Final report PV project Milicia

1. Project data

Project number: TEID115003

Project title: Multi Line Concentration modules using Advanced cell edge passivation solutions (MiLiCiA)

Penvoerder en medeaanvragers: LineSolar B.V. and Energy research Centre of the Netherlands (ECN)

Project period: 1 Sep 2015 – 30 Jun 2017

2. Content

2.1 Summary

The Multi Line Concentrator (MLC) photovoltaic module aims at reducing the total module's cost (including cells) by 30%, mainly by means of reducing the silicon consumption. It uses high-efficiency silicon strip cells at medium concentration levels together with low-cost and reliable Fresnel lenses. To achieve this, the cell efficiency must be >22% at concentration, which corresponds to a 1-sun efficiency of >20%.

This project is a continuation of the TKI project LISA (TEZ0114004), where a strip cell based on ECN's n-Pasha cell was developed. The cell's performance was limited by edge recombinations and contact resistance, reaching a peak efficiency of 19% at concentration. The Milicia project aimed at improving the cell efficiency by developing another cell architecture: the Interdigitated Back Contact - Front Surface Field (IBC-FSF) strip cell. Simulations showed that a dedicated IBC-FSF strip cell design is less affected by edge recombinations and it also presents the intrinsic advantage of lacking front metallization, resulting in less reflection losses. Furthermore, all interconnection is at the rear which will mitigate shading losses that occur on cells with contacts on both cells (like the one applied in LISA).

Firstly, all individual process steps were optimized and the specifications for > 20% IBC-FSF strip cell were met. However, integration of all process steps resulted in IBC-FSF strip cell structures with efficiency around 16% at one sun and reached efficiency peaks of almost 17% at 12 suns. Although this was a notable result considering that a new process recipe had to be developed from scratch, the cells did not manage to improve the final result of the n-Pasha cells from the previous LISA project. Unfortunately, in the final integration run unexpected p-n junction recombinations limited the performance, and more optimization is needed.

Therefore, the project could not reach its main objective of manufacturing >300W_p panels. On the module technology side, small module samples were tested according to IEC standards, the interconnection concept was proven and simulations were done in order to improve the mechanical properties of the module.

2.2 Introduction

The MLC technology replaces high-cost silicon solar cell material with low-cost light-concentrating optics, and therefore a fraction of the silicon will be consumed compared to conventional technology. The latter is realized by means of Fresnel lenses which focus the incident light with a concentration factor between 10 and 30 suns. This allows for a decrease in the module area occupied by solar cells, resulting in module manufacturing costs which are no longer dominated by the cost of solar cells. Moreover, the concentration of light increases the solar cell efficiency following semiconductor physical principles, improving the power output of the module.

The MLC module technology fits to all 4 ambitions as stated in the 2012 innovation contract Solar Energy (nowadays integrated in the TKI Urban Energy program). The Milicia project contributes to the development of high-efficiency (IBC) solar cell technology, high-efficiency module technology, cost reduction of modules and leads to a drastic reduction of silicon and silver consumption and thus is environmentally attractive.

The Milicia project consists of a technology co-development between LineSolar and ECN. ECN’s task was to develop the solar cell processes as needed in MLC modules. LineSolar’s task was to develop the module manufacturing process. The project is a continuation of the previous TKI LISA project, which researched two different cell technologies: the IBC with a Front Floating Emitter (FFE) and ECN’s n-Pasha. Strip cells based on these technologies reached peak efficiencies of 17% and 19% respectively, both around 12X concentration. One of the main losses was coming from recombinations at the unpassivated cell edge formed after (laser) cutting the cell out of the full size wafer. The strip cell geometry has an intrinsic higher perimeter-to-area ratio than standard squared cells, therefore minimizing these edge losses is of utmost importance. Simulations showed that the FFE layer of the IBC cell was providing a conductive path for the generated carriers to reach the edge, enhancing edge recombinations. As of the n-Pasha, the laser scribe line was cutting through the emitter leaving an open, un-passivated p-n junction which also enhanced edge recombinations. Based on simulations, an IBC cell with an n^+ doped Front Surface Field (FSF) was proposed as a candidate which should be less prone to edge losses. The FSF drifts the minority carriers towards the n-base, not providing a conductive path to the edge as the FFE does. Moreover, the cell does not have any cut-through p-n junction. Therefore, the IBC-FSF technology is an efficient cell technology that minimizes the edge losses without resorting to any edge treatment.

