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TNO report

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Final report Optisun

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Summary

In the period March 2005 and February 2007 TNO investigated a more efficient grid connected PV module, in close cooperation with the partners of the EU Optisun project (AllSun, Plastas, Solartec, Ibersolar, Semilab, Semifab and PERA). TNO was active in the following three new technologies that were studied in the Optisun project for the development of a new type of PV cell with a higher efficiency.

1. Subdivided solar cells. The Si-cells must be divided into eight segments with the same current output.
2. Back light reflector. The development of a back-light module to utilize the empty space between the cells and generate additional solar power by transferring the light to the rear side of the solar cell.
3. Parallel connection of groups of solar cells. Currently solar cells in a module are serial connected. If only a few cells are disturbed (e.g. dirt or shadowing), the power production of the total module reduces dramatically (up to 40%). Here the cell segments are serial connected whereas these "cell modules" are put in parallel thus minimizing the disturbing effects.

<u>Subdivided solar cells.</u>
The individual current outputs of solar cells in a module are not equal due to small differences in the processing from wafer to solar cell. The output of the total module will be defined by the lowest performing cell. Dividing a solar cell into eight equal segments, eight equal mini cells are created and therefore the output is optimal.

When dividing a solar cell into equal pie pieces, material has to be removed from the centre of that solar cell. To be able to make identical segments, the material removed must have a circular shape. Mechanical methods of cutting silicon are then no longer applicable. Laser-technology is an alternative and in this specific case probably the only solution. The number of sub-cells is defined by the voltage needed by the inverter. It was decided that the minimum voltage should be four Volts. The number of cell parts needed therefore is eight (each sub-cell delivers 0.5 Volt).
The following laser-types have been tested: Water jet Technology from TrennTek (Germany), Abrasive Water jet Technology from TrennTek (Germany), Laser cutting Technology from TNO (the Netherlands), Laser sublimating Technology from TRUMPF laser (Germany) and Laser Microjet® Technology from SYNOVA (Switzerland). Based on the research of the Optisun project, it is decided to use the laser jet to subdivide the cells.

<u>Development backlight reflector</u>
The EU Optisun project has shown that more efficient use of Si/efficiency of the solar cell can be obtained the using the backside of the PV cell. In figure 16 the principle of the back light reflector is shown. The "empty space" between the round cells is wasted on the PV module. The back light module brings light from "the empty space" between the PV-cells to the rear-side of the PV-cell and here generates additional solar power.

Optical module studies were performed for the optimum shape of the back light module by TNO. Optical studies show that a "dense" back-light module has a higher optical efficiency than a hollow back light module. Back light modules (dense and hollow) have been prepared based on this optimal shape. The disadvantage of the dense back light module in comparison to the hollow back light module is the weight of the module and the extra costs for the material. Preliminary calculations show that the economical efficiency of the hollow back light modules is about 10-30 % higher than

that of the dense back light modules. In the meeting of June 2006 it was decided to prepare hollow and dense back light modules.
In close cooperation with the Optisun partners TNO selected the substrate materials and the reflector coating material. All three commercial used reflector materials (SiO_2/TiO_2, Al and Ag) have good reflection properties. Silver (Ag) has the best reflection properties, but the difference with Aluminium (Al) is small and additional reflection obtained is out weighed by the additional costs. TNO selected Al as reflector material in the back-light module, because it is relatively cheap, easy to deposit on plastic module by PVD and has a high reflectivity (92%).
Two main preparation routes have been selected for the preparation of the back-light module. The first is the back reflector shaped out of plastic with an aluminium coating deposited on the surface of the shaped plastic (3D). The second route is a plastic plate (2-D) coated with aluminium and the back light reflector is shaped out of the plastic coated aluminium. The second route is easier and less costly in Al-coating (e.g. packaging laminates, alanod high reflection, Corus protac) but some damage will inevitably happen while shaping, leading to less-reflective spots. During the project the one-unit proto type hollow back light module has been up scaled to a four-unit proto type hollow back light module.
In total six four-unit proto type hollow back light modules by route 1 and nine four-unit proto type hollow back light modules by route 2 have been prepared and sent to the Optisun partners. In the Optisun project there was not enough time and capacity to test the back light modules prepared by TNO.

Integration (serial/parallel connection)
The separate modules of (a) segmented solar cell, (b) micro inverter and (c) backlight module were to be combined to form a prototype of the OPTISUN solar module. The interconnection of the separate solar cell parts was studied, as a result an interconnection foil was designed and corresponding interconnection types were studied.
The two interconnection methods investigated are soldering (using a lead free solder) and gluing (using electrical conductive adhesives).
First of all the final design of the cell was chosen as described in task 1.3. As a result of the investigation on the cell dividing two possible solutions were defined:

1. using etching paste,
2. using a water laser jet or laser sublimation technique to divide the cell in eight physically separated parts.

The interconnection solution has to be compatible with both options. The segmented solar cells will be mounted on a glass carrier similar to standard module manufacturing. Using the standard thermal lamination step within this process to cure either the conductive adhesive or to meld the lead-free solder the thermal load will be minimal.

Contents

1 Introduction

The goal of Optisun is the development of a more efficient and easy-to-install PV module with subdivided solar cells, back light reflector and a solar cell integrated micro inverter to increase the efficiency of the solar cell. In addition the solar cells will be parallel connected in order to control as few cells as possible to reduce the negative effects of environmental and climate influences.

The following four new technologies were developed in the Optisun project for the development of a new type of PV cell with a higher efficiency.
Subdivided solar cells. The Si-cells must be divided into eight subparts with the same current output.

1. Solar cell Integrated micro inverter. The development of a micro inverter for each unit that convert the voltage from 3→ 220 V.
2. Parallel connection of groups of solar cells. Currently solar cells are serial connected on a module. If only a few cells are disturbed, the power production will be reduces dramatically (up to 40%). Groups of the serial interconnected segmented solar cells will be parallel connected.
3. Back light reflector. The development of a back-light module to utilize the empty space between the cells and to transfer the light to the rear side of the solar cell to generate additional solar power,

The set-up of the Optisun project is shown in figure 1 below. TNO was active in WP 1 (the laser cutting of the Si solar cells), WP 3 (the development of the back-light reflector) and WP4 (the integration of the 4 technologies in the new type of PV cell). The results described in this end report of Optisun are obtained by TNO in close cooperation with the Optisun partners All-sun, Plastas, Solartec, Ibersolar, Pera and Semilab, Semifab in the period March 2005-February 2007. In chapter 2, 3 and 4 of this end report the results obtained in WP 1 (selection of method of cutting solar cells), WP 3 (development of the back light reflector) and WP 4 (Intergration)in chapter 3 the results are given respectively. In chapter 5 the conclusions are given.

