency range is yet to be shown. Repassivation approaches developed within the HighLite project may help to reduce cutting losses further.

On details for the optimized cutting and repassivation of the solar cell, we would like to refer to D3.5. Several approaches were established with very promising results. On the given samples, only Nafion™ was evaluated to reduce the cutting losses further. The AlO_x approach by CEA-INES is still open to be tested. It is safe to assume that the losses will be comparable. Most promising in this respect is that for both cell concepts cutting through emitter layers on the rear side can be avoided.

2.2.5. Cutting of POLO-IBC cells

Figure 6 shows the losses in percent by cutting the cells in half. Positive values show losses while negative would mean a gain. The loss in each IV-parameter was mostly 0.0% and less than 0.2% in median in pFF. The maximum loss of a parameter was 0.6% despite the shunt resistance, which was about 20%, which still did not influence the FF due to its high absolute values shown in Figure 5. The FF shows up to 1.3% gain, which is probably not a true value, as in particular the FF has the highest uncertainty due to the design of the measurement chuck. The efficiency was not influenced negatively by cutting the cells within the measurement uncertainty. We can conclude that a cell which is cut into four parts will also show no significant decrease in efficiency and so the aim of more than 24.3% efficiency on large cells is also reasonable.

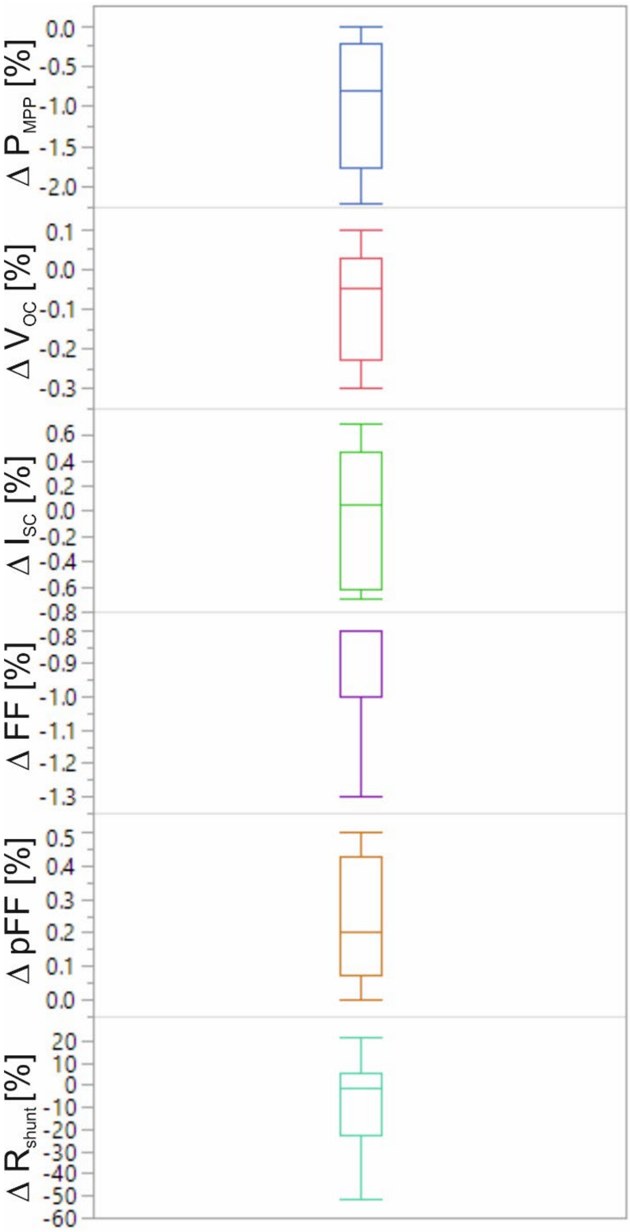

Figure 6: Losses of the IV parameters of the POLO IBC cells after cutting in half.

3. Risks encountered and expected impacts

3.1. Risks/problems encountered

Unfortunately, neither the polyZEBRA, nor the POLO process quite yielded the desired efficiencies due to various unforeseen reasons, e.g. a broken laser tool. However, simulations indicate that in both cases several low hanging fruits remain to be collected so that the desired efficiencies > 24.5% should easily be reached shortly after the end of the project. The same applies to the target cut cell efficiencies. Concerning reducing the cut losses, extensive work has been done. Losses of less than 0.2%abs. have been shown only on a lower efficiency level on ZEBRA and POLO IBC cells. To increase the TRL of these processes further, a subsequent Horizon Europe project (IBC4EU, No. 101084259) has recently started.

3.2. Expected impacts

Both technologies are key to the recently started IBC4EU project (No. 101084259) that continues the improvement and will bring the TRL to pilot production levels. The industrial partners for solar cell manufacturing in this project (Valoe Cells, KALYON PV) will evaluate the pilot production to show the industrial feasibility. Within WP8 of the HighLite project, promising cost structures for mass production for both cell concepts have been calculated, showing the suitability for unique, efficient and competitive solar cell production technology.

4. Conclusions

The most promising approaches proved to be the laser structured both-polarity passivating contact polyZEBRA cell (applied for patent by ISC) and the laser structured POLO IBC cell with a lean process flow by ISFH. Even though both concepts did not achieve the D10.3 goal of 24.5% cell efficiency due to unexpected equipment problems, this efficiency target is expected to be fulfilled as soon as these technical problems are solved.

Several cut cell repassivation methods and other cut cell recombination loss reduction methods were evaluated by the partners. Obtained results indicate that repassivation of cleaved wafers is possible and that cut cell losses can be substantially reduced. The target values could unfortunately not be demonstrated on the final devices.