This report demonstrates the challenges and achievements found along this project, both from the cell and the module perspective.

2.3 Objectives

The objectives as stated in the project proposal were:

1. Improved solar cell design able to reach 22% under light concentration with a manufacturing process compatible with current low-cost industrial processes.
2. A validated cell interconnection process which should result in the manufacturing of several MLC modules with a targeted output power of 310 W_p.
3. A module characterization setup to measure full-size MLC modules under artificial sunlight.
4. Conceptual design of solar power plants using MLC modules that can generate electricity at 10-15% lower cost level when compared with competing technologies.

2.4 Method

For the strip cell design, the simulation packages Quokka and Atlas were used to simulate the performance of different cell architectures at different irradiance levels. Cells with the most promising design were fabricated in the laboratories of ECN with common-use industrial techniques such as diffusion furnaces and screen printed metallization.

To characterize the cell performance, IV measurements were done both at ECN and Linesolar under artificial sunlight. Moreover, the Fresnel lenses developed in the previous LISA project were used to measure the cells under natural sunlight.

Module's mechanical properties were modelled with the software package Comsol Multiphysics.

2.5 Results

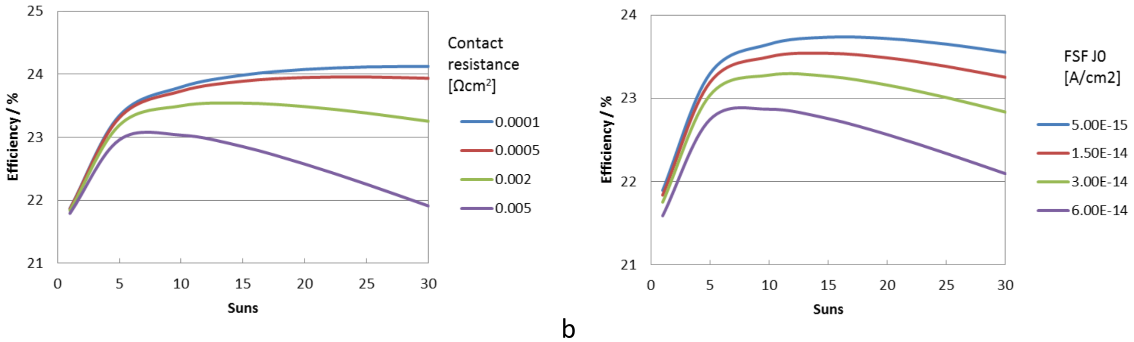
2.5.1 Cell design

A result of the LISA project was a design for an IBC cell dedicated for the concentrator application. The key features were: dead areas (outside the illuminated area and well passivated) to prevent edge recombination, low contact resistance and excellent front surface passivation. Device simulations were carried out to fine-tune this design, in particular to determine the optimal pitch and width of the backside metal contacts. A second issue was to identify the parameters that are critical to achieve 23.5% efficiency at 20x concentrated solar intensity. Due to the high competitiveness in the PV field, it was assumed that a higher efficiency was needed than the original target to be cost effective. However, during the course of the project 22% under concentration seemed to be good enough to be competitive.

The optimal design had contact pitches of 600 µm, and contact width of 100 µm for both polarities, assuming realistic values for the recombination and resistivity parameters. The optimal pitch is a compromise between a low lateral resistance and low recombination (electrical shading) losses. The contact width is an optimum between low contact resistance and low contact recombination.