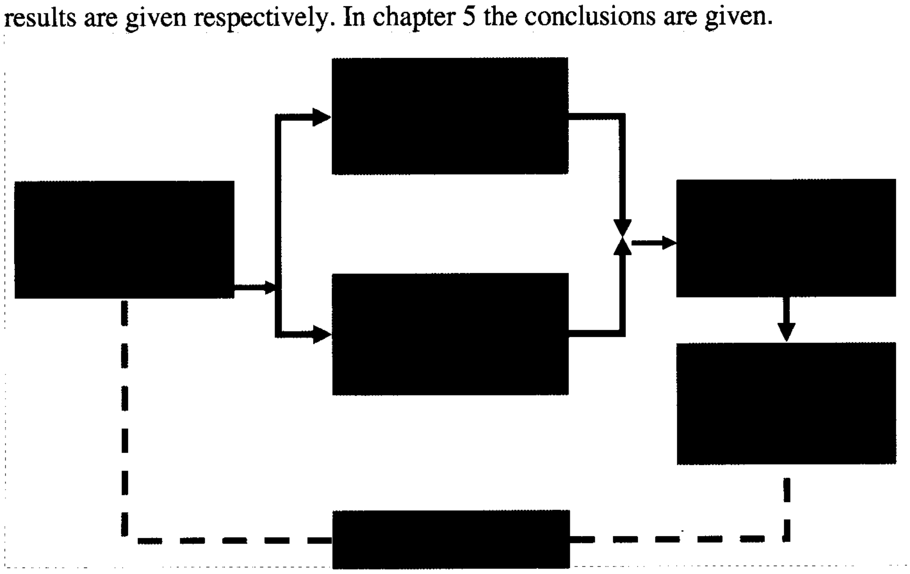


figure 1 Set-up of the Optisun project

2 WP 1 Technical Knowledge creation

2.1 Scientific Study of Methods for Subdividing Solar Cells and their Effect on Solar Cell Efficiency

Objective: Achieve an enhanced scientific understanding of methods for subdividing solar cell and their effects on solar cell efficiency.

Sub-task:
1.3.2 Separate the sub-cells completely, by laser dicing.
1.3.3 Separate the sub-cells without separating the wafer by trench formation realized by laser-ablation and etch isolation trenches.
1.3.4 Use inkjet printing of conductive paste as interconnection principle.
1.3.7 Collated knowledge design and produce subdivided solar cell with optimal performance based on laboratory experiments to be used in subsequent development.

2.1.1 Subtask 1.3.2 Separate the sub-cells completely, by laser dicing.

In task 1.3.2 it was defined, that the solar cell had to be (physical) divided into a number of sub-cells. When dividing a solar cell into equal and identical segments, material has to be removed from the centre of that solar cell. To be able to make identical segments, the material removed must have a circular shape. Mechanical methods of cutting silicon are then no longer applicable. Laser-technology is an alternative and in this specific case probably the only solution. The number of sub-cells is defined by the voltage needed by the inverter. It was decided that the minimum voltage should be four Volts, so the number of cell parts needed is eight (each sub-cell delivers 0.5 Volt).

The following laser-types have been tested: Water jet Technology from TrennTek (Germany), Abrasive Water jet Technology from TrennTek (Germany), Laser cutting Technology from TNO (the Netherlands), Laser sublimating Technology from TRUMPF laser (Germany) and Laser Microjet® Technology from SYNOVA (Switzerland). The results of the methods are listed below.

Water jet Technology from TrennTek (Germany)

Water jet cutting uses only a pressurized stream of water (at a pressure of 4000 bar and a resultant exit velocity of approx. 800 to 1000/s through a diamond nozzle) to cut through material (figure 2). Not all materials are suited to be cut this way. Material with naturally occurring small cracks or softer materials are the obvious materials. This technology did not apply to the Si-cells we provided them with. The silicon wafers were too brittle and this resulted in undefined cell breakage.

It was not possible to optimise this process in order to produce eight identical wafer or solar cell segments.

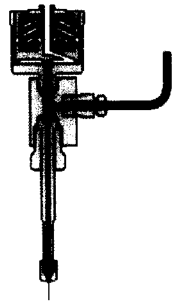


figure 2 Water jet cutting head, principle.

Final result: not applicable for Si-cells.

Abrasive Water jet Technology from TrennTek (Germany).

In the case of materials on which the pure-water method reaches its limits, the abrasive method is used. In the abrasive process, a fine-particle cutting agent is added to the water (figure 3). After addition of the abrasive, the water, air and abrasive are combined in the mixing chamber, collimated in the focusing nozzle and accelerated. The result of this technique is a high-energy jet which micro-erodes, i.e., drills and cuts, materials of great thicknesses and the most diverse consistencies, such as metals, ceramics, rock and bullet-proof glass.

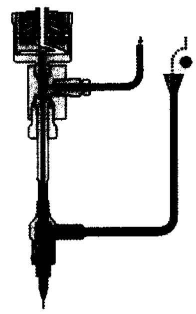


figure 3 Abrasive water jet cutting head, principle.

However, this particular method proved not to be applicable to the Silicon of the solar cells. The edges of the cut cell parts were very rough and did not meet the requirements. Final result: not applicable for Si-cells: poor edge-quality.

Laser cutting Technology from TNO (the Netherlands)
In this trial a Nd:Yag laser was used (1064nm, pulse repetition 50Hz, pulse length 1.22ms) in combination with O_2 gas assist (5bar). The cutting speed was 180mm/min and later changed to 300mm/min. Because of the fusion-principle the Silicon-material is melted and melting pearls that are created provide short-circuits from front side- to back side of the cell (figure 4 and figure 5).

