Final report PV project LISA

1. Project data

Project number: TEZ0114004

Project title: Line concentrating modules using IBC Strip cell Architectures (LISA)

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

Project period: 01-09-2014 to 31-12-2016 (end date extended from 31-08-2016)

2. Content

2.1 Summary

The MLC photovoltaic (PV) module aims at achieving a breakthrough cost level of 0.33 euro/Wp including cells, and relies on high-efficiency silicon solar 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 means a 1-sun efficiency of >20%.

During this project two different n-Silicon cell technologies have been thoroughly studied. The first one is the IBC cell with a Front Floating Emitter (FFE), which suffered from major recombinations at the unpassivated cell edges resulting after laser-cutting the strip cell. It reached an efficiency of only 17% at 12 suns. After simulating the cell device physics, it was proven that the FFE is actually favoring the edge recombinations. The second cell technology is based on the ECN's n-Pasha process. It was proven to be less sensitive to edge recombinations and the efficiency increased to 19% at 12 suns. However, it still didn't reach the project's objectives. The report suggests several recommendations to further increase the n-Pasha efficiency and also proposes a new cell technology which has a higher efficiency potential: the IBC with a Front Surface Field (FSF).

Although most of the effort was focused on the cell development, important improvements were done on the module side. The pick and place machine has been built, together with an artificial light source and IV-meter to measure the cell at high light irradiances. The proper process and materials to produce the Fresnel lenses have been identified and have successfully passed UV-exposure tests according to the IEC requirements. The laser scribe process has been optimized and a tool to mechanically snap the cells out of the wafer has been fabricated.

2.2 Introduction

The objective of the LISA project is to develop a breakthrough PV module technology at a low manufacturing cost level of 0.33 €/Wp, including solar cells. This is more than 30% below state-of-the-art module manufacturing costs as produced in Asia. The so-called MLC technology replaces high-cost Silicon solar cell material with low-cost light-concentrating optics. The latter is realized by means of Fresnel lenses which focus the light with a concentration factor between 20 and 40 suns. This allows for a decrease in the module area occupied by solar cells, resulting in a 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. The LISA 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 LISA project consists of a technology co-development between LineSolar and ECN. ECN will develop the solar cell processes as needed in MLC modules. LineSolar will develop the module manufacturing processes. This report demonstrates the challenges and achievements found along this project, both from the cell and the module perspective.

2.3 Objectives

The four main objectives of the project are:

1) Design of a custom IBC strip cell with an efficiency of >20% at 1 sun.
2) Development of an industrial cell cutting process to separate the strip cells from a fully processed large area IBC cell (156 x 156 mm^2). The cutting process shall not degrade the cell's efficiency more than $0.5\%_{abs}$ at the desired concentration level. The first pilot industrial cell cutting machine will be realized.
3) Development of an industrial pick and place machine for IBC strip cells, together with an artificial light source that can create an illumination level up to 40 suns and the corresponding IV meter to characterize the cell efficiency at these high irradiances.
4) Development of a MLC module assembly and manufacturing process using Fresnel lenses. A few full-size modules will be constructed with a targeted output power of 310 Wp or beyond. Mini-modules will be tested according to IEC61215 and IEC61730 standards.

2.4 Method

Several methods will be used depending on the individual objectives.

For the strip cell design, the software Quokka will be used to simulate the cell performance at different irradiance levels. The cells will be fabricated in the laboratories of ECN with common-use industrial techniques such as diffusion furnaces or screen printing metallization. The cell characterization will be done both at ECN and Linesolar laboratories. ECN owns sophisticated solar cell characterization techniques such as Suns-Voc, Dark Lock-in Thermography and High-Resolution

Electroluminescence/Photoluminescence, while Linesolar can measure the cell performance under concentrated artificial light.

Regarding the cell cutting process, the laser labs at ECN will be used and mechanical machines will be designed and developed by Linesolar from scratch.

As of the Fresnel lens development, ray tracing optical software will be used to design the lens structure. Several Dutch companies will be involved in the production of the lenses, from the manufacturing of the master metal cylinder containing the lens design to the selection of a proper low-cost lens material which can replicate the design contained in that cylinder. Linesolar will coordinate the activities among these companies and will conduct microscopy analyses and UV tests of the different samples.

