1. Gegevens project

Projectnummer	1621101
Projecttitel	**BEACON-** Advanced **B**oron **E**mitters **a**nd Industrial **Con**tact technology
Penvoerder en medeaanvragers	ECN.TNO Tempress Systems
Projectperiode	04.05.2017 – 30.09.2019

2. Inhoudelijk eindrapport

Samenvatting

Because of the rapid recent improvement of n-type solar cells thanks to the application of polysilicon based contacts at the rear, the front of the solar cell, having usually (particularly in industry) a uniform diffused boron emitter, has become limiting and needs to be improved more urgently than ever.
The objective of this project was to develop a novel diffused boron emitter process, and implement a selective emitter that is easy to manufacture. An efficiency improvement of 1%abs has been targeted, aiming for 23.0% efficiency at project end, with a low complexity process suitable to realize a cost reduction at module level.
The project focused on uniform and selective boron emitter diffusion processes, dielectric-layer surface passivation, and contacting technology for a diffused selective emitter with very low recombination. This also included the application of polysilicon passivating contact layers. All steps were supported by extensive characterization, analysis and modelling, and finally innovations based on the learnings have been integrated into completed solar cells.

Main results of the project are

- Boron diffusion tool and process optimizations enabling Industrially feasible uniform deep emitters for reduced contact recombination and . Such emitters have recently enabled efficiencies >22% for PERPoly cells in the Polaris project.
- Assessment and follow-up options for selective emitters based on either laser doping or screen-printed masks combined with chemical patterning.
- Improved understanding of emitter contacts enabling the insertion of an intrinsic polysilicon layer reducing the contact recombination of AgAl fire-through screen printed contacts from >1500 fA/cm^2 to ~500 fA/cm^2.
- Device concepts with 23% cell efficiency potential based on these innovations combined with busbarless contacting schemes.

Inleiding

Because of the rapid recent improvement of n-type solar cells thanks to the application of polysilicon based contacts at the rear, the front of the solar cell, having usually (particularly in industry) a uniform diffused boron emitter, has become limiting and needs to be improved more urgently than ever.

Doelstelling

The objective of this project was to develop a novel diffused boron emitter process, and implement a selective emitter that is easy to manufacture. An efficiency improvement of 1%abs has been targeted, aiming for 23.0% efficiency at project end, with a low complexity process suitable to realize a cost reduction at module level.

Werkwijze

The BEACON project is fully in line with the ECN and TKI roadmaps towards higher efficiencies and cost effective industrial cell concepts, which include e.g. a bifacial cell efficiency of 23% in 2020 at TRL6. It is a natural follow up of the TKI Nexpas (ended Q3 2017) and Antilope (ended Q4 2017) projects that both focused on the n+ polySi process on the rear of n-PERT cells. The Beacon project focused on the front side of these cells, which became the efficiency limiting factor, and developed a high-quality, industrial boron emitter and contacting technology. In the Antilope project, initial simulation studies on more advanced boron emitters structures were performed and demonstrated the potential. The ambition of the BEACON project was to provide the necessary developments, IP and knowhow to enable industrial, cost effective n-PERT or PERPoly cells based on high-quality emitter passivation (both surface and contact regions) and screen-printed contacts with cell efficiencies up to 23%.

The project focused on uniform and selective boron emitter diffusion processes, dielectric-layer surface passivation, and contacting technology for a diffused selective emitter with very low recombination. This also included the application of polysilicon passivating contact layers. All steps were supported by extensive characterization, analysis and modelling, and finally innovations based on the learnings have been integrated into completed solar cells.

Execution of the project was done in very close cooperation between ECN.TNO and Tempress. Brainstorming on the most promising strategies to follow, as well as design and practical execution of the experiments took place in mixed teams from both partners.

Resultaten en discussie

Throughout the project, device simulations served as valuable tool for steering the development towards the most promising direction. At the project start, it was soon concluded that highly resistive emitters (150-170 Ohm/sq) can only be beneficial in combination with very narrow (<<20 µm) fingers for the cell metallization.

As this was (and still is) not yet in sight for industrial processing, the project focused on emitters of around 100 Ohm/sq that are compatible with mainstream screen printing technology.

Figure 1 shows the calculated cell efficiency as function of the recombination parameter of the emitter surface (J0,em) and of the emitter contacts (J0,c). In the upper right the starting point of PERPoly cells with 21.5% can be seen.

21.92502	10	20	30	40	50	60	70 J0 em
3000	21.81	21.74	21.68	21.63	21.57	21.52	21.48
2000	22.01	21.93	21.85	21.78	21.72	21.66	21.60
1500	22.13	22.03	[illegible]	[illegible]	21.80	21.74	21.68
1000	22.27	22.16	[illegible]	[illegible]	21.89	21.82	21.75
500	22.44	22.30	22.19	22.08	21.99	21.91	21.84
300	22.51	22.37	22.24	22.13	22.04	21.95	21.88
200	22.56	22.40	22.27	22.16	22.06	21.97	21.90
100	22.60	22.44	22.30	22.19	22.09	22.00	21.92
J0 cont							
FF= 80%			contact fraction 2.5%				
Jsc = 39.8 mA/cm2			rear J0pass, J0contact: [5; 80] fA/cm2				

Laser selective emitter +0.2-0.5%

Best PERPoly

Deep emitter potential +0.5%

deep selective emitter +0.7 - 1 % (best: poly)

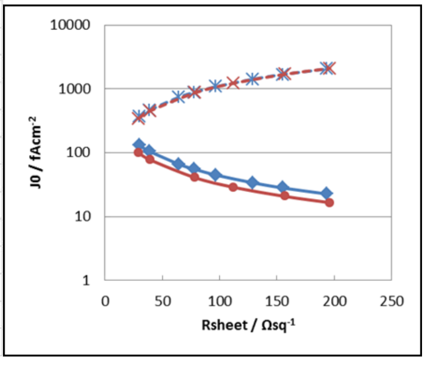


Figure 1. Calculated solar cell efficiency as function of the recombination parameters (J0 em, J0 cont), starting from ~21.5% PERPoly cell (left) and J0,em (solid lines) and J0,c (dashed lines) as function of sheet resistance for deep (red) and shallow (blue) emitter profiles.

The graph on the right shows the J0,em as function of the sheet resistance (solid lines). It can be seen that for 100 Ohm/sq emitters, values are between ~20 fA/cm2 and 70 fA/cm2 for deep emitters with low surface concentration, and shallow emitters with high surface concentration, respectively. Also shown in the graph are the J0,c values of these emitters (dashed lines), which show an opposite trend with emitter sheet resistance compared to Jo,em.

Throughout the project, activities aimed at different strategies to improve the cell efficiency (see also Figure 2).

- developing deep uniform emitters as next industrial upgrade with the potential to gain ~0.5% efficiency
- developing selective emitters to reduce the contact recombination under the fingers further
- applying polysilicon to reduce the recombination of the emitter contacts.

For these concepts, research was done on the emitters themselves (WP1), on the contacts (WP2), and also on integration into working solar cells (WP3).

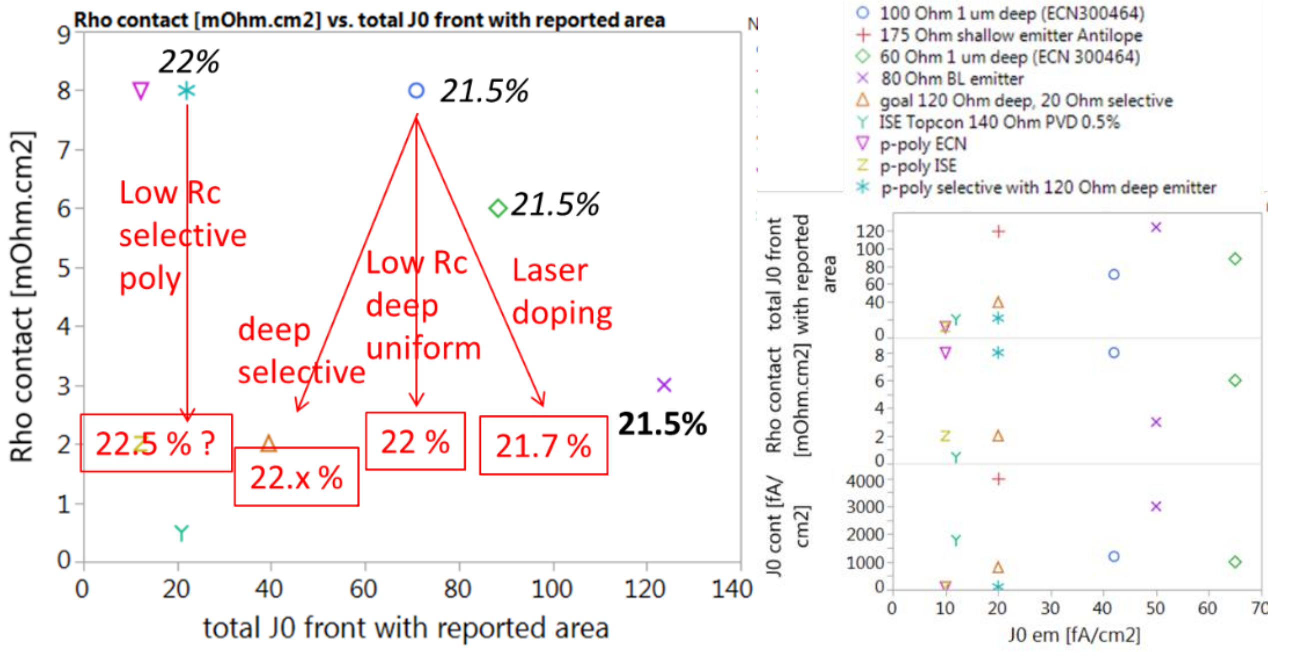


Figure 2. Overview of the different strategies to improve the solar cell efficiency by improving emitter passivation and contacting. The graph on the right shows a summary of different emitters available at the beginning of the project.

WP1 Development of Boron emitter diffusion

1.1 Lightly doped emitter with ultra low J0, and 1.2 Passivation of the emitter

As will be discussed in section 2.1, a strategy to reduce the recombination in the emitter can be to make a deeper, lowly-doped emitter. This can be achieved by having a drive-in at elevated temperatures for prolonged times. Such approach has been tuned for different drive-in temperatures in a Tempress BBr_3 diffusion furnace. A high uniformity can be achieved both across the full 600 wafer load as well as within a wafer. A deep (~0.9 um) and lowly doped (1E19 cm^{-3}) emitter has been achieved.

Emitter passivation by polySi

While the above results on emitters are all with AlOx/SiNx passivation stacks, one of the main developments in Beacon was the application of intrinsic polysilicon to reduce contact recombination (J0,c). This concept is shown in Figure 3. Implied Voc values for PERPoly half fabricates without metallization in Figure 4 and Figure 5 also show a (small) benefit of the polysilicon layer on the emitter passivation (implied Voc).