FUSION CUTTING

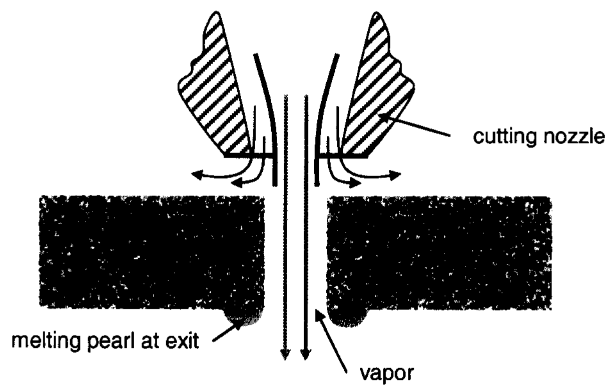


figure 4 Principle of fusion cutting by laser, with a great chance of melting pearls building short-circuits

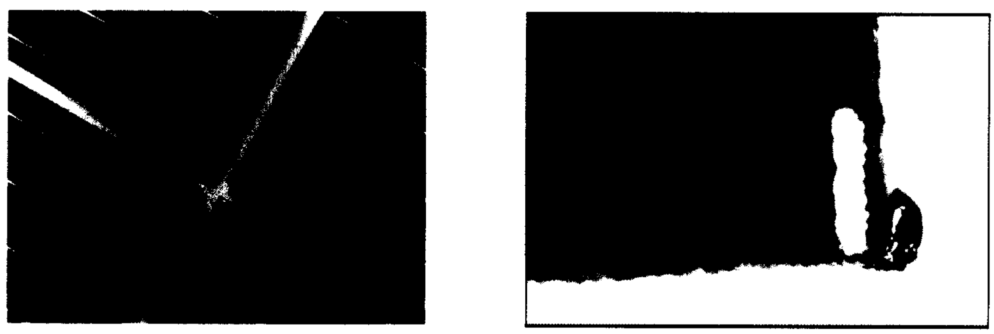


figure 5 Examples of laser cutting a Si-cell resulting in short circuits by melts (right).

This means the laser fusion cutting technique is not applicable to an active solar cell. Cutting the Si-wafers before processing might be an option to avoid these short-circuits, in practice processing single cell-parts will lead to other forms of short-circuits.
Final result: not applicable for Si-cells: melts are creating short-circuits.

Laser sublimating Technology from TRUMPF laser (Germany)
Because of the short-circuits created by the melted silicon material of the cell an alternative way of cutting the silicon had to be found. Since a circular shape has to be removed from the centre of the cell, mechanical solutions are no option. By cutting through the cell by removing thin layers of silicon material by evaporating the silicon, hardly any melt occurs. This silicon vapour precipitates on the cell side that faces the laser source. Thus, it will not create any short-circuits from front- to backside (figure 6).

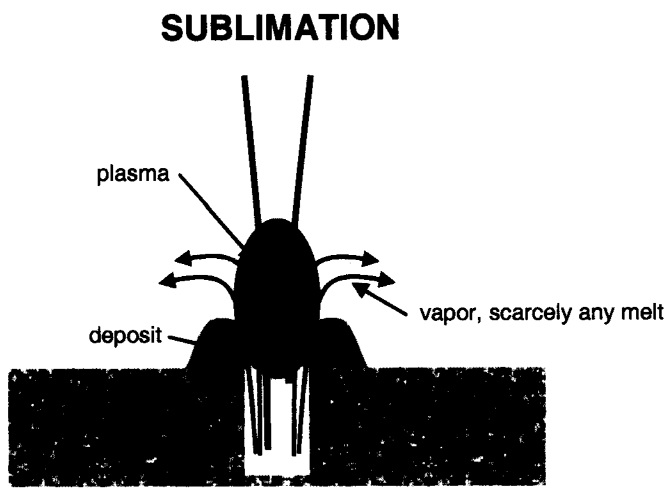


figure 6 Principle of the sublimation of a material by laser.

This technique requires a number of repetitions of the laser beam over the same position on the material and therefore is time-consuming.
In table 1 a comparison is made between fusion cutting (by melting the silicon) and sublimation (where the material is evaporated). Sublimation seems a faster process, but it should be taken into account that the final sublimation through the material is accomplished by repeating the sublimation-patterns a number of times and thus consuming precious process time.

table 1 Laser fusion cutting vs. sublimation cutting of Silicon wafers (source TRUMPF laser)

	Fusion cutting	**Sublimation**
Energy level	J	mJ
Pulse duration	1 to 1000 µs	1 to 1000 ns
Intensity	10^6 to 10^7 W/cm^2	> 10^9 W/cm^2
Groove width	> 100 µm	< 100 µm
HAZ	> 10 µm	< 10 µm
Burr	Melting pearl at the exit	Burr at the entrance
Processing gas	High pressure to blow out	- (cooling: in certain cases)
Fouling	Spilling (protection glass)	No spilling, vapour
Ablation rate	-	< 10 mm^3/min
Processing speed	Up to 100 mm/s	Up to 5000 mm/s
Beam guide system	Focusing optic	Scanner technology

Final result: applicable for Si-cells, though deposit is left on the laser-faced surface on both sides of the cut line. This deposit does however not create short-circuiting between both sides of a cell segment. This type of laser is used in trench formation (paragraph 1.3.3) as well.

Laser Microjet® Technology from SYNOVA (Switzerland)

This technology uses a hair-thin water jet to guide the laser beam. This laser beam is contained within the water jet by internal reflections (figure 7). The water jet cools the material while the laser beam is used to cut, to scribe or to mark the material. This cooling effect minimizes the heat affected zone (HAZ). The water also washes away the material that might otherwise be left on the surface. The final result is a smooth cutting surface (figure 8).