However, the simulations also showed that the higher 23.5% efficiency could only reached at concentration factors of about 15 or less (Fig. 1a). At higher concentration levels the series resistance losses, dominated by contact losses, limited the efficiency. It was found that contact resistivity values $< 0.5\ m\Omega.cm^2$ would be required to meet 23.5 % efficiency at 20x solar intensity. This is about 5 times lower than what is currently achieved with standard metallization pastes. However, 23% under concentration should be within reach, so better than the original target.

A second critical parameter was the passivation of the front side; the recombination parameter J_0 of the front side should be lower than 15 fA/cm^2 (Fig. 1b). Such a low value is a challenge for a phosphorous diffused front side, as it requires a relatively light doping with an extremely good surface passivation. A good surface passivation of a textured P-diffused surface is not easily achieved, and the lowest J_0 values reported in the literature were in the order of 35 fA/cm^2. By simulations alternatives were investigated such as passivation of the wafer by an Al_2O_3 oxide layer. An Al_2O_3 oxide layer turned out not to be suitable because the inversion layer that Al_2O_3 induces on the substrate enhances edge recombination. Other options included a flat surface or passivation with a-Si. All these options led to too large optical losses, which are prohibitive for a high efficiency at 20x solar intensity. Fortunately, as shown in Figure 1 it was possible to make a front-side P-doped passivation with $J_0 < 25$ fA/cm^2, good enough for 23% peak efficiency at a wide range of concentrations.



a b

Figure 1 The simulated impact on the cell efficiency as function of the solar concentration of (a) the contact resistivity and (b) the front side recombination parameter J_0 .

2.5.2 Cell manufacturing

A completely new process flow to manufacture the IBC-FSF strip cells was designed. The rear side processing was based on ECN's IBC with Front Floating Emitter (FFE) cell process, however, the change of the front side, and the requirements for concentrated light application induced modifications to the known IBC-FFE process. Simulations revealed that a heavy emitter has a beneficial effect on (contact) conductance. As higher processing temperatures associated with a heavier emitter can degrade the wafer's quality, this effect was investigated experimentally, and resulted in degradation of the FSF passivation quality. Therefore, only a standard emitter diffusion could be used in the cell. The passivation of the n^+-doped FSF front side was initially insufficient, but was improved, and finally resulted in very low values of the recombination current, as shown in Figure 2. Best J_0 values were < 25 fA/cm^2 per side.