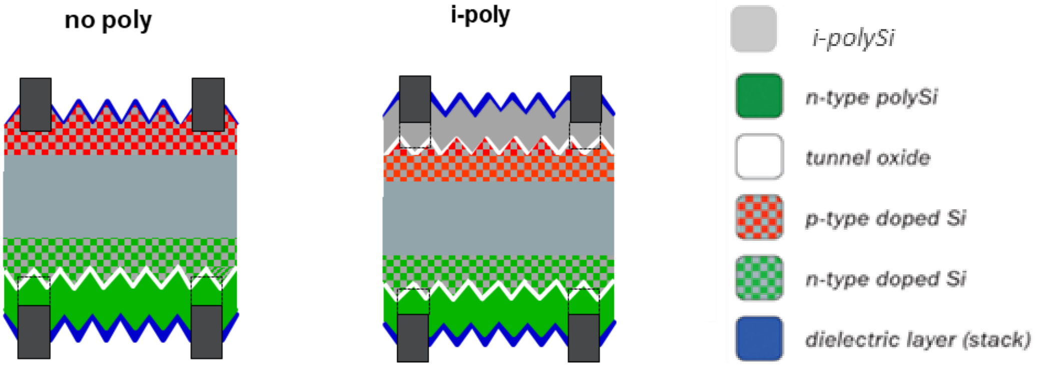


Figure 3. Concept of inserting an intrinsic polysilicon layer under the emitter contacts between emitter and dielectric layer stack.

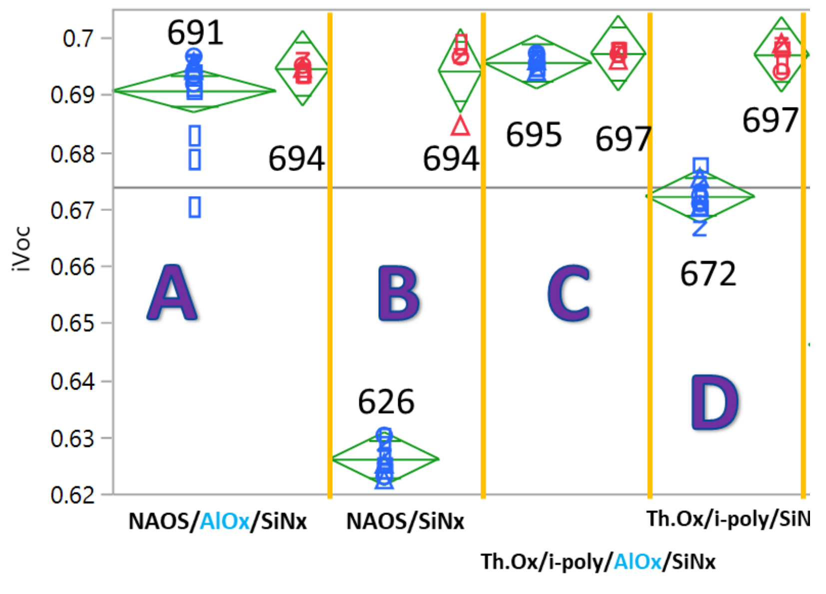


Figure 4. implied Voc before (blue) and after (red) firing for PERPoly half-fabricates with a standard p+ emitter with (A) and without (B) Al_2O_3 passivation below the SiNx, and a p+ emitter passivated by intrinsic polysilicon and capped with (C) and without (D) Al_2O_3 layer below the SiNx .

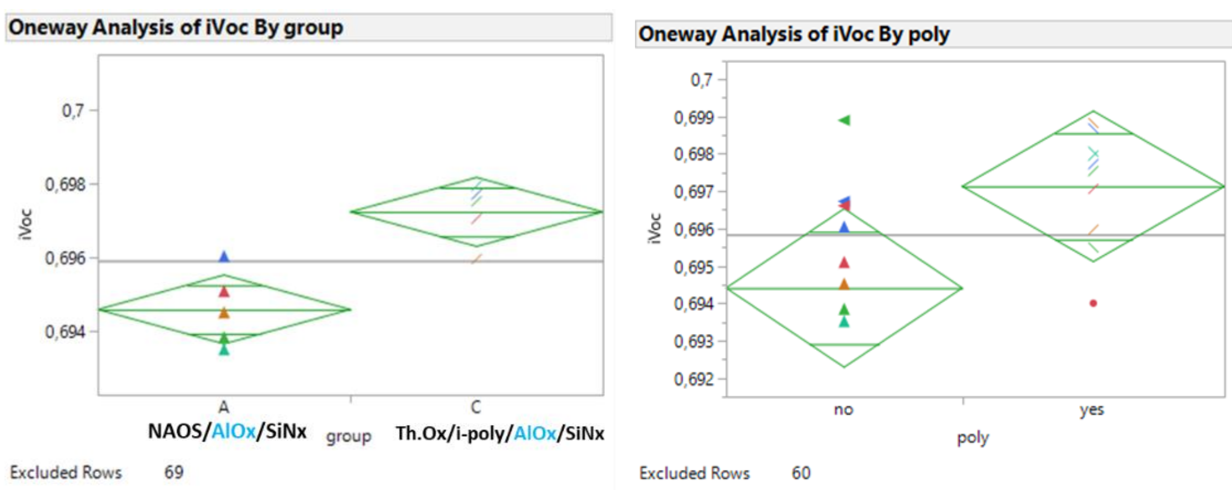


Figure 5. Detailed statistical analysis comparing distinct selections of the experiment, showing significant improvement of emitter passivation by the insertion of an intrinsic polysilicon layer between the emitter and the dielectric layers.

1.3 Emitter profiles for metal contacts and 1.4 bulk lifetime effects

In order to reduce the contact recombination, the highly recombinative contacts need to be shielded from the bulk by a highly doped and/or deep emitter. This can also be seen in the right graph of Figure 1, and is further detailed in section 2.1 below. While deeper uniform emitters with 100 Ohm/sq are described above in 1.1, a selective emitter allows for much lower sheet resistances under the fingers, yielding even better shielding.

Therefore, several efforts were undertaken in the BEACON project to develop such deep profiles with high doping concentration, and also the patterning of selective emitters.

Figure 6, Figure 7, and Figure 8 show the emitter profiles, sheet resistance, and uniformity of the sheet resistance when increasing the drive-in temperature from 900 to 1000ºC.

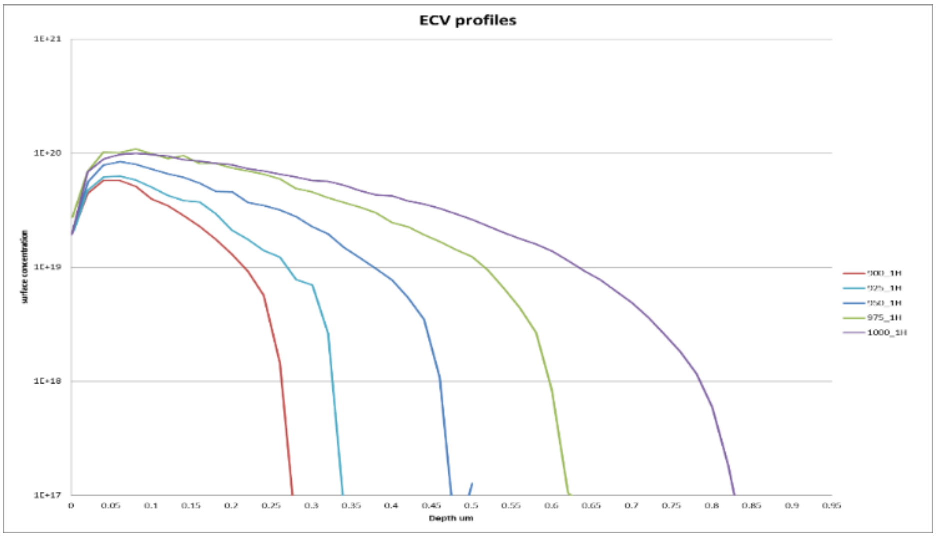


Figure 6. ECV profiles of deep emitters diffused for 1h at temperatures varying from 900ºC to 1000ºC.

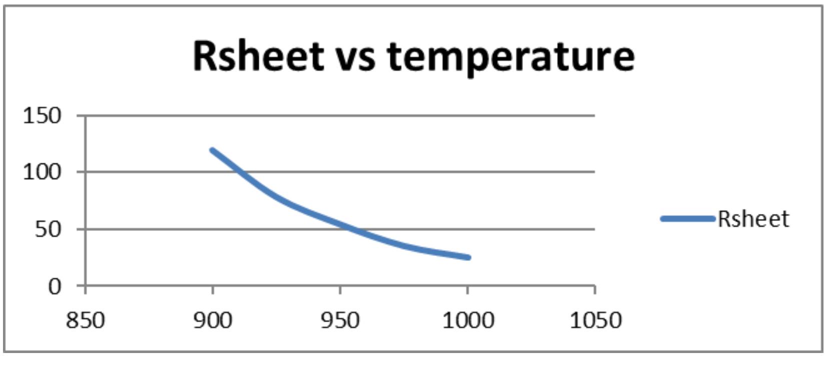


Figure 7. Sheet resistance decreasing as function of diffusion temperature when keeping other parameters constant.

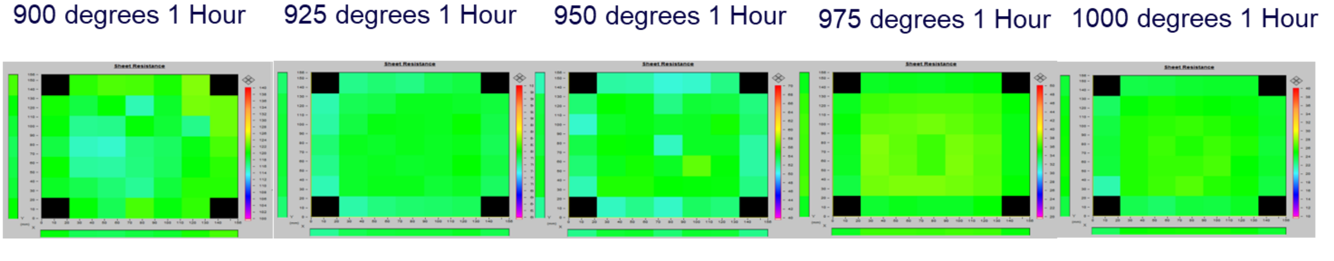


Figure 8. Sherescan plots showing excellent uniformity of the deep emitters.

As expected, emitters get much deeper (from 300 nm to almost 1 um), sheet resistance decreases drastically due to heavier drive-in of the dopants from > 100 Ohm/sq to around 30 Ohm/sq, and a very promising observation was that all these emitters show excellent uniformity.