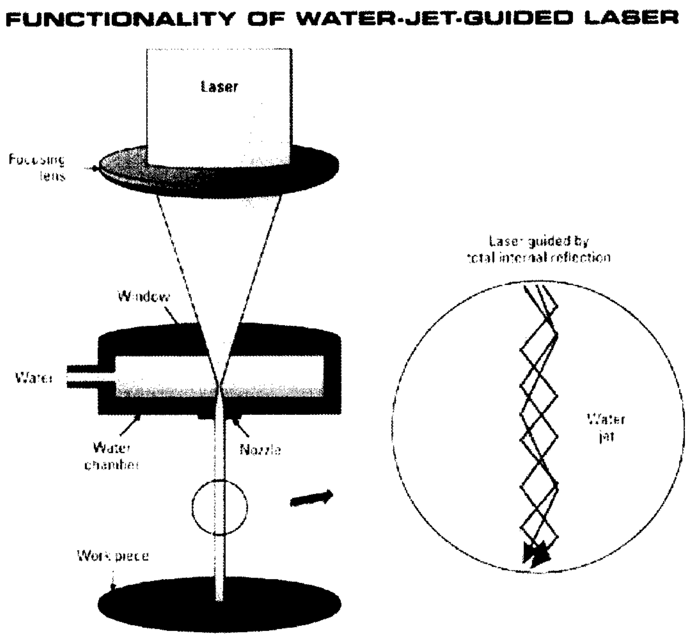


figure 7 Schematic overview of laser water jet principle.

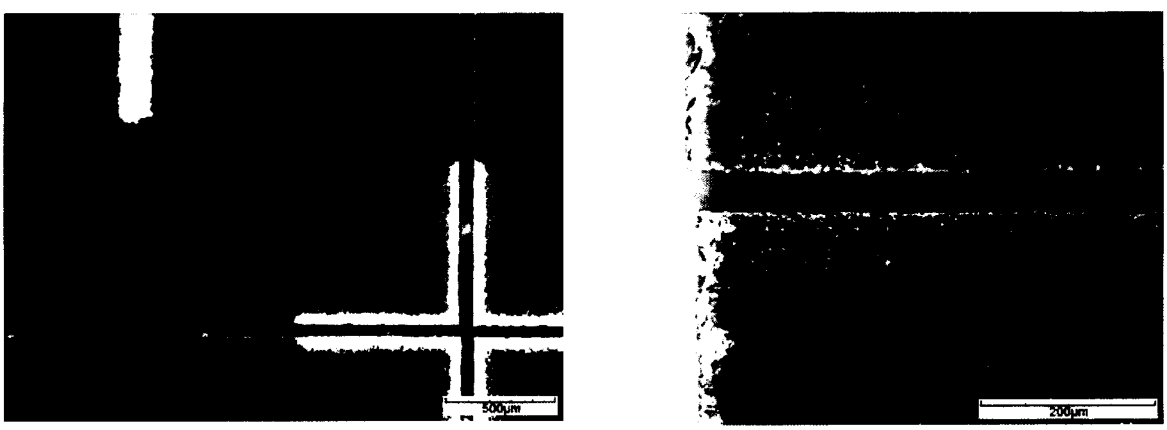


figure 8 A microscope image of a solarcell edge after trenching with the water-jet-guided laser shows that the bottom line is very regular and the kerf is clean.

Final result: applicable for Si-cells and best selection in terms of edge-quality.

Conclusion:
After testing the following laser-types : Water jet Technology from TrennTek (Germany), Abrasive Water jet Technology from TrennTek (Germany), Laser cutting Technology from TNO (the Netherlands), Laser sublimating Technology from TRUMPF laser (Germany) and Laser Microjet® Technology from SYNOVA (Switzerland) the Laser Microjet® Technology from SYNOVA (Switzerland) and TRUMPF laser (Germany) were selected. The Laser Microjet can separate the cell parts completely without making short-circuits, but is an expensive technique. The TRUMPF laser is cheaper, but leaves a deposit on the front side of the cell which will not effect the electrical performance of the cell in terms of short-circuiting but does cover an extra part of the active front side.

2.1.2 *1.3.3 Separate the sub-cells without separating the wafer by trench formation realized by laser-ablation and etch isolation trenches.*

To minimize the mechanical stress on the cut wafer parts, the centre of the 4" wafer will be cut out using a laser. To start with, the diameter of the removed part will be 15mm , finally the diameter of this centre-hole will have to be optimized.

The first idea
Each cell has to be divided into a number of sub cells to be able to collect enough power to feed an inverter. Divide a cell into separate parts might introduce difficulties one could avoid by not physically dividing the cell into sub cells. Electrically this will be necessary but also possible if not cut into eight sub cells. At first the idea was to cut dashed lines from the centre to the outer side of the cell using 3mm Si-10 mm groove-3mm Si- 10 mm groove – 3 mm – 10 mm groove – 3.5 mm Si (as shown in figure 9). In this way, the cell can be handled as one piece during the module making.

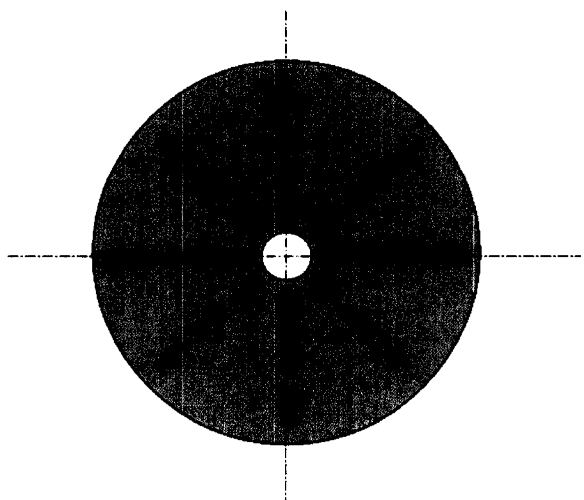


figure 9 Solar cell with laser-grooves.

This process of producing a cell is translated into a process-flow as shown in figure 10. There is one major uncertainty, for it is not clear whether the electrical separation by laser grooves will be sufficient to guarantee an optimal electrical result. Another issue is the mechanical strength of the wafer after laser cutting the centre hole and the grooves.
The problems will most likely not occur in the picking & placing and the possible breaking of the cells neither in the electrical behaviour, but will probably focus on the encapsulant filling the grooves and create thermal-mechanical stress. Due to the mismatch of the coefficients of thermal expansion (CTE) of Si and encapsulant the filling of those grooves with EVA will lead to more or less uncontrolled breaking of the cells during lifetime of the module, while facing the temperature-cycling of day and night.
The edges of the grooves will act like perfect crack-initiators. The form of the grooves, 10mm long and as wide as needed for the laser cutting has a very unfavourable aspect ratio. Making “dots” in stead of “stripes” would at least improve the aspect ratio.