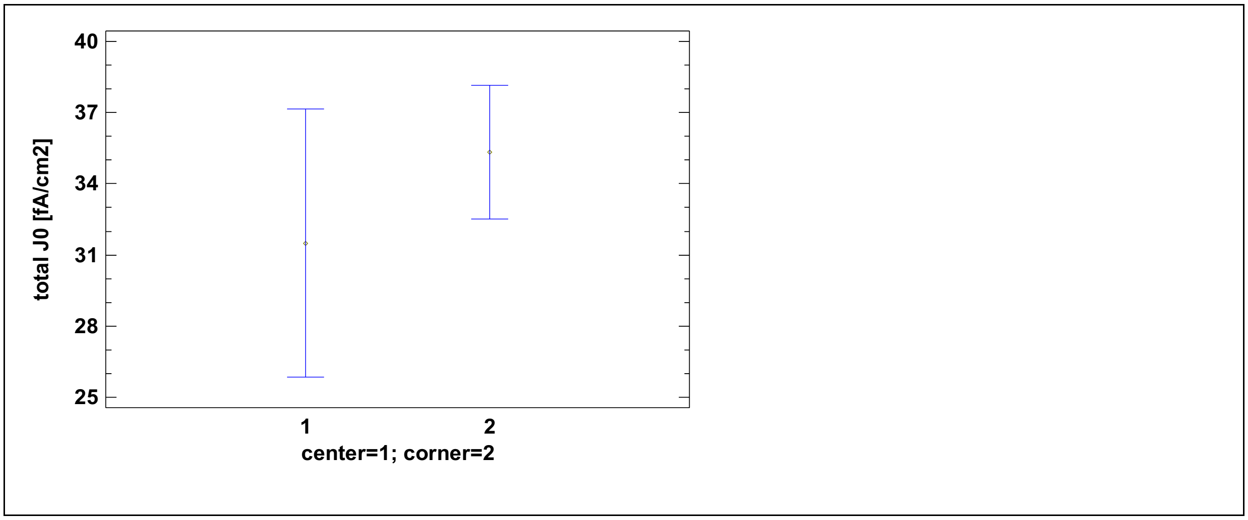


Figure 2 Average of total J_0 (both sides together) of center and corner areas of the wafers with symmetrically diffused and passivated FSF. Per side an average J_0 of <20 fA/cm^2 can be calculated. The error bars represent the least significant difference.

After these initial tests and meeting the requirement for at least 22% efficiency under concentration, the final cells were manufactured according to the new IBC-FSF strip cell flow. A specially designed rear side architecture was applied to the wafers, as sketched in Figure 3. Only the center part of the wafers was processed into strip cells for concentrated light application; for the two edges of the cells the design for 1-Sun IBC was kept, i.e. the rear unit cell design that is standard for ECN's IBC-FFE cell, in combination with the n^+-doped FSF. This allowed us to verify the cell manufacturing process using the standard (IBC) characterization equipment at ECN.

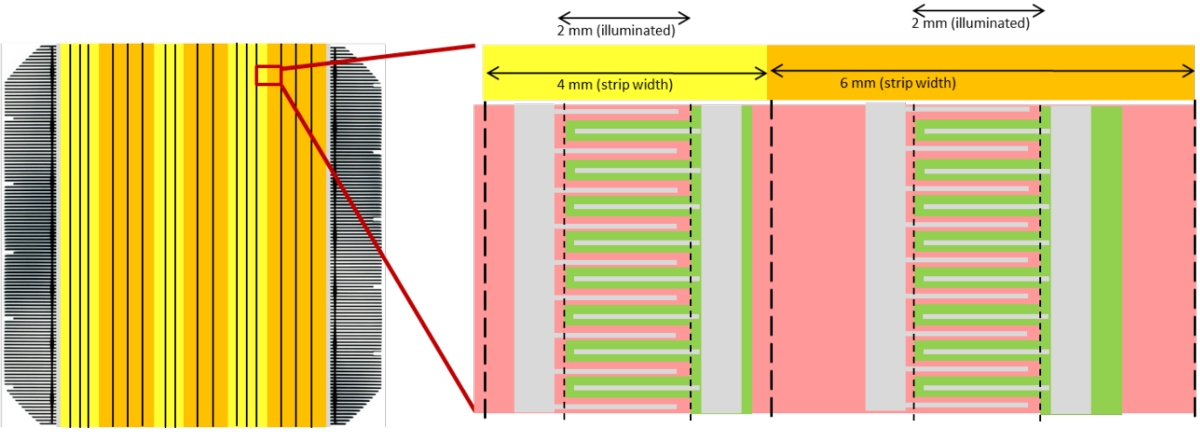


Figure 3 left: wafer with IBC cell edges that are compatible with standard IBC characterization at ECN and strip cells in the middle; right: zoom-in on the strip cell design, with emitter (green), BSF (pink) and metal (grey) areas, and strip width and illuminated width indicated by dashed lines.

Variations in the processing included the use of a gap or no gap between rear emitter and Back Surface Field (BSF) areas, and the use of a flat (non-textured) front side instead of standard textured. The IBC cell edges were evaluated using the class AAA solar simulator at ECN, and contacted through the standard back-contact chuck. The cells without gap between emitter and BSF and with a textured front side performed best, but yielded efficiencies of only close to 16%. The reason for this low efficiency was found to be pn-junction recombination, of which a fit is shown in Figure 4. Because ECN's baseline on large area IBC-FFE, called Mercury, shows stable and good pn-junction passivation the high recombination in IBC-FSF strip cells was unexpected, and probably caused by the additional process steps needed to make high-efficiency strip cells.