Unfortunately, the diffusion parameters required to achieve such deep emitters, especially for industrially acceptable throughput times, bring too high thermal budgets and high temperatures such that the bulk of the wafer can be affected. The defects generated during these boron diffusions lead to drastically decreased lifetimes and (implied) Voc, which make these processes incompatible with industrial n-type CZ wafers.

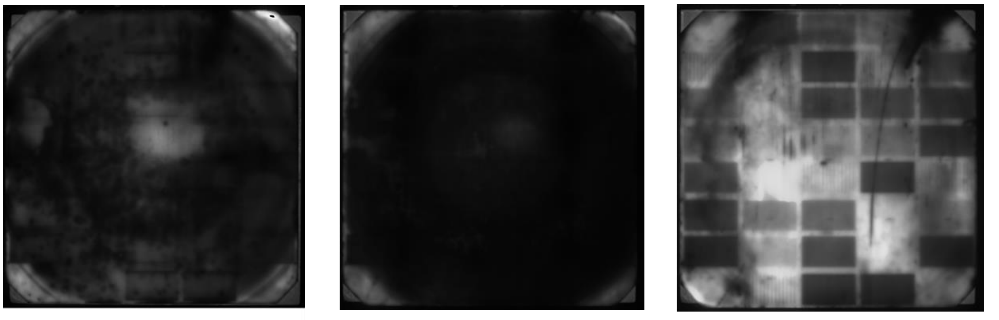


Figure 9. PL images of samples diffused at 1000, 925, and 900ºC showing ring patterns indicating severe damage to the bulk.(Rectangular shapes are from defined test patterns applied on the samples).

In order to fabricate structures with selective emitters, it is important to find an industrially compatible process flow that generates a deeper, higher doped profile under the metallization, and a lower doped area in between the fingers.

An elegant solution for this was developed in BEACON: After a standard boron diffusion, the boron containing glass (BSG layer) is patterned, such that in a following drive-in step, BSG is only present at positions where later the metal fingers are applied. During the long second drive-in at high temperature, a deep profile is formed with high (surface) concentration, as required for effective shielding of the contacts and thus low J0,c. During this drive-in, also the emitter profile between the fingers becomes deeper, and the surface concentration decreases, enabling lower J0,em for the same sheet resistance ~100 Ohm/sq. Figure 10 shows the combination of such profiles as obtained with a drive-in at 960ºC for 16 h.

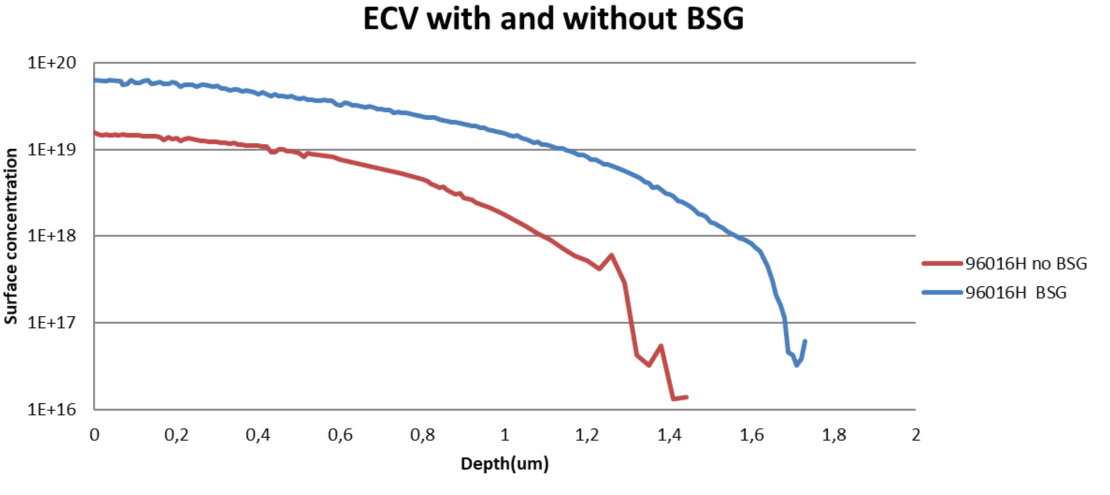
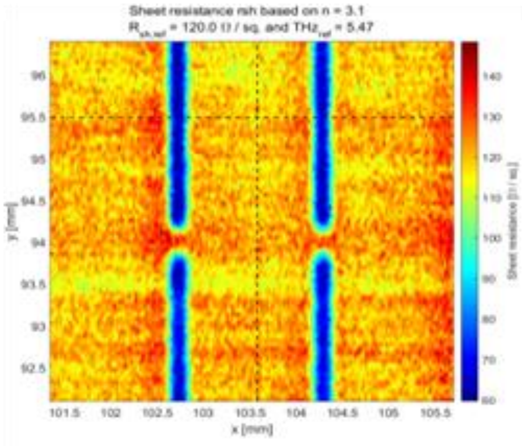


Figure 10. ECV showing emitter profiles for samples where drive-in was done with and without Boron glass (BSG) present.

In a next step, it was also shown that such diffusions can indeed be done on one sample, with BSG patterned in lines, see the THz image on the left in Figure 11. As follow-up, a DoE has been designed to come to more industrial, that means shorter – drive in times, as sketched in the table on the right in Figure 11.



	time				
drive in T	2 h	4h	16h		
1000	X				
960	X	x	X	2 micron deep	
920			X	1 micron deep	

Figure 11. Successful proof-of-principle for a selective emitter process based on patterning boron glass before drive-in, and original DoE agreed for the selective part of the emitters aiming at effective shielding of the contacts to reduce recombination.

Unfortunately, several unexpected issues have been observed when processing this experiment with a larger batch of wafers, see Figure 12. The sheet resistance of the resulting emitters, and also their within-wafer-uniformity, was not uniform over the different positions in the diffusion tube. In addition, an unexplained observation was that depending on the thickness of the BSG layer before drive-in, the (non-)uniformity was qualitatively different.

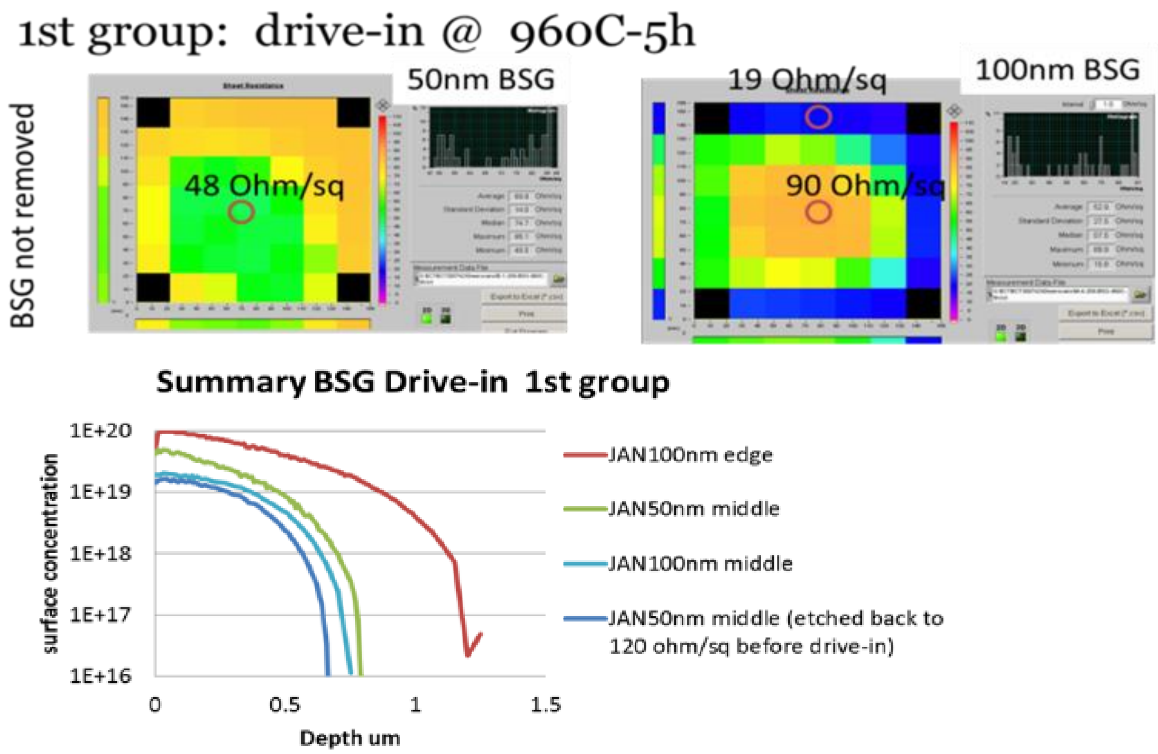


Figure 12. Sherescan (top) and ECV (botto) showing non-uniform doping profile and sheet resistance after long drive in.

Figure 13 summarizes the findings of a series of experiments with variation of loading, BSG layer, and drive-in conditions. Conclusion was that this process sequence is not well enough controlled and would require efforts beyond the scope of this project to optimize. Further efforts for selective emitters therefore focused on laser doping, and alternatively intrinsic polysilicon was introduced as means to reduce the recombination under the emitter contacts, see below and section 2.1 of this report.