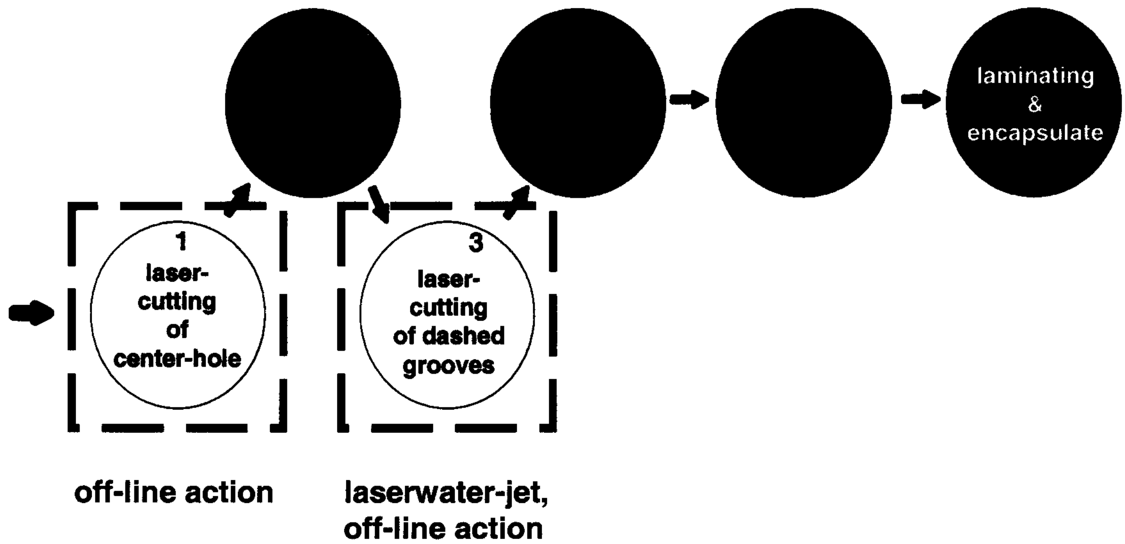


figure 10 Process-flow of partly cut cell-segments.

This way of making the cell-parts needed for the micro-inverter will not be a robust process. It will never be sure at what point in the production process the cell might break into an undefined number of parts, or whether the cell will break at all.

Alternative idea
This alternative could even be much easier to realize, for the parts are meant break into segments at the end of the process in a controlled manner. This will also make the part of electrical separation more defined and less vulnerable. This process is shown in figure 10.

Depending on the time at which the 15mm circle is laser-cut from the wafer/cell a specific type of laser should be used. In case the hole is cut before the wafer is processed, almost “any” laser can do. The possible damage done to the silicon by laser can probably be undone by etching those damages away. After etching, the cell can be processed in a normal way. In the end, after the cell-processing is completed, the definite number of cell-parts will be marked using a scribe pen/wheel or laser (step 4 in figure 11).

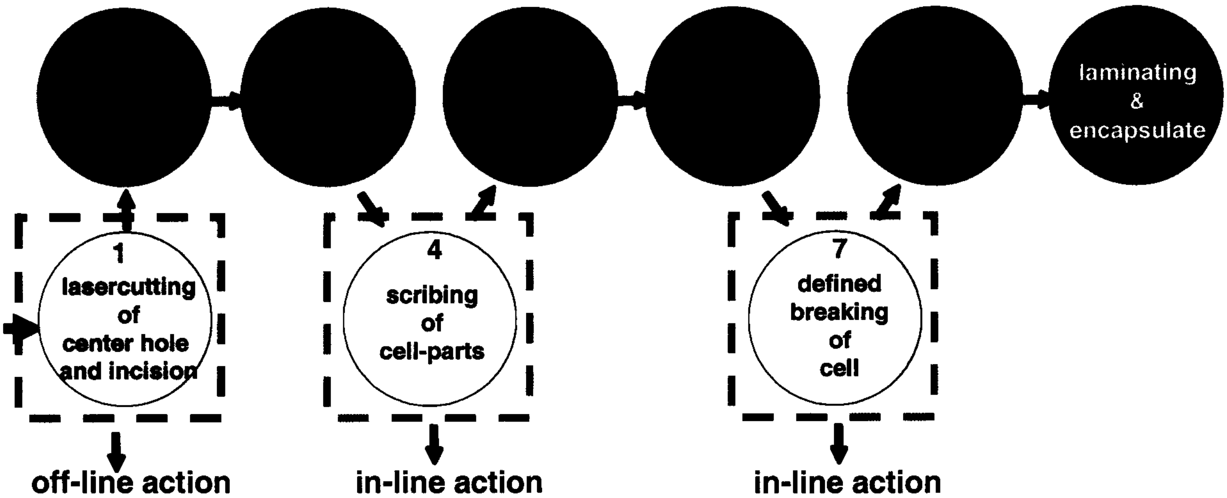
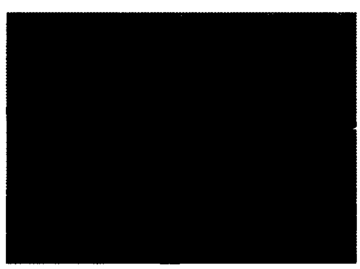
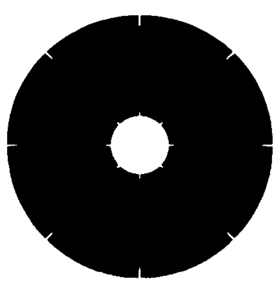


figure 11 Process-flow of non cut wafers, scribed and broken just before final process step.

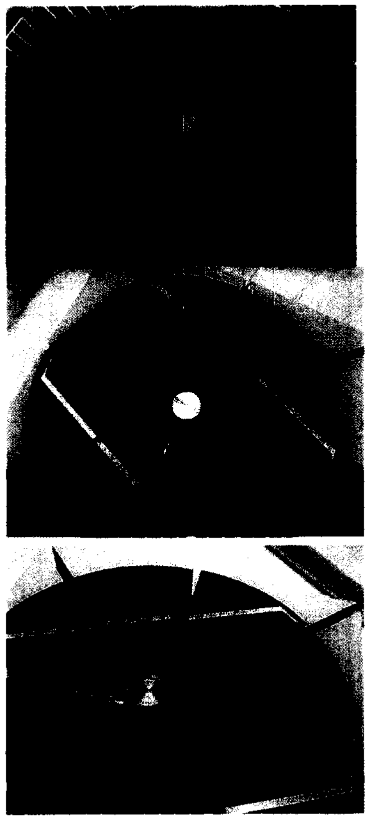
The final step will be the positioning of the scribed-cells into the backlight-module. The backlight module can be equipped (since it is a molded piece) with extra "walls" that will act like sharp knives to let the cell be broken over the scribed lines on the front side. After laser cutting the center-hole, the laser should also make small incisions in both the inner circle and outer circle of the Si-wafer. In between those marks, the final scribed lines are made, as shown in figure 12.