For the objectives that are more related to the industrial manufacturing of the MLC module (pick and place machine, module assembly) Linesolar will design and build all the components from scratch, as well as program all the needed software.

2.5 Results

2.5.1 Cell design and characterization

Before starting the LISA project, Linesolar managed to develop some custom IBC strip cells. These cells are relatively low-cost IBC cells made with selective rear-side processing, front-floating emitter (FFE) and screen printing metallization. Since ECN's Mercury IBC cells are also based on FFE and screen printing metallization, these current IBC cells were a good starting point to get an insight on the cell behavior under concentrated light conditions. The strip cells were separated from the wafer by laser scribing from the rear of the cell followed by mechanical snapping (details in section 2.5.2). This leads to non-passivated cut edges that are believed to cause performance loss. To quantify this loss, a detailed characterization of these IBC-FFE cells was conducted at the ECN's labs. Different measurement techniques were used, such as:

- IV with illumination levels ranging from 1 sun to 33 suns, to obtain the overall efficiency of the cell and its main electrical parameters: Jsc, Voc and FF.
- Transmission Line Method (TLM), to assess the series resistance of the cell.
- SunsVoc, Photoluminescence (PL) and Electroluminescence (EL) to investigate the effects of the highly recombinative edges.

It was found that the 1 sun efficiency decreases from 17.5% to 11.5% after laser scribing the edges. With light concentration, the efficiency of the laser-scribed cell can peak at 17% at 12 suns. SunsVoc showed that the loss in efficiency was strongly affected by a loss in pseudo-FF, which means that there are plenty of extra recombination centers in the cell. PL and EL showed decreased carrier lifetime at the cell edges, which confirms that the extra recombination centers are located at the non-passivated edges. This recombinations limit the increase of efficiency with irradiance, which is the big potential of solar cells under concentration.

2D computer simulations were performed to further understand the measurements. The bottleneck was identified to be the FFE, which efficiently transports the holes laterally, helping them to reach the area above the laser-scribed edge. Once there, part of them can diffuse to the defective edge where they recombine, decreasing the cell efficiency.

The IBC-FFE cell architecture is too sensitive to edge recombinations to be a suitable candidate for the MLC. Simulations showed that other IBC front passivation techniques (FSF or non-doped passivations) are less sensitive to edge effects because they do not provide a transport channel for the holes to reach the edges and can yield efficiencies beyond 22% at concentration. This could be a robust solution but would require an intensive process development because the current ECN's IBC process is based on FFE. Moreover, the commercial availability of such IBC cells was not secured at the moment. Therefore, it was decided to move to a more standard cell architecture based on n-Si with metal contacts both in the front and in the rear. ECN has a lot of experience and has developed its own process in the last years: the n-Pasha cell, reaching 1-sun efficiencies above 20%. Simulations showed that this cell configuration is also less sensitive to edge effects and has the potential to achieve efficiencies beyond 22% at concentration. Another great advantage is that the MLC cell can be obtained from a standard n-Pasha cell which is produced in a mass-scale by Yingli (Panda).

ECN performed computer simulations to optimize the front and rear grid of the n-Pasha cell for concentration applications. The main loss factor at 20X was identified to be the front and rear contact resistance. A batch of 24 wafers was processed using different screen-print metal pastes and carrying out a firing optimization in order to optimize the contact resistance. The best process resulted in rear and front contact resistances of 1 and 4 mΩcm^2, respectively. Two different front grids were designed, one having a gap in the middle to reduce reflection losses (2-busbar design) and the other one having continuous front fingers (1-busbar design) to provide an easier interconnection (Figure 1).