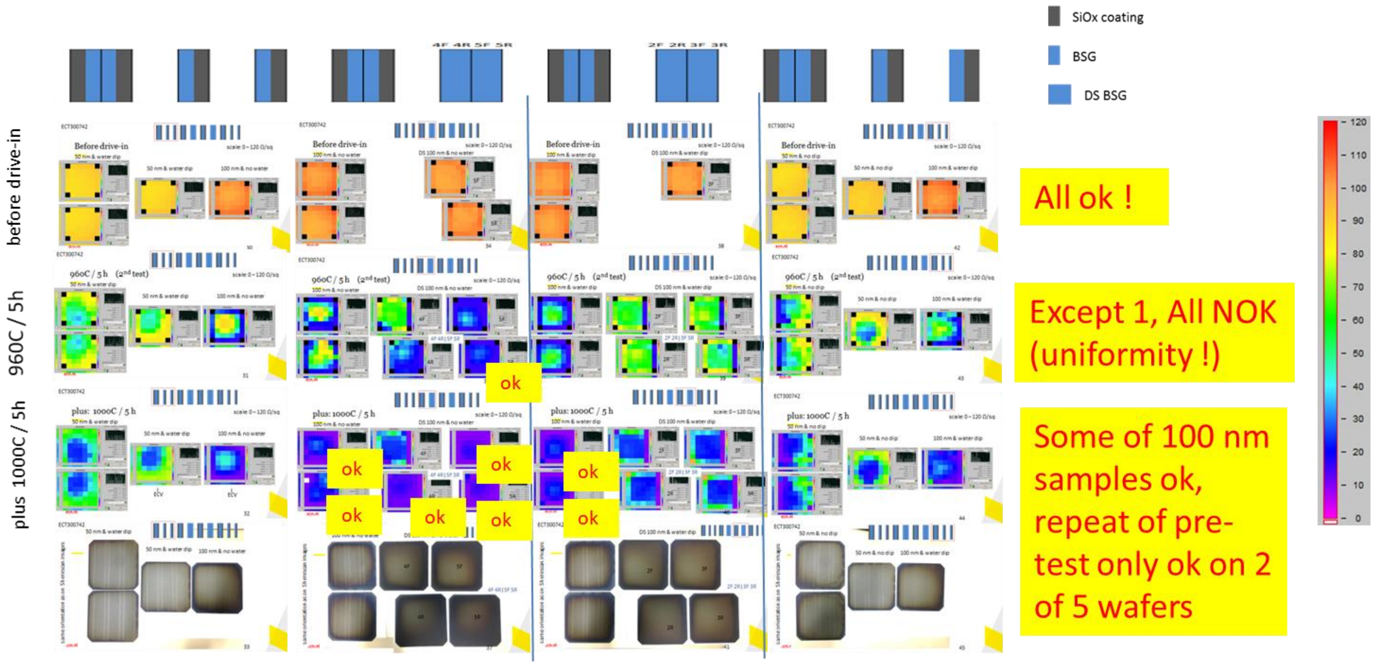


Figure 13. Overview of trial runs for selective emitters in different configurations and with different boron glasses, showing poor uniformity and reproducibility of the process, probably due to variations in the boron glass before diffusion.

Laser doping

Another route to reduce contact recombination is through making area-selective boron emitters, where BBr3 is locally driven-in underneath the metal contacts, e.g., by a laser pulse. This has been briefly explored within the Beacon project. Figure 15B provides an overview of the sheet resistance and J_0 for homogenously laser doped BBr_3 emitters. It is clear that laser settings can be found which severely reduce the R_{sheet} (reaching <50 Ohm/sq while starting from a uniform 85 Ohm/sq BBr_3-diffused emitter) while simultaneously the J_0 can still be reasonably low (<400 fA/cm^2) for a region below the metal contact. After initial promising results, it was decided to discontinue the laser doping experiments because the laser equipment at a partner company was not available anymore. Without this equipment, we had no route to further evaluate the laser doping.

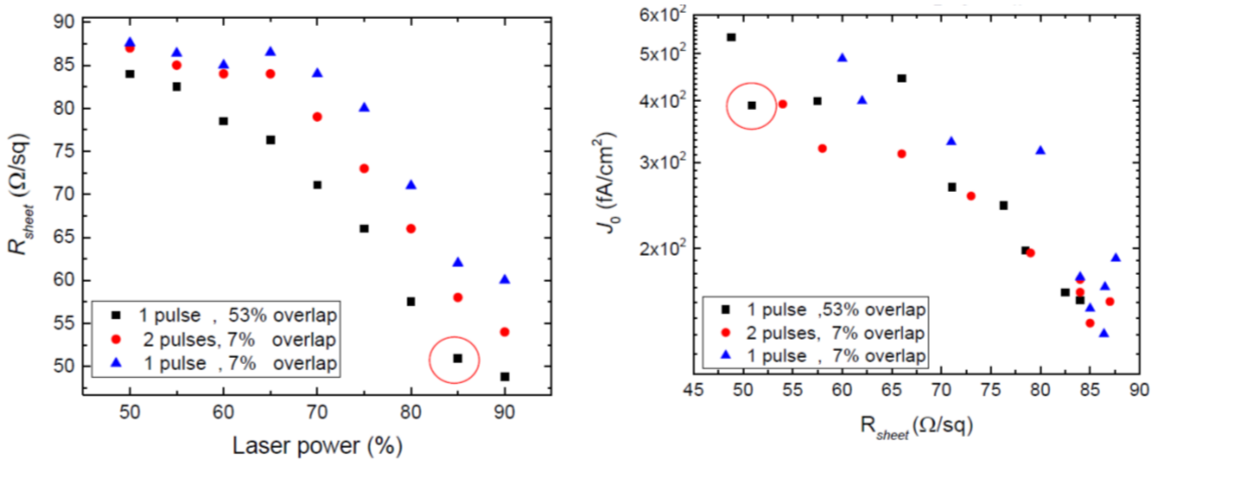


Figure 14. Rsheet of boron doped emitter as a function of laser power and pulse setting (left) and J0 of the emitter as function of Rsheet (right).

Intrinsic poly-Si as buffer layer

Another approach to reduce contact recombination developed in Beacon is the application of an intrinsic polysilicon layer. This lead to an improved bulk lifetime compared to the baseline samples without intrinsic polysilicon on the emitter. As is shown inFigure 14 excellent bulk lifetimes of ~> 3 ms are obtained with polysilicon, compatible with cell efficiencies well above 23%.

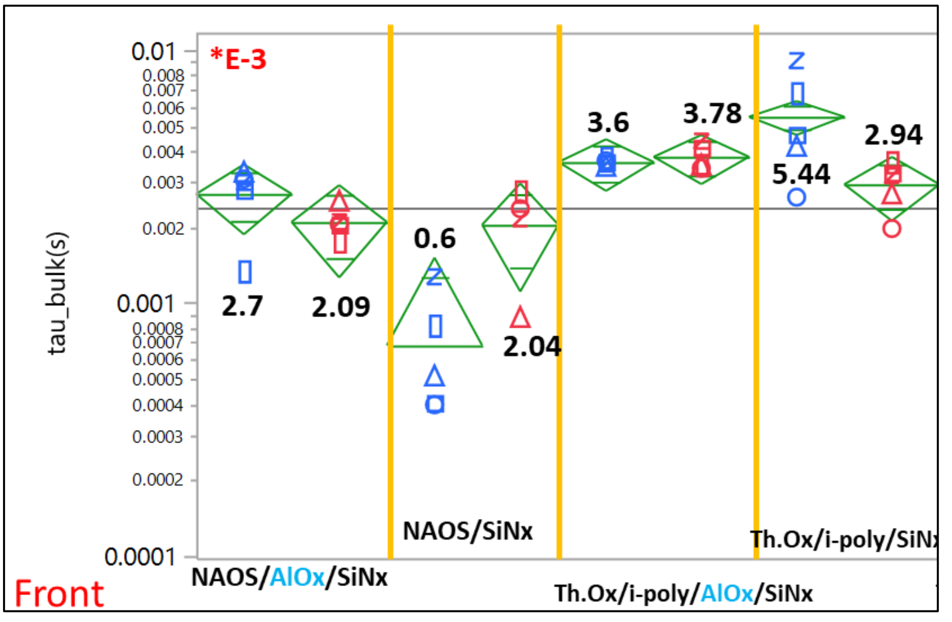


Figure 15. Bulk lifetime exceeding 2 ms for all PERPoly cells, and boosted by the presence of polysilicon to ~>3 ms.

Deliverable/ milestone	Description	Due	Owner	Explanation
D1.1	**report on uniform emitter drive-in, oxidation and etch-back processes**	**M12**	**Tempress**	**Deep emitter development, including for areas under contact in selective emitter**
D1.2	**report on optimized chemistry and coating for emitter with low concentration**	**M18**	**ECN**	**Included in D1.1**
D1.3	**report on selective emitter process**	**M24**	**ECN**	**Etch-back of BSG and laser doped emitter**
M1.1	**Jo of passivated emitter ≤20 fA/cm2, Rsheet ≤150 Ohm**	**M12**	**ECN**	**Decision to work on 100 Ohm/sq emitters, ~30 fA/cm2 is state of art for these.**
M1.2	**Jo of passivated emitter ≤10 fA/cm2, Rsheet ≤170 Ohm**	**M24**	**ECN**	
M1.3	**Bulk lifetime exceeding 2 msec after processing**	**M24**	**ECN**	**3 ms with intrinsic polysilicon, > 2 ms without**

WP2 Metallization processes

In this workpackage, contacts to the emitters, including samples with polysilicon under the contacts, have been studied, simulated and further developed.

2.1 Models and characterization for contact recombination

The shielding of the contacts to reduce recombination by deeper and higher doped emitters were modeled with the software: EDNA2, from Pvlighthouse.com.au. The following assumptions/input parameters were used:

- Substrate: 5 ohmcm n-type Si
- Boron doping profile: errorfunction. Peak concentration was varied, as well as depth. Zpeak=0.1 um

- Surface texture: Total J_0 is multiplied by 1.7
- Metal coverage: 2.5%
- Surface passivation: not ideal, J_{0s}=10 fA/cm^2
- Physics: Fermi-Dirac statistics, Yan &Cuevas band-gap narrowing model, Richter Auger model
- Metal recombination has S_{eff}=10^7 cm/s (thermal velocity)

Results of the simulations are shown in Figure 16 as function of emitter depth for different peak doping profiles, and in Figure 17 as function of the emitter sheet resistance.

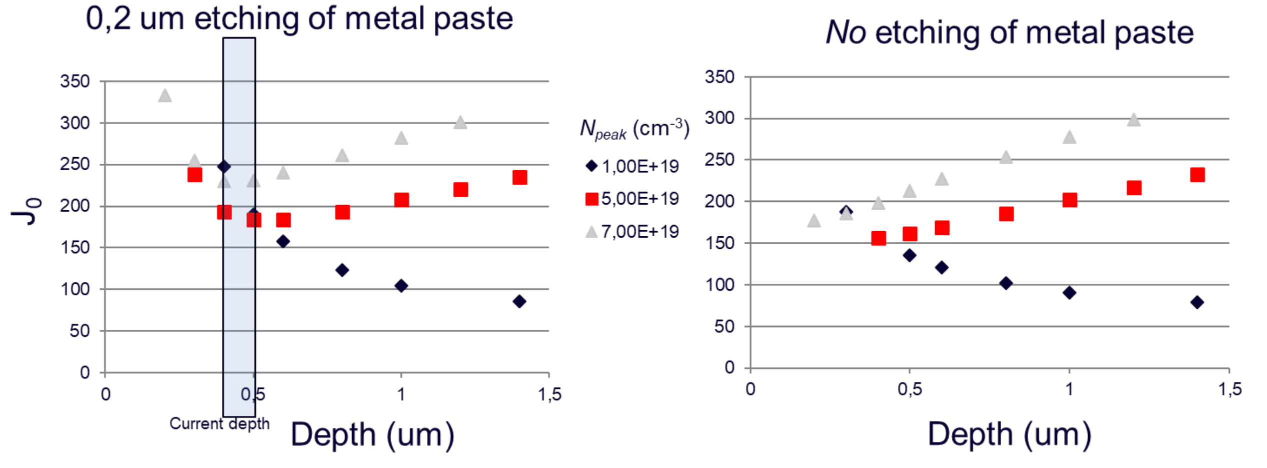


Figure 16. Simulated J0,contact as function of emitter depth for different peak doping levels. Left: assuming 200 nm penetration of metal paste, right: neglecting penetration of metal paste (ideal non-fire-through contact).