Model of breaking-tool that could be integrated within the backlight module.



Drawing of pre-worked solar cell, with scribed lines (dashed) and cuts.



Step 1:
Positioning of cell over the breaking-tool
(picture above).

Step 2:
Breaking cell in two equal parts.

Step 3 + 4:
Breaking the cell in four and finally in eight equal parts.

figure 12 Breaking of pre-worked solar cells step by step.

The next step will be fastening interconnecting-tabs on the rear side of each of the cell-segments. The cell is still in one piece at this moment.

While placing the cell into the backlight module-position, pressure is applied to the cell in a precise matter, and the cell will be broken into the desired number of segments. These segments are physically separated by the ribbons on the back reflector, which were used as knives to break the cell (figure 13).

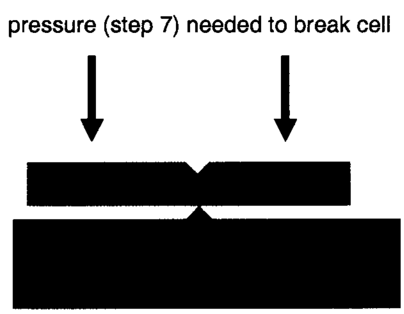


figure 13 Cross section of a part of the back reflector and a part of the cell with scribe line.

Benefits of the second process (not proven jet) are:
- no mechanical weakening of the wafer by just removing the centre of the wafer
- processing of a complete wafer to a complete cell
- scribing of the cell by diamond wheel or laser (sublimation)
- controlled breaking and physically dividing into segments, solving the electrical
- problems of shunting between front- and rear side between the cell-segments

Conclusion:
For this moment, it is decided to use the laser jet to subdivide the cells. Because of the price for such a system is very high the sublimation-technique is also an option.
The other option is the use of an etching paste. This part of the research was carried out by Solartec.

3 WP 3 Development of backlight module

3.1 Light Transmitting Materials

Objective: Select a material for the light transmission element of the backlight module that will provide and maintain optimum light transmission efficiency during use.

Sub-task:

3.1.1 Use developed cells, and calculate the wavelengths of light that are most crucial to power generation. Identify materials that have high transmission coefficients for these wavelengths of light to optimize the match between photovoltaic cell and transmissive material.

3.1.2.1 Consider the environmental, chemical and thermal conditions that can be experienced by the component and select a material from those identified in task 3.1.1 that will retain its light transmission properties and other required properties for the expected service life of the component.

3.1.1 Use developed cells, and calculate the wavelengths of light that are most crucial to power generation.

When analysing the solar panel efficiency several aspects are important. These are:

- Effective area of the solar panel
- Type of material
- Mode of operation

In this case the following assumptions are made:

- The base material is Silicon and can not be adapted
- The solar cells are fixed in the solar panels and the solar panels have fixed orientation. The solar panel orientation cannot be altered. (No tracking)
- The solar cell effective area is fixed and cannot be altered
- Shading effects of electrical bonds and wiring are not considered in the calculations

These restrictions rule out a lot of optimisation options. Parameters that can still be used are the solar panel design, the use of solar concentrators or back reflectors.

Effective area of Solar panel

The closest packing is achieved by using the hexagonal packing shown in figure 14.

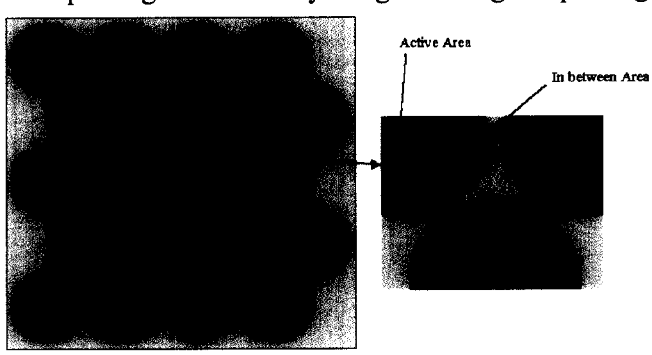


figure 14 Hexagonal packed solar panel

figure 14 Hexagonal packed solar panel

Except for the edges six neighbours surround each cell. In between the cells some area is left unused. For a large plate the area loss is about 10% when the neighbouring cells touch. In practice however there will be some space in between the cells.

The part of the overall area A_0 that is covered by effective area A_e is describe by:

$$A_e / A_0 = \left(\frac{Rc}{s}\right)^2 \cdot \frac{8\pi\sqrt{3}}{12}$$

where s is the cell spacing. Filling in limiting case Rc =s/2 one finds that 90.6% of the area is effectively used. Assuming a 2mm separation a value 87.2% results.

For small solar panels the packing could very well be chosen orthogonal. This packing uses the edges somewhat more efficiently. In figure 15 a sketch of such a panel is given.