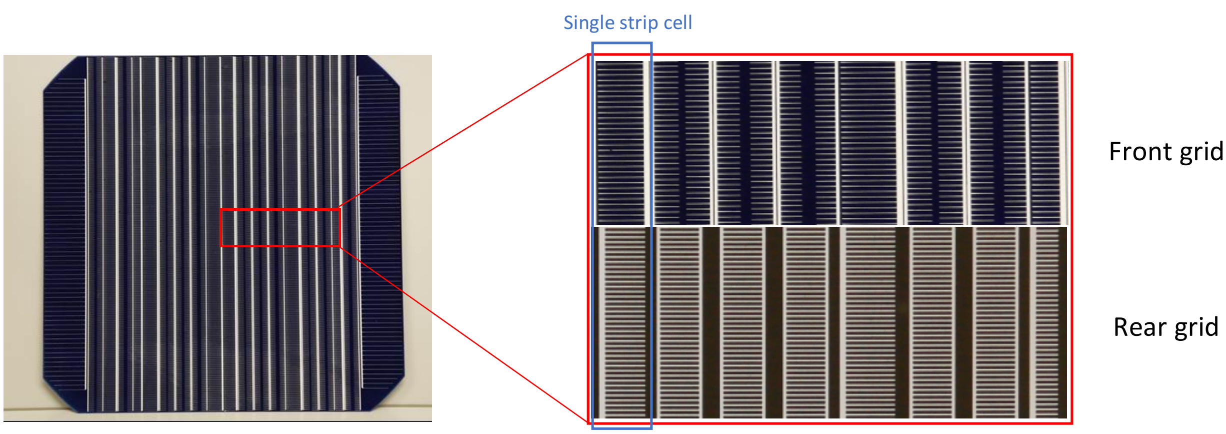

Figure 1. (Left) Photograph of one of the wafers manufactured in the project. The wafer contains 18 different strip cell designs plus two extra wider strip cells at the wafer edges. (Right) Zoom-in at 8 strip cells. Out of these 8 cells, three have a 1-busbar design (#1, 5 and 8 counting from left to right) and five have a 2-busbar design (#2,3,4,6 and 7). The rear grid of these 8 strip cells is also shown below.

The graph below compares the efficiency of the best n-Pasha cells with that of the IBC-FFE cell. The cells were measured with the LED solar simulator developed within this project (see section 2.5.4). Both the 1-busbar and 2-busbar designs outperform the IBC-FFE architecture by more than 1.5%$_{abs}$ at all illumination levels (Figure 2). The efficiency improvement comes from different causes. First, the n-Pasha architecture is intrinsically less prone to edge effects. Second, the edge effects are further reduced because the n-Pasha cells are wider than the IBC-FFE cells (7mm vs 3.3mm), thus the edges are further away from the illumination area. Since the manufacturing process of the n-Pasha cells is cheaper, we can fabricate wider cells without increasing the costs. These two first causes increase the efficiency at irradiances between 1 and 13 suns, where the effect of the edge recombinations is stronger. Moreover, the n-Pasha cells have lower series resistance. Since the series resistance effect on the efficiency is stronger at high irradiances, the n-Pasha cells can keep a high efficiency at high irradiances, while the IBC-FFE efficiency start decreasing quickly at irradiances higher than 12 suns.

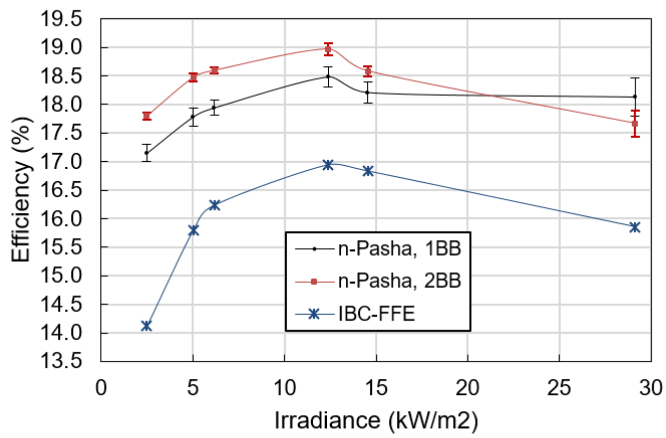

Figure 2. Efficiencies of the n-Pasha cells (1 and 2-busbar design) versus that of the IBC-FFE cell. The measurements were carried out in the artificial light source (red LED's). Only the central 1.3mm of the cell's width are under illumination.