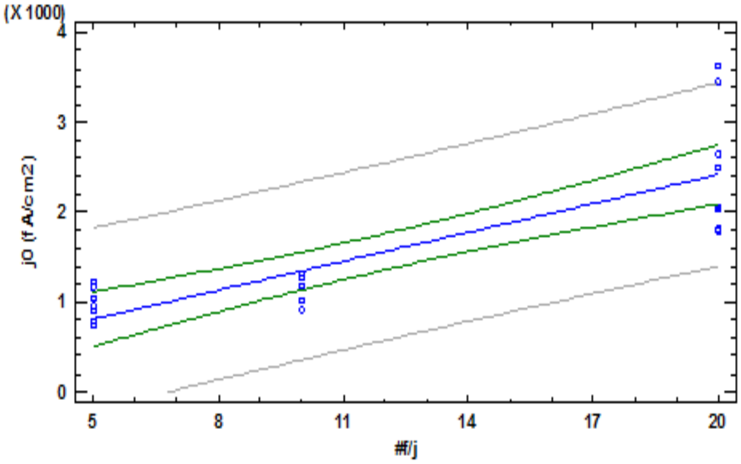


Figure 4 Fit of the pn-junction recombination, measured on test structures without gap between emitter and BSF (processing according to best cells). The x-axis shows the number of pn-junctions/cm in a test structure, and the y-axis the total measured J_0.

As the strip cells have more pn-junctions/cm than the edge cells, the 1-Sun performance of the strip cells will be even lower, which was not verified. The strip cell characterization and analysis is described in the next section.

2.5.3 Strip cell characterization

The cells were measured under artificial concentrated light with the red LED setup developed during the LISA project. Measurements on samples with and without laser-scribed edges showed that the peak efficiency (under light concentration) of non-scribed cells didn't exceed 17.5%, while scribed samples stayed generally below 17%. Figure 5 shows that the efficiency difference between 6-mm wide cells with and without laser-scribed edges is only $0.5\%_{abs}$. On the other hand, the loss for 4-mm cells was much higher (not shown). Although the scribed/non-scribed comparison was done with cells from different wafers, these results indicate that the 6-mm wide IBC-FSF cells are much less sensitive to defects coming from the unpassivated cell's edge compared to 4-mm wide IBC-FSF cells.

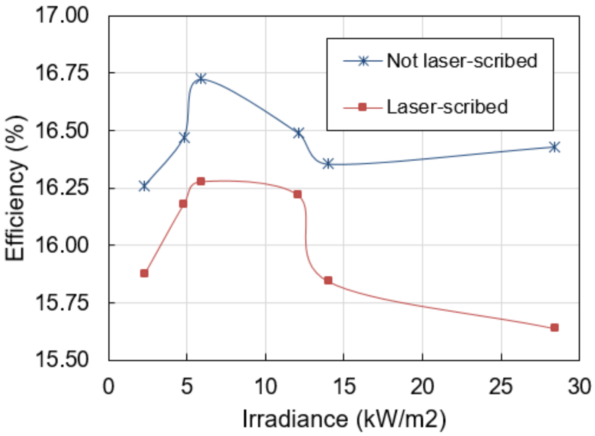


Figure 5. Efficiencies of a 6-mm strip cell at different concentration levels before and after laser scribing. Scribed and non-scribed cells belong to different wafers that where manufactured with the same process flow.

2.5.4 Interconnection of n-Pasha strip cells

During the design and development of the IBC-FSF cells, the interconnection method was tested using n-Pasha cells. Single cells were connected to a copper substrate via Electric Conductive Adhesive (ECA) following this process:

1. Laminate two copper sheets on a glass substrate. The sheets should be separated by a distance which depends on the strip cell width.
2. Stencil print line of ECA at the edge of one of the copper sheets. The line print was discontinuous to minimize ECA costs.
3. Pick and place the strip cell in such a way that the rear busbar falls on top of the discontinuous line of ECA.
4. Print small ECA "bridges" to connect the front busbar to the second copper sheet. A total amount of 20 bridges were used at first in order to minimize busbar resistance losses.
5. Cure the ECA by placing the sample on a hotplate under a certain pressure.