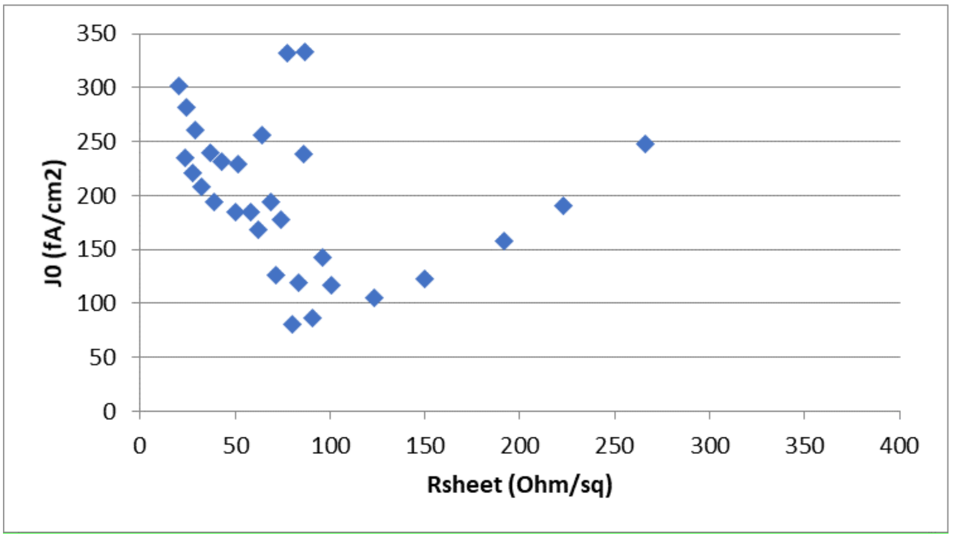


Figure 17. Total J0 as function of emitter sheet resistance (data shown for 200nm etching depth).

From these simulations, it has been concluded that

- a lower peak doping level is an effective route to reduce J_0

- For low peak doping levels (e.g., 1E19 cm^{-3}) the emitter should be as deep as possible

-Lowly doped, deep emitters can enable a lower J_0, butshould be found .butshould be found .

- but routes should be found to enable contacting of lowly doped surface.

The reduction of contact recombination with a deeper emitter has been also found experimentally on the samples fabricated at different drive-in temperatures between 900-1000ºC (see section 1.1, Figure 6)

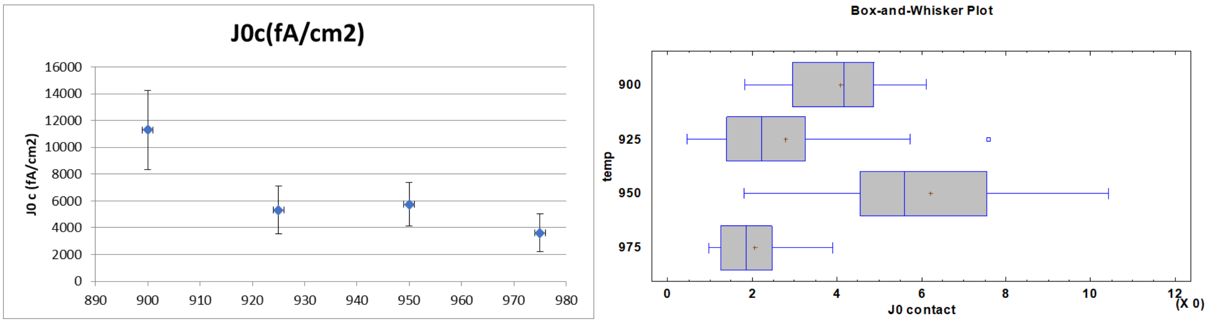


Figure 18. Reduction of contact resistance with deeper and higher doped emitters fabricated with higher drive-in temperature.

Scanning electron microscopy (SEM) analysis has mainly be performed to understand the origin of high contact recombination of baseline emitter contacts, and the reduction in J0,c when introducing polysilicon as sketched in Figure 3. The sample preparation for investigating different aspects of the contacts is stepwise illustrated in Figure 19.

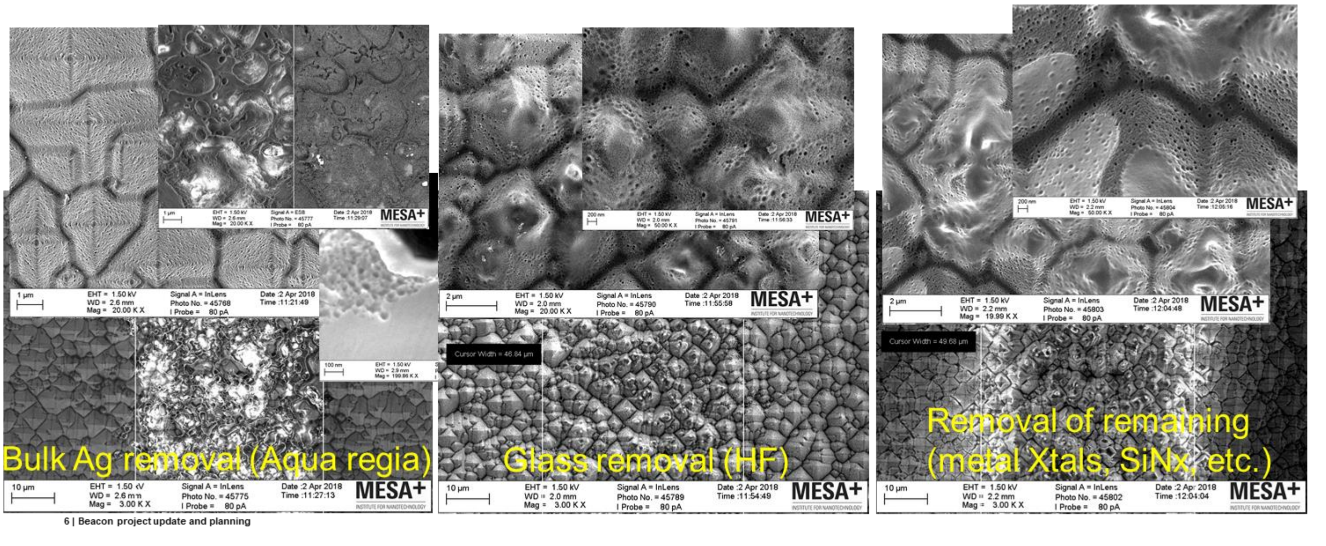


Figure 19. Overview of SEM analysis at different stages of sample preparation.

As can be seen in Figure 20 on the left, in a baseline sample the dielectric layers are fully removed under the metal contact. In contrast, when inserting an intrinsic polysilicon layer, only the tip area of the pyramids is damaged, while the slopes and valleys of the pyramids are still well passivated. This explains also why the contact recombination is reduced from >1500 fA/cm2 for the baseline sample to around 500 fA/cm2 with the polysilicon layer without large influence on the contact resistance, see below..

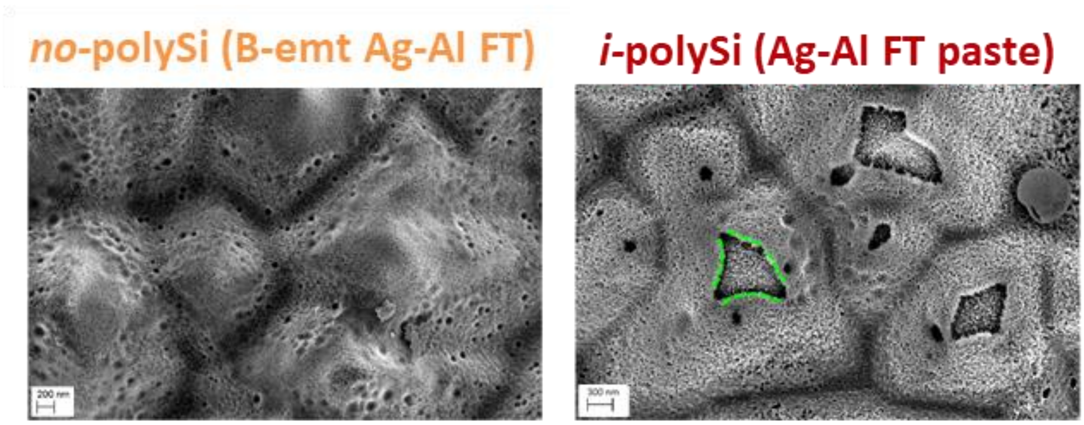


Figure 20. Damaged pyramids due to contact with Ag/Al paste that fully removes the SiNx layer under the contact (left) and reduction of the damaged area to the pyramid tips in presence of an intrinsic polySi layer (right).

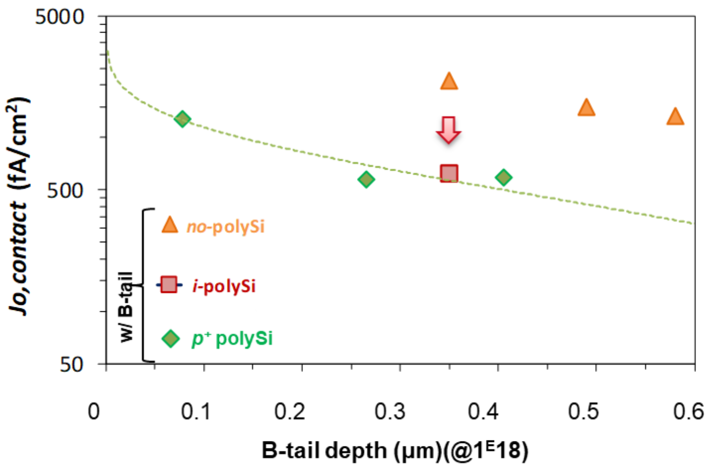


Figure 21. Reduction of J0,c of emitter contacts by inserting intrinsic polysilicon. The effect is comparable to contacts with p-type polysilicon.

Efforts were also undertaken to study in more detail the intrusion of the metal into the cell, and potentially visualize the shielding by a deeper emitter. For this purpose, 3-d x-ray tomography scans have been recorded at MASER b.v. Unfortunately the desired information could not be deduced from the cross-sections generated from these scans. Natural restrictions in resolution of the technique, combined with difficulties in imaging due to high contrast between the Si wafer and the metal contacts, only allowed more macroscopic observation of the samples as shown in Figure 22.