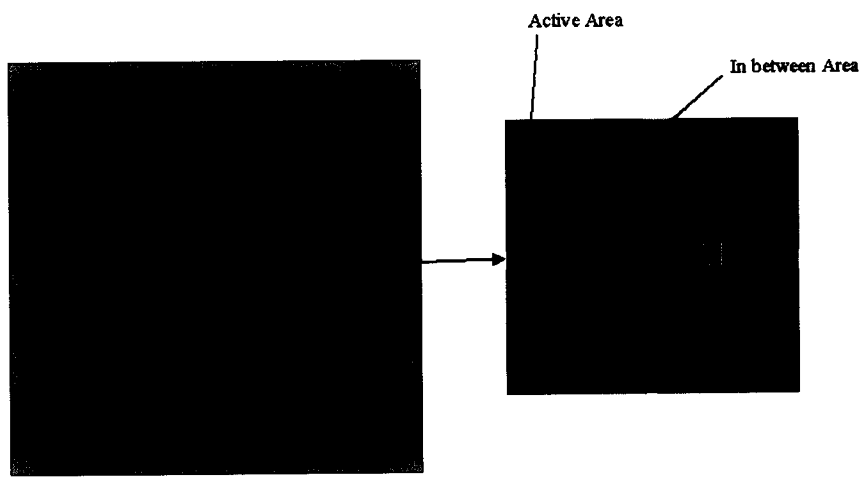


figure 15 Orthogonally packed solar panel

Now the effectively used area is described as:

$$A_e / A_0 = \left(\frac{R_c}{s}\right)^2 \cdot \pi$$

Filling in Rc =s/2 (touching cells) one finds that 78.5% of the area is effectively used. Assuming a 2mm separation a value 75.5% results.

Back reflectors

Back reflectors are used to utilise the area in between the solar cells. The light that falls onto the back reflector is directed to the cells' rear side where part of the light is absorbed. In figure 16 a sketch is given of the back reflector principle.

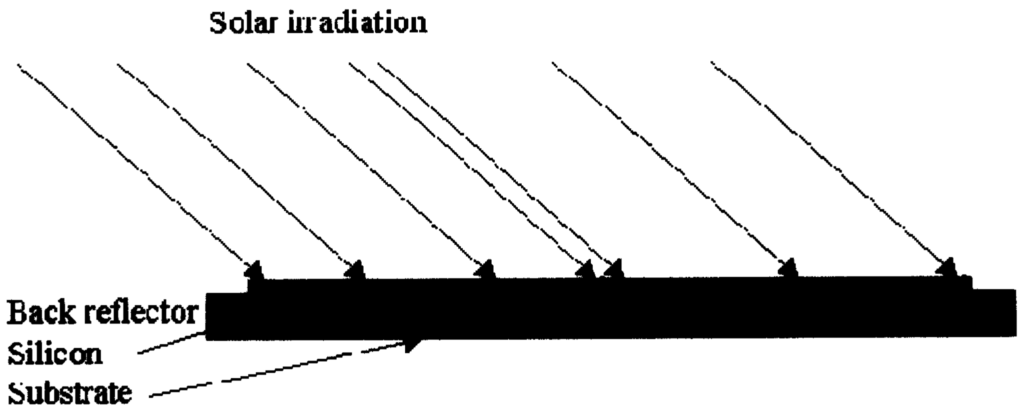


figure 16 Back reflector principle

The value of the back reflector is mainly determined by the added area and the cells back side conversion efficiency.

In general the light conversion efficiency of the cell rear side will be lower (about 6%) than on the cell front side (about 15%). The extra area is described for hexagonal packing by:

$$A_{extra}/A_0 = \left(\frac{s^2}{8\sqrt{3}} - \frac{\pi R_C^2}{12}\right) \Big/ \frac{\pi R_C^2}{12}$$

And for rectangular packing by:

$$A_{extra}/A_0 = s^2 - \pi R_c^2 / \pi R_c^2$$

Filling in Rc=s/2 one finds 9.4% and 21.5% for hexagonal and rectangular packing respectively.

Solar concentrators

In order to use a larger part of the solar panel front area, a lens can be placed in front of each cell. In figure 17 an example of such a configuration is given.
A solar concentrator (lens) converges a collimated beam of light into a convergent cone of light. This means that the PV-cell behind a lens can be smaller than the beam of light falling onto the lens. In practice there are some limitations and effects that reduce the achievable area reduction.

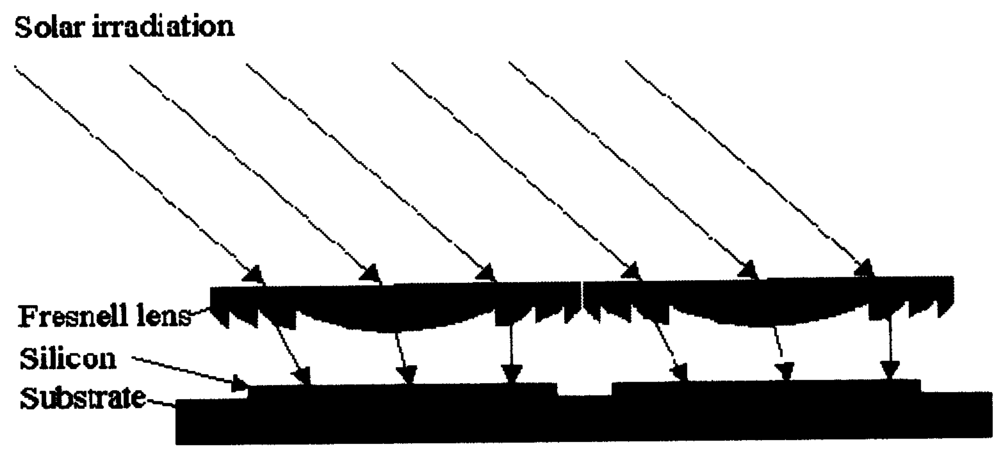


figure 17 Fresnell lens as solar concentrator

Fundamental limitation

As the direction of incidence changes, the position of the light spot on the PV-cell will change as well. The limiting rule that is valid here is the preservation of etendue. The product of size and angle of an image is constant throughout the optical system.

A solar panel should collect light over a large range of angles of incidence. (Observe a large part of the sky) This then automatically implies that the reduction of area is limited. In the extreme case where the angle of incidence varies from -90° to +90° no reduction of size can be achieved. A more realistic assumption would be to require ±45° of sky coverage. This results in a maximum achievable reduced size (diameter) by 50%. The angles of incidence are different in two directions. In the direction where the sun passes (East to West) the full angle is about 180°, whereas in the other direction (North to South) the variation over the year is about 45°. Consequently the size reduction in the North to south direction theoretically can be larger.

Losses by additional layers

Adding a layer of optics to the optical path will introduce additional losses. At each surface part of the light is reflected. The largest part of the reflected light will not fall on the PV-cell.

A typical number here is that a glass window (uncoated) reflects about 8% of the incident light at perpendicular incidence. For larger angles of incidence this number increases. Using Anti-Refrection (AR) coatings this value can be improved. What can be achieved here depends on the exact configuration and illumination.