These causes allow the n-Pasha cell to have a slightly higher current and higher FF with respect to the IBC-FFE cell. However, the IBC-FFE showed a much higher Voc. ECN performed further simulations to better understand the effect of concentrated inhomogeneous light and showed that the increase of Voc with irradiance depends on the length for which rear and front fingers 'overlap'. The longer this length, the lower the Voc increase. This overlap is almost the entire strip width for n-Pasha cells (7mm), while it is only 1.3mm for the IBC cell, hence explaining why the IBC cell has higher Voc. The simulations showed that the Voc of the n-Pasha cell could be increased by shortening the rear fingers, but this would come together with a drop of FF, in such a way that the overall efficiency does not increase (it could even decrease if we shorten the fingers too much).

2.5.2 Cell cutting process

The envisioned cutting process is to first do a laser scribe along the cell's length and then mechanically snap the cell apart. The scribe groove must be deep enough to allow a successful snapping. Otherwise, the snapping could result in a breakage along the wafer's diagonal (the crystal orientation of the Si material), breaking the entire wafer. On the other hand, the scribe groove induces a lot of recombination centers which reduce the cell's performance, therefore it must be as shallow as possible. This trade-off required an optimization.

A laser scribing optimization has been conducted with two different lasers at the ECN's laser labs: a 32W green (515 nm) laser and a 15W infrared (1064 nm) laser. The optimized pulse width, frequency, speed and number of passes have been identified. The groove depth was only around 33-45% of the wafer's thickness, and the cells could be mechanically snapped without breaking the whole wafer. For n-Pasha cells the scribe was done from the rear in order not to scribe through the p-n junction. A suitable infrared laser was acquired by Linesolar.

For the snapping process, two different solutions were explored. Originally, a device was designed which would snap all the strip cells within a wafer simultaneously. It consisted of several custom-developed pieces made with injection mold, each one having the same width and length of a strip cell. Two pieces were used per cell, one on top of cell and another on the bottom. All the upper pieces were joint together forming an array, and the same was done with the bottom ones. In such a way, the wafer could be inserted within the top and bottom arrays. Once inserted, the arrays could be slightly bent, snapping simultaneously all the cells. However, it turned out that many cells were snapped through the wafer's diagonal, breaking the entire wafer. This option was therefore abandoned.

A second device was designed, this time being a successful one (Figure 3). The device has a loading position where the laser-scribed wafer is placed. Then the wafer is brought up to a higher position, where the laser scribe line is aligned with an edge. Two cameras can be installed to improve the alignment accuracy. Once aligned, the upper part of the device is manually pushed and creates a force perpendicular to the wafer, which snaps the cell along the laser scribe line. The device can only snap one cell at a time, but it does it with a wafer breakage probability of nearly 0%. This first prototype is a proof of concept and can be easily adapted to a production line.

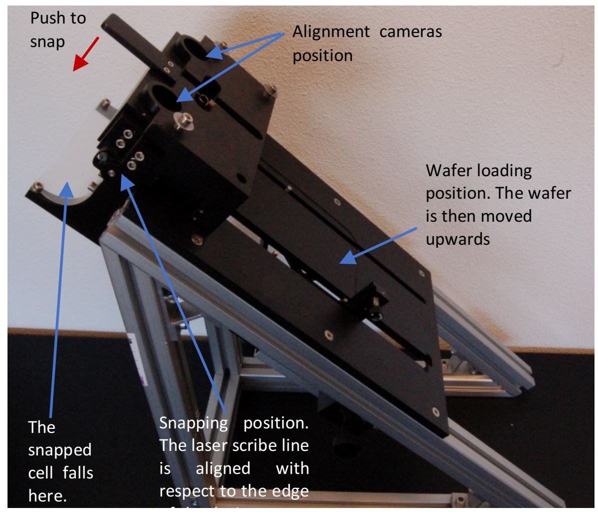

Figure 3. Photo of the snapping machine.

However, no matter how much we optimize the laser settings, the scribe-and-snap process always results in a highly recombinative, unpassivated edge. By comparing simulations with experiments, the surface recombination velocity (proportional to the edge recombinations) is around 10^6 cm/s. This value is too high and prevents the cell from reaching the envisioned efficiencies of 20% at 1 sun and 22% at concentration.