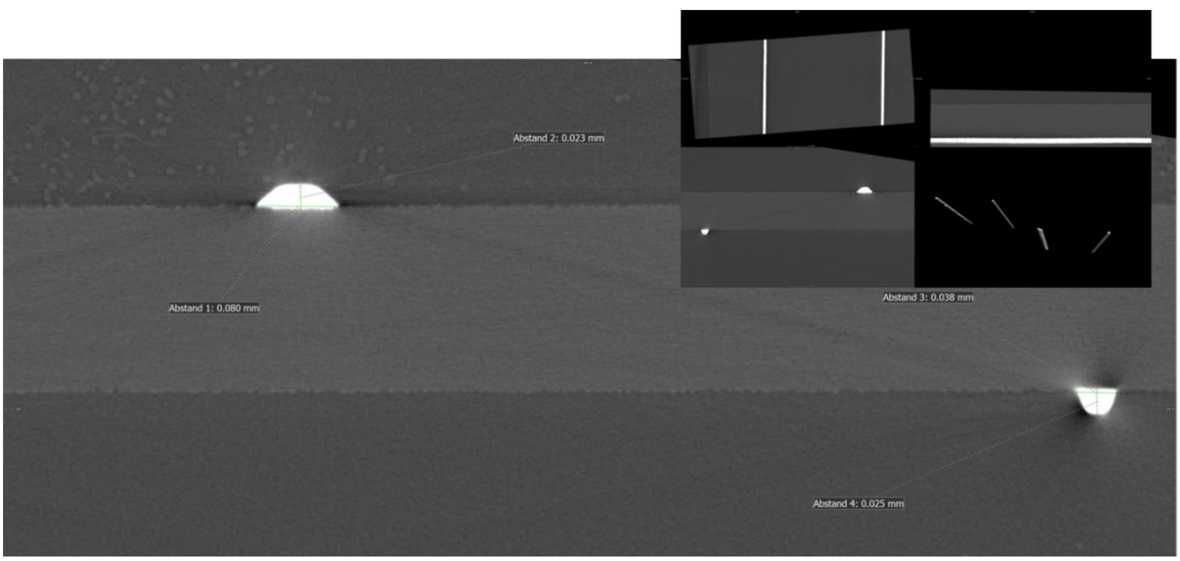


Figure 22. Cross section(s) of a 3-d x-ray scan showing the silicon cell wafer with metal contacts on top and bottom of the solar cell.

2.2 and 2.3 Fire-through and non-fire through contact development

Contacting of deeper emitters which have a lower dopant concentration by screen printing pastes, is not straightforward, as the contact itself requires a high enough dopant concentration. At the beginning of the project, it was considered highly problematic to find a promising combination of a uniform emitter which could be contacted with sufficiently low J0,em..

Figure 23 shows that this has been solved in the BEACON project. While the image on the left shows for a particular paste A high absolute values for contact resistance, and also large variation over the wafer (in line with non-uniformity of the experimental boron emitter used here), paste B shows reasonably low contact resistance (down to 3 $mOhm.cm^2$, average 5 $mOhm.cm^2$) and far less spread.

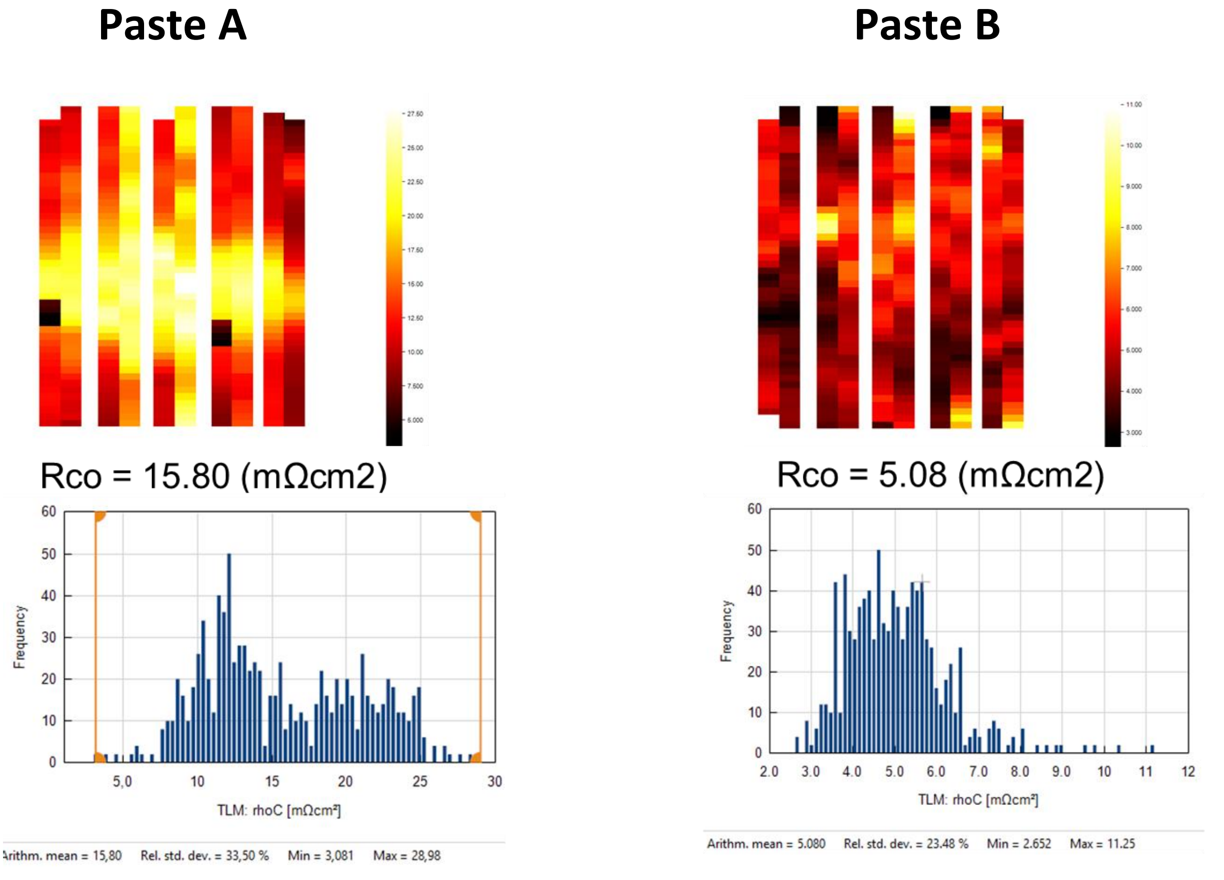


Figure 23. TLM analysis of the contact by Ag/Al pastes on deep Boron emitters (note the different scales in the graphs).

As the presence of Al in commercial paste for contacting B emitters is generally considered a source of enhanced contact recombination, an interesting idea has been tested in the BEACON project to make contact to the B emitter with Al free Ag screen printing paste. As the paste does not contact the B emitter directly, an n-type polysilicon layer has been inserted, and the idea was to obtain an ohmic contact to the n-polysilicon layer, while the junction between the highly doped n-type polySi layer and the B emitter should act as tunnel-recombination-junction with low resistance as in a Zehner diode. In practice, this concept could not be realized within the framework of the project, actually several issues were observed leading to a poor IV characteristics (Figure 24):

- the boron profile is probably too much depleted to form a proper tunnel junction
- the contact by the Ag paste to the n-polySi layer was too resistive in itself
- the sample showed non-uniform lifetime and dopant profiles

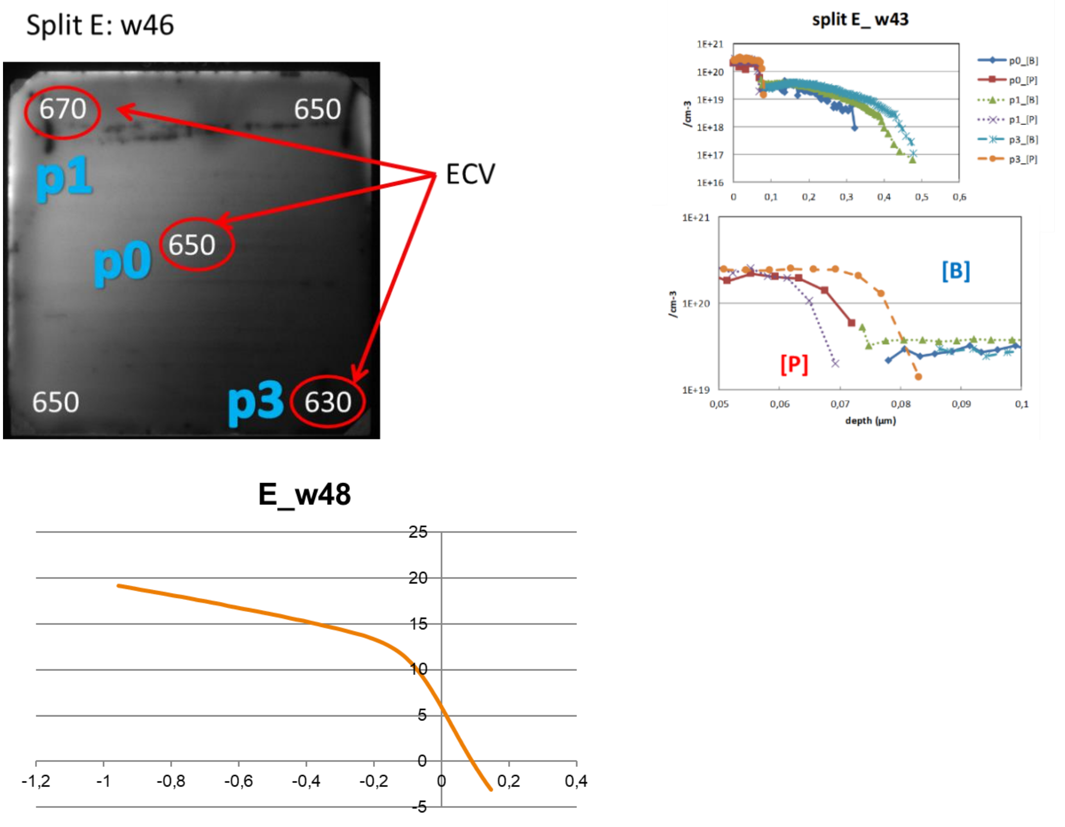


Figure 24. IV curve (bottom), PL image and ECV curves of a solar cell with n-polysilicon/B emitter tunnel junction and Ag contacting the n-polysilicon. Unfortunately the tunnel junction between (n)polysilicon and the B emitter is not effective and leads to a reverse diode resulting in excessive series resistance.