Once the sample was cured, the interconnected cell was measured outdoors under concentrated natural sunlight. Two different types of lenses were used, with concentration factors of 18X and 30X. In Figure 6 an impression is given by pictures of the lens system with an n-Pasha and an IBCcell. A 2-axis mini solar tracker was designed and built to correctly align the system, while a pyranometer was used to measure the irradiance in the plane of the cell.

Several samples were made and measured at sunny days with irradiances above 900 W/m^2. It was found that the total lens+cell system efficiency was just above 15%, and it was never higher than the efficiency of the same cell without any lens[1]. The best sample showed a FF loss of only 0.9%$_{\text{absolute}}$ after placing the 18X lens, meaning that the interconnection's resistance was fairly low. However, the increase in V_{oc}

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[1] To calculate the total lens+cell system efficiency, the area considered was the total lens area. On the other hand, to calculate the efficiency when no lens was used, the area used was the strip cell area.

when using concentrated natural sunlight was not high enough to compensate for this FF loss and other lens losses, namely the (intrinsic) loss of diffuse light and the loss of direct light due to the lens defects.

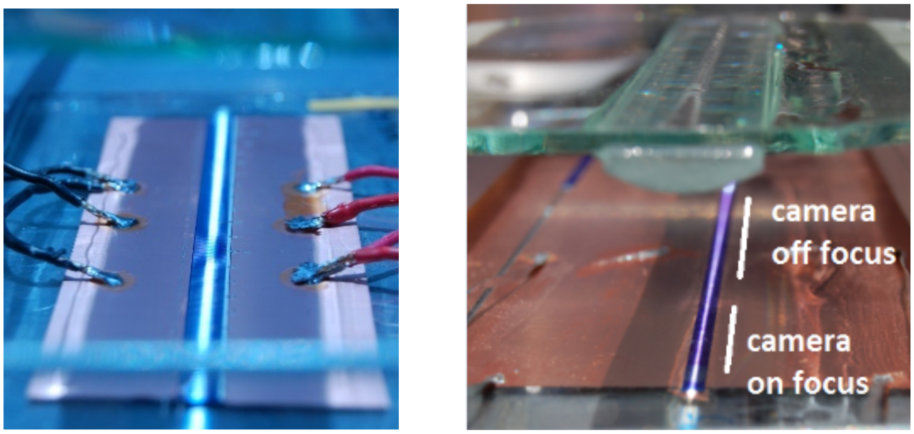

Figure 6. (Left) Picture of a 7 mm wide n-Pasha strip cell illuminated by concentrated sunlight using the 30X lens. The beam of concentrated light is around 2 mm wide. (Right) Picture of an IBC cell under the 18X lens. The beam width is less than 1mm.

2.5.5 Module testing and optimization

Before creating MLC mini-modules, a first selection of the frame materials and frame-to-glass adhesives was carried out. Climate chamber tests were performed to assess the durability of the frame adhesion against humidity and thermal cycling. The tests were performed at KIWA B.V. according to IEC specifications and used samples consisting of a front glass plate, a rear glass plate with the copper foil laminated on top and the metal frame joining the two glasses. The samples didn't pass the tests and the whole module design was re-considered.

The new module design is now more similar to a standard PV module: the strip cells are encapsulated between a front glass (which doesn't contain the lenses) and a backsheet foil. The lens plate is fixed above the glass plate by means of aluminum profiles. Mechanical FEM simulations were carried out to select the proper profile design that minimizes deflections of the glass plate at heavy mechanical loads. This is of major importance because large deflections of the lens plate would deviate the focused line of sunlight causing a huge performance loss. Calculated deflections were lower than 2 mm at a uniform load of 2400 Pa. In Figure 7 two examples of simulated profiles are shown.