2.5.3 Industrial pick and place machine

A first pilot industrial pick and place machine has been successfully designed and built. All its components are perfectly functional, namely the loading buffer plate, the vacuum gripper to pick up the cells and two cameras responsible for the alignment of the cell with respect to the fiducials on the module copper's foil. The software has been coded by our machine vision engineers. It can pick, align, and place a cell in 7-8 seconds.

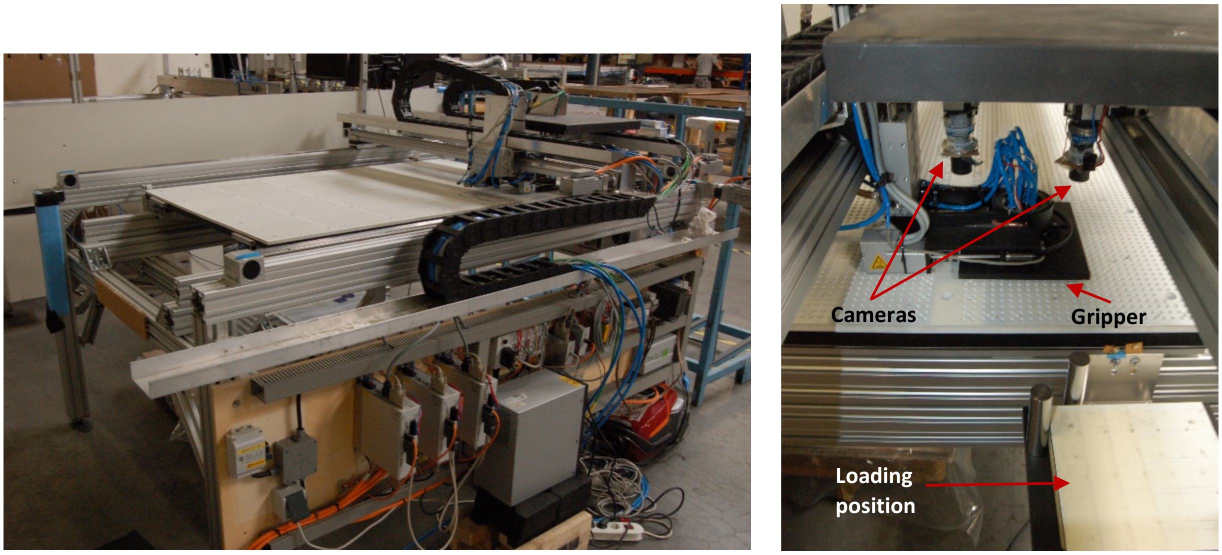

Figure 4. (Left) Picture of the whole pick and place machine, designed for full size 1.6m^2 modules. (Right) Close-up at the main components: the alignment cameras and the vacuum gripper which picks up the strip cells.

2.5.4 Artificial light source

An artificial light source has been successfully designed and built. It consists of two LED banks, each bank containing 30+ red LEDs and connected to a power supply. The LEDs flash can last between 1 and 5 seconds. The light is reflected in the internal mirrors and directed towards a 1.28mm-wide slit. The cell can be placed directly on top of the slit, so that the slit width (times the strip length) determines the illumination area.