When writing the project proposal, non-fire-through screen printed metallization was considered a promising alternative to reduce contact resistance and contact recombination.
In other projects ECN.TNO had found that damage due to opening of contacts e.g. by laser increased the contact recombination to the level of fire through pastes, and that the contact resistance of non-fire through pastes was not better than that of fire-through pastes. Only non-fire-through contacts fabricated with non-industrial techniques as used for laboratory record devices, like patterning by photolithography, and PVD metallization can achieve these improvements.

Therefore it was decided to introduce another concept for reducing J0,c: The intrinsic polysilicon layer already mentioned above. Figure 25 summarizes the performance of these contacts and the improvements with respect to the baseline without polySi.

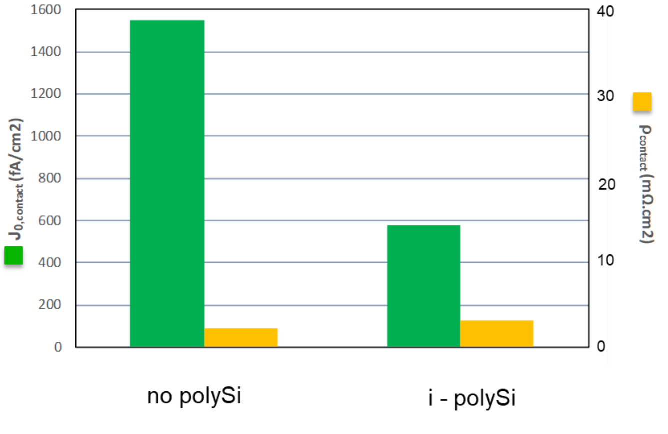


Figure 25. Reduction of J0,contact while keeping low Rcontact when inserting an intrinsic polysilicon layer under the emitter contact.

Deliverable/ milestone	Description	Due	Owner	Explanation
D2.1	Report on recombination tests and modeling contacts on deep dopant profiles	M12	ECN	J0,c analysis, and simulation of contact shielding,
D2.2	Report on characterization, modeling, and performance of Ag/Al fire-through pastes	M18	ECN	Analysis by SEM and 3-D x-ray, and J0,c characterization of emitter contacts with and without polysilicon
D2.3	Report on performance of Ag fire-through and non-fire-through pastes	M24	ECN	Ag contacts tested with n-polySi tunnel conctact (not successful). Non-fire-through contacts not tested further (results from other projects did not indicate (sufficient) potential)
M2.1	Decision on strategy for optimization of firing through contacts	M6	ECN	
M2.2	$Rho_{contact}$ <100 mohm-cm^2 on test samples	M12	ECN	3-4 mOhm.cm2 for metal area, leading to >100 mOhm.cm2 for full area.
M2.3	$J_{0,contact}$ <500 fA/cm^2 (specific) on test samples with deep dopant profiles	M15	ECN	Achieved with i-polysi
M2.4	$J_{0,contact}$ <=10 fA/cm^2 (cell level) and $Rho_{contact}$ < 100 mohm-cm^2 with selective emitter	M24	ECN	J0,c ~12, Rhocontact~ 160 mOhm.cm^2 for cell with i-polySi. Limited by specific contact resistivity and line definition (width).

WP3 PERPoly cell process integration

3.1 Process flow integration

The concept shown in Figure 3 to introduce an intrinsic polysilicon layer in the passivating stack for reduced contact recombination has been successfully demonstrated also in complete devices. In first instance a blanket layer of polysilicon was introduced, in order to analyze the concept without being affected by potential processing complexities. Later on, the polysilicon layer has been patterned into polysilicon fingers to reduce parasitic absorption in the polysilicon layer. Figure 26 shows the IV data of the four experimental splits in the first cell experiment.

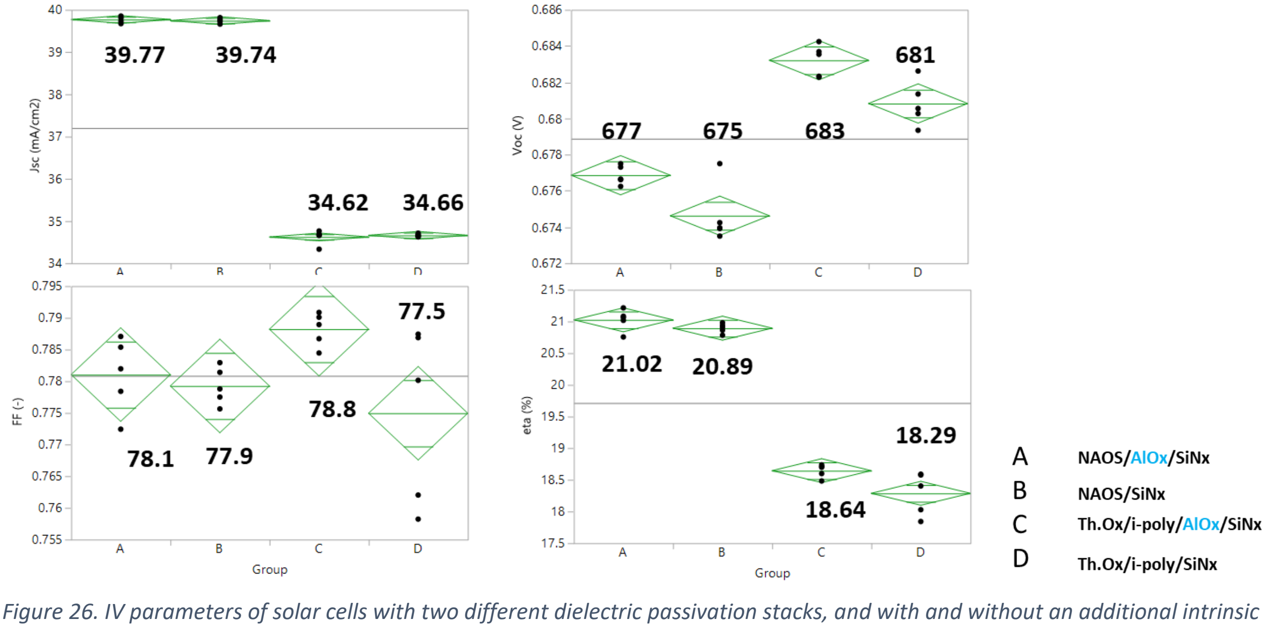


Figure 26. IV parameters of solar cells with two different dielectric passivation stacks, and with and without an additional intrinsic polysilicon layer.

As expected, Jsc is >10% lower due to absorption in the polySi layer. The benefit of better emitter passivation and lower contact recombination results in 6 mV higher Voc (see also Figure 27). An interesting observation is that the FF increases with the introduction of the polySi layer, despite a slightly higher contact resistivity (see above in section 2.2, Figure 21). This can be explained by the higher pseudo fill factor obtained with the polySi layer present (Figure 27), which is attributed to better uniformity probably as a result of additional thermal annealing and more uniform emitter surface passivation by the intrinsic polySi. Analysis showed that the bulk lifetimes cannot explain this large gain in pFF of 1% absolute.

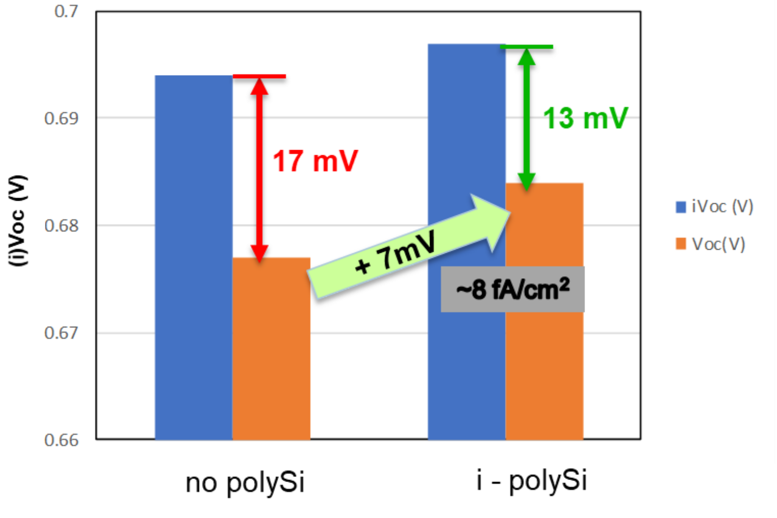


Figure 27. Benefit of the intrinsic polySi layer for implied Voc (emitter passivation) and Voc (emitter + contact passivation).

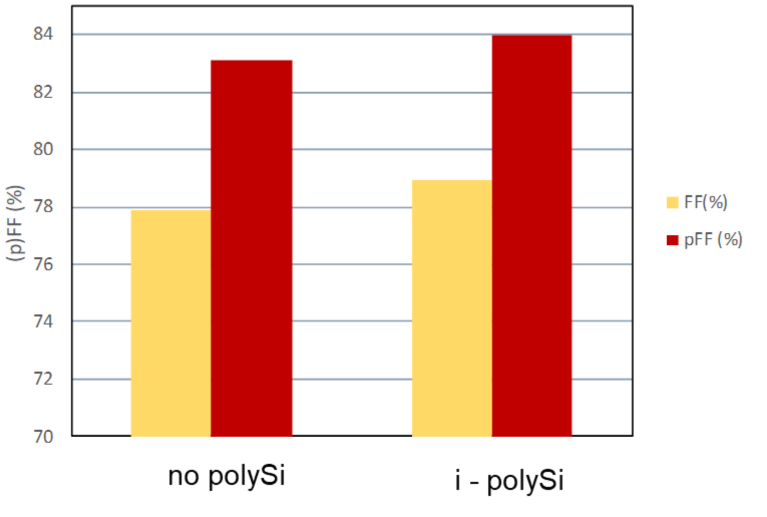


Figure 28. Benefit of the intrinsic polySi layer for the pseudo fill factor (pFF), and resulting gain in fill factor (FF).

In a next step, the polysilicon layer was patterned to be present only under the metal fingers, and leaving some tolerance for alignment. As shown in

Figure 29, the Jsc of the samples with patterned polySi (splits on the right of the graph) is comparable to the Jsc of the cells without polySi on the left side of the graph. As in the previous experiment, samples with blanket polySi (middle) show >10% lower current density due to parasitic absorption.