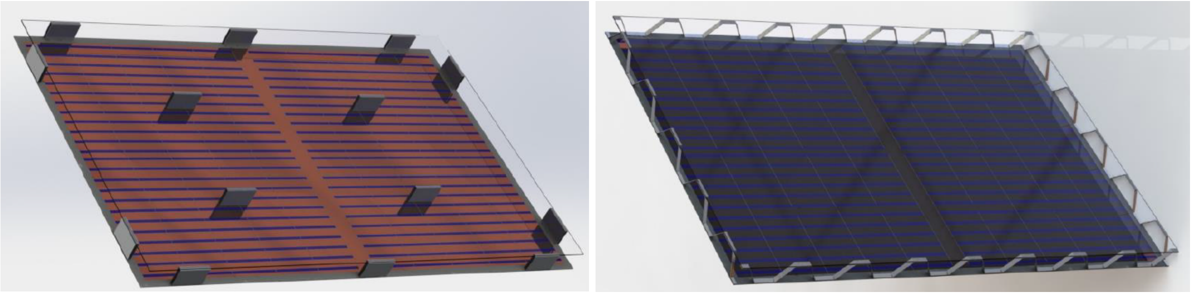

Figure7. Two of the profile concepts simulated: extrusion profiles (left) and zig-zag profiles (right). Both ensure the demands of air circulation and water drainage. The support pieces in the center of the module guarantee a minor lens plate deflection.

2.6 Discussion

Since the biggest project bottleneck has been the cell efficiency, most of the effort has been focused on the manufacturing, characterization and understanding of the strip cells. Figure 8 shows the efficiencies of the three best cells measured during the LISA and Milicia projects under artificial concentrated light after being cut out from the wafer.

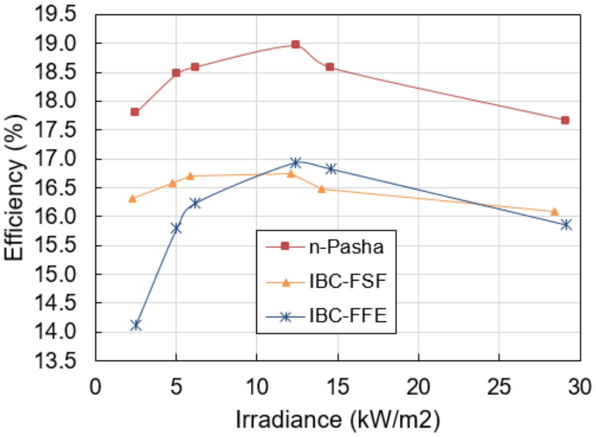

Figure 8. The efficiencies measured under artificial concentrated light for the three best laser-scribed cells of each category.

The IBC-FSF strip cells developed in this project have not been able to surpass the efficiencies of the n-Pasha strip cells developed in the LISA project. One of the theoretical advantages of the IBC-FSF cell design developed in this project is the strong resilience against edge recombinations coming from the laser-scribed edges, and this has been proven experimentally. All individual process steps have met the requirements to achieve the efficiency aimed for (evaluated on test structures). However, in the final integration run high recombination losses at the rear side pn-junctions limited the cell performance. At the time of this project, ECN did not have an off-the-shelve process recipe for IBC-FSF and we were aware that starting a process from scratch would involve some risks. However, brainstorming sessions concluded that the n^+ FSF option was safer than other IBC front passivation options such as poly-Si or Al_2O_3. Al_2O_3 would create an inversion layer that could help the minority carriers reach the highly recombinative edges, and simulations showed that poly-Si would cause a considerable absorption of light.

The IBC-FSF recipe for the front side passivating coating developed showed that initially the process was not reproducible enough and resulted in lower front side passivation quality. However, this was solved later by adjusting the passivation layer. Unexpectedly, the pn-junction recombination in the cells of the integration run was limiting the peak efficiency of non-laser-scribed cells (hence *without* edge-recombinations yet) to 17.5% at 10 suns, a peak efficiency lower than that of laser-scribed n-Pasha cells (*with* edge recombinations). Unfortunately, the resources at that time of the project were not enough to continue researching the deep cause of these losses and further optimize the process.