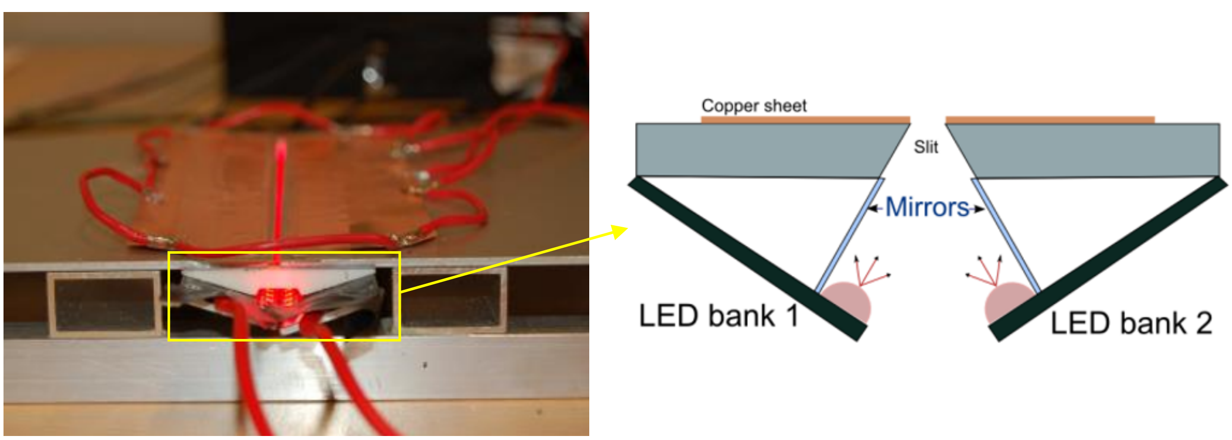

Figure 5. (Left) Photo of the artificial light source, comprised of two banks of red LEDs that can achieve an intensity up to 30 suns at the exit slit. (Right) Sketch of the main components. The light coming from the LEDs is first reflected at the mirrors before being directed towards the exit slit. The copper sheet provides a connection to the front busbars of the n-Pasha cell.

The power supply allows to get irradiances up to 30 suns. There is no need to go higher in intensity because the efficiency peak of all the cells so far happens to be between 10-17 suns (Figure 2). Since the LED spectrum is different from the sunlight spectrum (AM1.5), a spectral mismatch analysis has been carried out and a correction factor for the measured current has been calculated. The setup incorporates a Keithley source-measurement unit (SMU) which is able to perform a pulsed IV measurement within the LED flash. A software has been developed to manipulate the SMU and vary all the IV sweep settings.

The setup can be easily incorporated onto the pick and place machine. However, most of the work has been R&D characterization of the strip cells, which needs a clean environment and a minimum number of parameters that change between each measurement. Therefore, it was more convenient to have an R&D light source and IV meter separated from the industrial pick and place machine.

2.5.5 Module assembly and manufacturing

One of the critical components of the MLC module is the Fresnel lens. To fabricate the lens, its structure is first transferred to a metal cylinder by a high-precision laser process, and this cylinder can then be rolled onto any viscous material to transfer its shape. The lens material is itself a low-cost UV-curable lacquer that can first acquire the shape of the metal roll and then become solid after a short UV exposure. Two Dutch companies were involved in the metal cylinder process and optimization of the lacquer's chemical composition.

During this project, several lens samples were fabricated by using different cylinder designs and different types of lacquers. Three main tests were performed: (1) surface profilometer measurements on the metal cylinder to check that the lens design was properly transferred to the metal roll, (2) microscopy inspections to confirm that the lens shape was properly transferred from metal roll to the ultimate lacquer material and (3) UV exposure tests of the lacquer materials according to the IEC 61215 standards. The result was the identification of a successful lacquer material that can survive 15 kWh/m^2 of UV exposure without degrading its transmission. The lens got the shape of the metal cylinder but with some defects at the lens edges. This may result in some loss of light and needs further research.