	A1	A2	B1	B2	C1	C2	D2	E1	E2	F2
Emitter	B	B	B+	B+	B	B	B+	B	B	B+
Front	BL	BL	BL	BL	i-poly	i-poly	i-poly	i-poly finger	i-poly finger	i-pol finge
metal	He	LG	He	LG	He	LG	LG	He	LG	LG

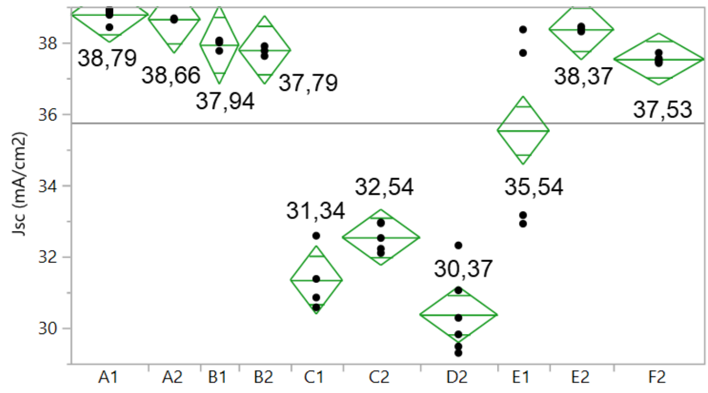


Figure 29. Increase in Jsc due to patterning of the intrinsic polysilicon (splits E1 ,E2 and F2 compared to C1, C2 and D2).

In summary, the Beacon project has yielded an n-type cell (PERPoly) process with a deep uniform emitter, and the application of an intrinsic polysilicon layer to reduce J0,em and J0,c to values as low as 20-30 fA/cm2, and ~500 fA/cm2, respectively

In the Polaris (HER) project, 5-busbar PERPoly cells have been fabricated with >22% efficiency [C.J.J. Tool et al., Asian PVSEC 2019] and FF > 80-80.5% making use of a similar deep uniform emitter. Tempress has achieved, together with a customer and processing at ECN.TNO, 22.4% cell efficiency with a multi-busbar cell. Figure 30 (right) shows calculations for busbarless cells yielding ~22.7-22.8% efficiency already with a FF of 80% for the currently obtained J0, em and J0,c values. With measured FF above 80-80.5% on 5-busbar cells, it is expected that a FF of >81% and an efficiency >23% can be achieved with a busbarless PERPoly cell

An alternative route to >23% efficiency in a 5-busbar cell could be explored by further reduction of J0,c or the application of much narrower fingers (e.g. by plating) as assumed for the calculations on the left in Figure 30.

Voc	698.3862	10	20	30	40	50	60	70	
	3000	698.3505	695.0439	692.1133	689.4819	687.0942	684.9089	682.8943	
	2000	702.1855	698.3862	695.0753	692.1413	689.5072	687.1172	684.93	
	1500	704.3403	700.2351	696.6944	693.5814	690.8039	688.2966	686.0115	
	1000	706.6917	702.2269	698.4219	695.1067	692.1693	689.5325	687.1403	
	500	709.279	704.3853	700.2735	696.7278	693.611	690.8305	688.3207	
	300	710.3912	705.3019	701.053	697.4059	694.2111	691.3686	688.8085	
	200	710.9659	705.7727	701.4518	697.7517	694.5164	691.6419	689.0558	
	100	711.5536	706.2523	701.8568	698.1023	694.8254	691.9182	689.3056	
Eff	23.03256	10	20	30	40	50	60	70	J0 em
	3000	23.03	22.92	22.83	22.74	22.66	22.59	22.52	
	2000	23.16	23.03	22.92	22.83	22.74	22.66	22.59	
	1500	23.23	23.09	22.98	22.87	22.78	22.70	22.62	
	1000	23.31	23.16	23.03	22.92	22.83	22.74	22.66	
	500	23.39	23.23	23.09	22.98	22.88	22.78	22.70	
	300	23.43	23.26	23.12	23.00	22.89	22.80	22.72	
	200	23.45	23.28	23.13	23.01	22.90	22.81	22.72	
	100	23.47	23.29	23.15	23.02	22.92	22.82	22.73	
	J0 cont								
	FF= 80%			front contact fraction		1	%		
	Jsc =	41.22	mA/cm2	rear J0pass, J0contact: [5; 80] fA/cm2					

689.1133	10	20	30	40	50	60	70	
3000	685.5184	683.4575	681.5492	679.7723	678.11	676.5483	675.0757	
2000	691.7054	689.1133	686.7579	684.5998	682.6083	680.7596	679.0345	
1500	695.462	692.4862	689.8184	687.4008	685.1904	683.1546	681.2677	
1000	699.8604	696.3674	693.2914	690.5434	688.0601	685.7949	683.7127	
500	705.1659	700.9376	697.3057	694.1225	691.2893	688.7366	686.4139	
300	707.6367	703.0194	699.1043	695.7058	692.7033	690.0141	687.5789	
200	708.9669	704.1268	700.0529	696.5355	693.4405	690.6774	688.1818	
100	710.3694	705.284	701.0378	697.3927	694.1994	691.3582	688.799	
22.3824	10	20	30	40	50	60	70	J0 em
3000	22.27	22.20	22.14	22.08	22.03	21.97	21.93	
2000	22.47	22.38	22.31	22.24	22.17	22.11	22.06	
1500	22.59	22.49	22.41	22.33	22.25	22.19	22.13	
1000	22.73	22.62	22.52	22.43	22.35	22.27	22.21	
500	22.90	22.77	22.65	22.55	22.45	22.37	22.29	
300	22.98	22.83	22.71	22.60	22.50	22.41	22.33	
200	23.03	22.87	22.74	22.62	22.52	22.43	22.35	
100	23.07	22.91	22.77	22.65	22.55	22.46	22.37	
J0 cont								
FF= 80%			contact fraction 2.5%					
Jsc = 40.6 mA/cm2 (Bbless)			rear J0pass, J0contact: [5; 80] fA/cm2					

Figure 30. Calculated Voc and efficiency depending on J0,c and J0,em for busbarless PERPoly cells, on the left with lower metal fraction as expected for advanced metallization like plating.

3.2 Evaluation industrial feasibility and cost assessment

- Cost vs benefit of uniform deep emitter
  - Deep emitters can be fabricated by either increasing the temperature or extending the drive in time. Higher drive in temperatures require longer cooldown times. So either way will result in longer processing times. From the cost models we can obtain the relationship between cost and processing time.
  - For the economic feasibility a clear relation between emitter depth and efficiency is required. However in practice we see that a lot of factors are in play and interacting with each other. For example as described above higher tempreatures might lead to material degradation, so the initial material quality is an important parameter.
  - Looking at industry practice we have observed that boron processing times are accepted up to 3 hrs processing time. It is clear that also the industry recognized the importance of having a deep boron diffusion profile. From this we can calculate the added cost for a boron step.
  - The value for efficiency is a volatile factor which is strongly related to market conditions. For the analysis described here we assume a value of €0,35 per Wp, which is based on the ASP of a module.
  - This means that adding a 3 hrs boron diffusion process adds 1,9 €ct per cell, so in order to be economically viable it needs to add 0,05 Wp per cell which translates to an absolute efficiency increase of about 0,2-0,3%, before it becomes economically viable to use.

- Intergating the deep emitter with other steps
  - The deep emitter process can be combined with the other steps that are required to make a cell with carrier selective poly contacts, like the poly depositon, etch resist print, etching and cleaning tool. For economic viability this technology should yield 1-1,2% higher absolute efficiency compared to the current state of the art PERC lines. Meaning the efficiency should be in the range of 23,2-23,7%

Deliverable/ milestone	Description	Due	Owner	Explanation
D3.1	Process flow for 22.5% PERPoly cell	M12	ECN	PERPoly cell with Beacon innovation(s) and multibusbar design.
D3.2	Process flow for 23.0% PERPoly cell	M24	ECN	PERPoly cell with Beacon innovations and busbarless design.
D3.3	Cost assessment and industrial feasibility of PERPoly with novel emitter and contacting schemes	M24	Tempress	Deep emitter is feasible if 0.2-0.3% efficiency is gained
M3.1	Selective emitter integrated in PERPoly cell process	M12	ECN	Selective emitter replaced by patterned polysilicon fingers
M3.2	Decision on use of wet oxidation in emitter process	M18	Tempress	Wet oxidation is used for advanced emitters

Mogelijkheden voor spin off en vervolgactiviteiten

As described above, the findings within the Beacon project have already been applied to optimize the front side of PERPoly cells fabricated in the HER Polaris project.

The use of (intrinsic, doped) polysilicon fingers to reduce J0,contact can be beneficial and further investigated/improved in other TKI projects like Bright, Saturnia, CORE, etc., including also other device types like IBC cells.

Tempress has now improved the boron diffusion recipe of the BBr_3 diffusion system, allowing customers to reach higher solar cell efficiencies using Tempress Systems equipment.

Conclusie en aanbevelingen

The main conclusions of the project are

- with today's diffusion and metallization technology, a deep uniform emitter is on short term the best cost effective solution for high-efficiency PERPoly (industrial TOPCon) solar cells
- multi-busbar or busbarless cells pave the way to achieve >22.5-23% efficiency with such cells
- Fire-through metallization will remain the work horse for the industry, as alternatives are far more challenging to realize, and progress is still being made. Polysilicon has a dominant role to (further) reduce J0,c.

Recommendations

- use and promote deep uniform emitters
- further develop processing and concepts of polysilicon fingers
- An industrial solution for fabricating polysilicon fingers is still lacking, both processing and process flow wise. This could be the topic for (higher-TRL) follow-up projects
- laser doping is still an interesting concept for selective emitters with even better J0,c. This will require dedicated projects, preferably in international context to optimize the uniformity of the dopant source in high-throughput diffusion tools at full load, and the laser process itself.

3. Uitvoering van het project

De problemen (technisch en organisatorisch) die zich tijdens het project hebben voorgedaan en de wijze waarop deze problemen zijn opgelost

Technically as well as organizationally the project went quite smoothly, and cooperation between ECN.TNO and Tempress was excellent. Main (technical) challenges were related to the selective emitter processing both based on drive-in at high temperature and/or long times as well as with laser doping. Also the non-fire-through metallization was not promising (enough) anymore after the project had started.
All these issues have been tackled by focusing on the deep industrial emitters and intrinsic polysilicon (fingers) in the later phases of the project.

Toelichting op wijzigingen ten opzichte van het projectplan

n.v.t.

Toelichting wijze van kennisverspreiding

Nationally, the results have been presented and discussed at the semi-annual TKI Urban Energy days, in the recent editions also including other project teams and partners beyond the Beacon team.

In addition to that results have been presented at the recent international PV conferences:

IEEE PVSC in Chicago, June 2019. Oral presentation by Jochen Loffler and paper by M.Stodolny et al., and EUPVSEC in Marseille, September 2019, oral presentation and paper by X. Lu et al.

Toelichting PR project en verdere PR-mogelijkheden

Tempress uses their existing marketing channels and sales network to promote among other things the results that are of interest for the industry. In Sept. 2019 Tempress organized a so called Topcon workshop to show customers the capability of boron diffusion, poly silicon deposition and annealing tools, these can be used for cell technologies similar to what is described here.

Toelichting op de verschillen tussen de begroting en de werkelijk gemaakte kosten

Only minor differences between planning and actual cost, see separate financial reporting for details.