From the module perspective, a validated interconnection process was stablished by means of ECA. Several 1-cell samples were connected to a copper substrate and measured under natural concentrated sunlight, both with n-Pasha and IBC strip cells. Since the cell technology was not definitively fixed during the project, it was decided that instead of further testing the interconnection process, which is cell-dependent, it was more worthwhile to test the full module configuration. Therefore, IEC tests were performed on dummy mini-module samples and the module configuration was further optimized through mechanical FEM simulations.

2.7 Conclusion and recommendations

Overall, the LISA and Milicia projects have researched two cell architectures, the n-Pasha and the IBC-FSF strip cell. During the course of LISA and Milicia none of them has reached the target efficiency of 22% under concentration: n-Pasha strip cells reached a peak efficiency of 19% and the IBC-FSF ones 17%. Although the IBC-FSF has demonstrated to be quite resilient against edge defects and all process steps have met the requirements for cell efficiency above 22%, other types of recombinations have unexpectedly limited its performance. This high-impact bottleneck, which needs more optimization, has prevented other project objectives such as manufacturing 300 W_p modules or the conceptual design of MLC-based solar power plants that can be competitive with other technologies.

The n-Pasha is heavily affected by edge recombinations and it is limited in fill factor (FF) by the contact resistance. The easiest way out for the FF limitations would be to further optimize the paste and firing conditions. Less resistive pastes are already available at the moment, thus higher FF could in principle be achieved compared to the results from the LISA project. The IBC-FSF is less affected by edge recombinations but it is heavily affected by unexpected higher p-n junction recombinations (the same processing is applied in ECN's Mercury process sequence and has shown to be stable, even in an industrial environment). The IBC-FSF process must be further optimized and the origin of the p-n junction recombinations should be revealed in order to benefit from the lower edge recombinations and the lack of front grid shading losses. The IBC cell presents the extra drawback of lacking straight-forward industrial manufacturers, although this could very well change in the near future.

3. Project implementation

The current project has dedicated a big effort in the strip cell design, characterization and understanding (Work Package 1). Time was spent in simulating and understanding the pros and cons of the three most plausible front passivation options of the IBC cell (poly-Si, Al_2O_3 and n^+ FSF). Once the FSF decision was taken, the main bottlenecks were technical and mostly came from the fact that there was no IBC-FSF cell process available at ECN at that moment. Unfortunately, the resources were not enough to reach a well optimized IBC-FSF process flow.

The total realized project costs have exceeded the budgetted project costs. This was mainly due to additional hours required by LineSolar to measure cells and to analyze and understand why the performance was lower than expected. This also resulted in a lower remaining budget for hardware and therefore small shift between the amounts spent in hardware and hours. LineSolar's project budget was €118.800, consisting of € 100.800 in hours and €18.000 in materials and 3rd party costs. In the actual project costs, LineSolar has spent approximately €147K, more than the budgetted €118K. Of the € 147K, € 138K were spent in hours and € 9K in hardware.

At ECN the project cost are close to the budget. The main activities carried out at ECN were:

- advanced 2D modelling of the IBC-FSF strip cell to determine the best design for low light concentration applications and to mitigate recombination losses at the edge of these cells;
- developing a process for these IBC-FSF strip cells (individual process steps and total integration);
- characterizing and evaluating the quality of individual process steps and full solar cells with strip architecture.

With respect to the different categories the ECN cost (all rounded numbers) were: € 106.071 personnel hours, € 19.525 laboratory equipment cost, and € 3.938 materials and consumables (e.g. metallization screens). In total it corresponds to € 129.533 (based on so-called EZS rates)

The knowledge acquired during the project is not at a high enough Technology Readiness Level (TRL) to be directly transferred to the society or third parties or for the creation of spin-offs yet.