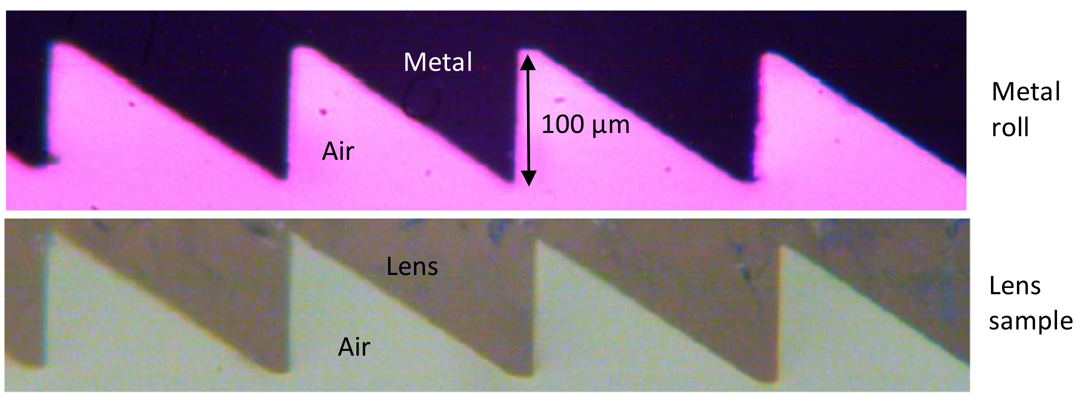

Figure 6. Microscope images of a small cross sectional part of the metal cylinder (top image) and its replica onto a lens sample (bottom).

The lens was originally designed to have a concentration factor of 40 suns, i.e. a lens width of 40mm that concentrates the light onto a line of 1mm. Cell measurements showed later that the cell efficiency peaks between 10 and 20 suns. This imposes no extra challenge, since the lens design can be easily adapted to this concentration factor.

2.6 Discussion

Since the biggest project bottleneck has been the cell efficiency, most of the effort has been focused on the design, characterization and understanding of the strip cells. It was soon revealed that the IBC-FFE cell is not suitable for small (3-5 mm) strip cells with non-passivated edges. The FFE provides a channel for the holes to easily reach the edges and recombine. Consequently, the IBC-FFE cells can lose up $4\%_{abs}$ in efficiency (1sun) just by laser scribing the edges.

The alternatives to IBC-FFE were IBC-FSF or n-Pasha cell structures, which were both proven by simulations to be less sensitive to edge effects and to have high efficiency potential. The IBC process of ECN is based on IBC-FFE, so they do not possess a process recipe for IBC-FSF. On the other hand, ECN has already a mature n-Pasha process and it is easier to find an industrial manufacturer. Therefore, it was decided to try the n-Pasha architecture to process the next batch of strip cells.

After optimizing the metal grid and doping levels, the new n-Pasha strips outperformed the IBC-FFE strips with an efficiency improvement of at least $1.5\%_{abs}$ at all illumination levels, peaking at 19% at 12 suns. Although this is a major boost, it is not good enough to reach the project goals of 20% at 1 sun and 22% at concentration. The 1 sun efficiency is below 17.5%, which means that recombinations at the unpassivated edges are still remarkably affecting the efficiency. Possible efficiency improvements could be achieved by (1) passivating the edges, (increases Voc and pseudo-FF) and/or (2) lowering even more the contact resistance (which is limiting the FF).

Finding an industrially feasible edge passivation technique is not trivial. One possibility is to do the laser scribe somewhere in between the cell process, so that diffusion processes which take place after the scribe passivate the scribe groove. However, a wafer with 20 scribe lines is quite unstable and prone to breakage, and it is believed that the process steps after the scribe will result in too many broken wafers. Other possibilities include chemical passivation techniques. This requires a lot of experimental trials and these techniques can be challenging to implement in a production line. Yet another option could be to change the laser scribe method. Methods such as the Thermal Laser Separation (TLS) claim less defective edges, and this could result in less recombination centers.

Selecting n-Pasha also means changing the module interconnection method. The n-Pasha cell requires front-contacting and the envisioned method is to contact the front busbar(s) to the copper foil via electric conductive adhesives (ECA). These materials can degrade with UV exposure, therefore tests will be needed in order to quantify this degradation.

Another strategy is to try the third cell architecture: IBC-FSF. This requires a new process development by ECN but it is believed to be an easier alternative than exploring different passivation techniques with high risk factor. Moreover, this cell architecture is less prone to edge recombinations than IBC-FFE, while still benefits from the high voltage and current potential of the IBC cell. One of the main bottleneck of the n-Pasha cell is its low voltage due to the long “overlap distance” of front and rear fingers. Simulations show that by designing a short overlap distance of the rear fingers of the IBC cell and making this distance equal to the illumination width, the Voc (and therefore efficiency) can be maximized. Moreover, as long as the FSF reduces the effect of the edge recombinations, the current of the IBC-FSF cell has also the potential to overcome the n-Pasha’s current thanks to the absence of a front grid.

2.7 Conclusion and recommendations

Low-concentration PV (LCPV) technologies based on Silicon are a very attractive solution to reduce the costs of the PV module manufacturing by decreasing the amount of expensive Silicon and replacing it with low-cost optics. Different Silicon PV technologies can be used and the current project has been very valuable to understand the advantages and limitations of two of these, namely the IBC-FFE and the n-Pasha technology, both based on n-Silicon.

We can analyze the objectives of the project point by point:

1) Design of a custom IBC cell with efficiency >20% at 1 sun. This objective failed, and it was discovered that the IBC-FFE cell is too sensitive to edge effects to have such an efficiency. Since this milestone has a high impact factor in the MLC project, most of the resources were used up in improving the cell efficiency. Another cell technology, namely the n-Pasha, was explored and obtained a much higher efficiency than the IBC-FFE. However, the efficiency was still below the objectives of the project: below 17.5% at one sun and a peak of 19% at 12 suns.

2) Develop an industrial cell cutting process. The laser scribing process has been optimized to result in the shallowest groove possible to induce the least edge defects. Moreover, a mechanical snapper has been successfully built. However, the laser damage is one of the biggest players in the final cell efficiency, and it is likely that the laser process has to be modified depending on the cell architecture chosen. Since the optimum cell architecture is still not clear, no time was spent on building the whole industrial cutting machine (scribe + snap).

3) Develop an industrial pick-measure-buffer and place process. The pick-buffer-place machine has been successfully built and it is perfectly functional. A cell can be picked, aligned and placed in 7-8 seconds. The artificial light setup (+IV meter) has also been built and allows measuring the cell performance within the irradiance range of interest, but it has been kept separated from the pick-buffer-place machine because the project is still in R&D phase regarding the strip cell development. Once the cell efficiency is good enough, it is easy to implement the light setup together with the pick and place to start optimizing the production process.

4) Develop the MLC module assembly and manufacturing process. Since the cell efficiency objective was not met, most of the resources were used in the cell design optimization, characterization and further modelling to understand the efficiency bottlenecks. Consequently, there was little time for the last part of the project and no full-size working modules were built. However, crucial advancements have been done in the Fresnel lens by manufacturing a metal cylinder with the lens structure and finding a proper lacquer material that can easily get this structure transferred and can also survive the IEC UV test.

We believe that there is room for improvement regarding the cell development. There are two routes: one is further optimizing the n-Pasha structure, which is already at 19% efficiency. Edge passivation techniques or contact resistance optimizations can help in this direction. The other possibility is to move to IBC-FSF, which also shows less sensitivity to edge effects than IBC-FFE and can benefit from the advantages of the IBC cells over n-Pasha cells (higher voltage and current). A continuation of this project should clearly decide for one of these two options. Once the cell efficiency is good enough, the module manufacturing will be more straight-forward because a lot of progress has already been done: pick and place machine, artificial light source, Fresnel lens process and materials, etc.

3. Project implementation

Problems that appeared, technical and organizational, and how were they resolved.

Explanation of changes of the project.

The current project has dedicated an unexpectedly big effort in the strip cell design, characterization and understanding (work package 1). All the problems were technical and mostly came from the strong edge effects that result from the unpassivated edges after the laser cutting. A big effort was put to quantify this effect and to explore the new cell architecture, the n-Pasha. This decision deviated from the original project proposal of working only with IBC cells, but it has three main justifications:

1) Simulations showed that the n-Pasha was less prone to edge effects compared with IBC-FFE.
2) ECN already had a lot of experience with the process of n-Pasha.
3) The industrial implementation of the n-Pasha cell is much more straightforward than for IBC cells. The latter had no clear manufacturer at the moment of the decision.

Explanation of differences between budged and actual costs

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Toelichting wijze van kennisverspreiding

Toelichting PR project en verdere PR-mogelijkheden

The knowledge acquired during the project is not useful enough to be directly transferred to the society or third parties or for the creation of spin-offs yet. However, we have learnt which cell technologies are clearly not suitable for LCPV applications with silicon solar cells (IBC-FFE), which are more challenging (n-Pasha), and which have the potential to yield much more promising results (IBC-FSF).