Fresnell lens shade

In order to reduce the over thickness of the solar panel the lenses should be strong. (Low focal numbers). In general this type of lenses is thick. To reduce the lens thickness the lens surface is build up out of segments, rather than a single surface. This results in a jump of the surface at the edge of each segment. For a single angle of incidence the jumps can be aligned to have a minimum shade width on the PV-cell. Since the angle of incidence varies a lot (and even more at the back side of the lens) there will be light loss due to the jump shades.

Calculated examples
Two cases are regarded in some more detail, a first based on a back reflector and a second based on a solar concentrator. The calculations performed here are rough calculations assuming a steady state situation. To find more accurate results all the daily and annual variations should be taken into account. This results in an integral of the time dependant efficiency over a year's period.

Back reflector
For the back reflector design two configurations are regarded, the orthogonal and the hexagonal packing. For each case a simple reflector is designed and the corresponding efficiency is estimated. To find this simple design a number of back reflector designs were modelled in a optical ray tracing program. Shapes and dimension are altered to find a proper solution.
In the calculations the following assumptions are made:

- Solar cells are based on 100mm Si wafers
- Complete front and back surfaces are active. This means there is a 100mm effective
- area on front and back
- The minimum gap between the wafers is 2mm, resulting in a 102mm spacing
- 98% reflection efficiency for mirror surfaces
- Shading effect electrical connections not implemented

Orthogonal packing
For the orthogonal packing a reflector results that looks like the sketch in figure 18. The shape is based on a toroïd that is cut in half and cut out by a rectangle.

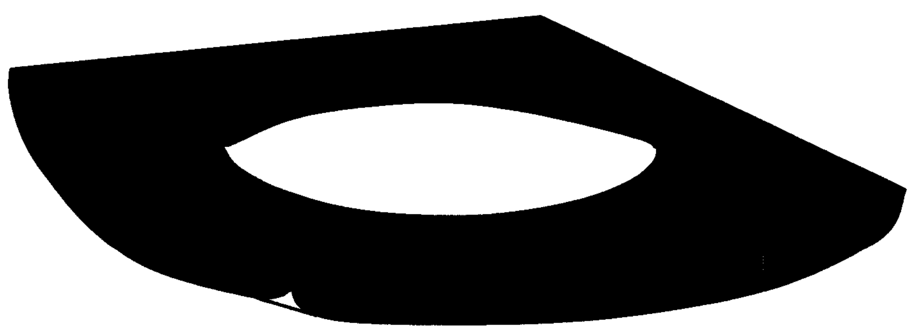


figure 18 Back reflector Author/artist impression

In the figures below (figure 19 and figure 20) the results of the ray tracing calculation are shown. The reflector is roughly a spherical reflector where a rectangular section is cut out. Dots outside the circle miss the PV-cell. Colour indicates the angle of incidence. Blue is 0°, green is 20° and orange is 40°.

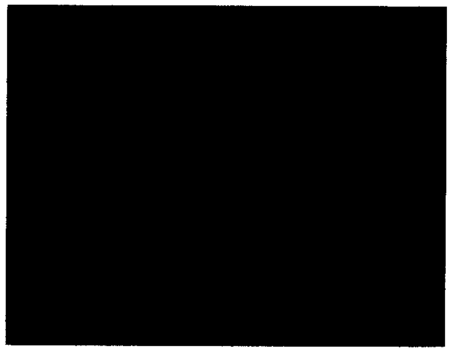


figure 19 3D-view of a single cell in ZEMAX model

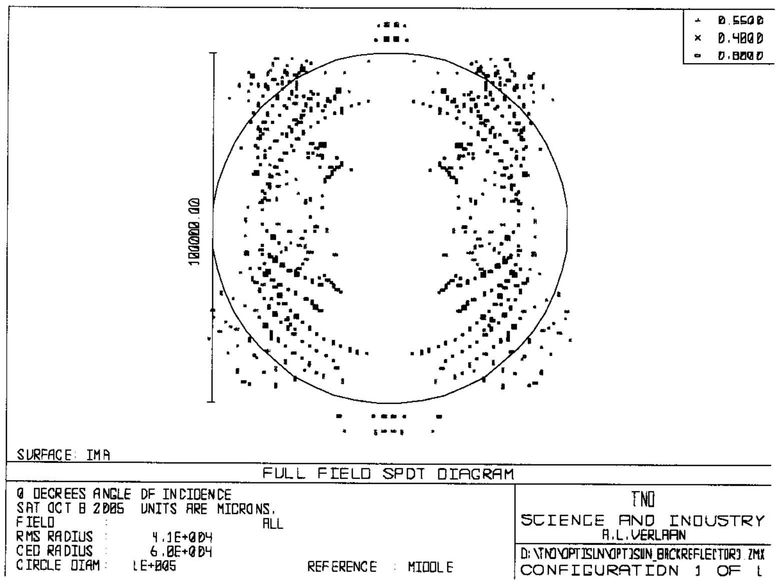


figure 20 Rays of light falling on the PV-cell backside.

In figure 19 the hollow reflector is shown. A similar analysis can be performed using a solid reflector. figure 20 shows where the light falls on the PV-cell backside. Here only rays of light are considered that fall in to the gap between the PV-cell and the edge of the cell. As can be seen the collection efficiency decreases with the angle of incidence. The exact numbers depend on the design but the trend will remain. There is some space for improvement by further optimisation of the reflector shape.

To find the extra collected energy the extra area is multiplied with the relative PV-cell efficiency and the back reflector efficiency.
The results are given in the table below (table 2).

table 2 Overall extra power as a function of angle of incidence.

Angle of incidence	Missing rays collected	Overall extra power
0	100%	12,5%
20	84%	10,5%
40	60%	7,5%

Repeating this exercise for hexagonal packing yields values that are lower because the extra area is a lot smaller. This is despite the increase in the missing rays collected numbers.

Angle of incidence	Missing rays collected	Overall extra power
0	100%	5.7%
20	98%	5.6%
40	87%	4.9%

Solar concentrator

The solar concentrator used here is a PMMA Fresnell lens placed in front of the PV-cell. See figure 17. The lens focuses the light at a distance behind the PV-cell. This means that the spot is only reduced a bit.

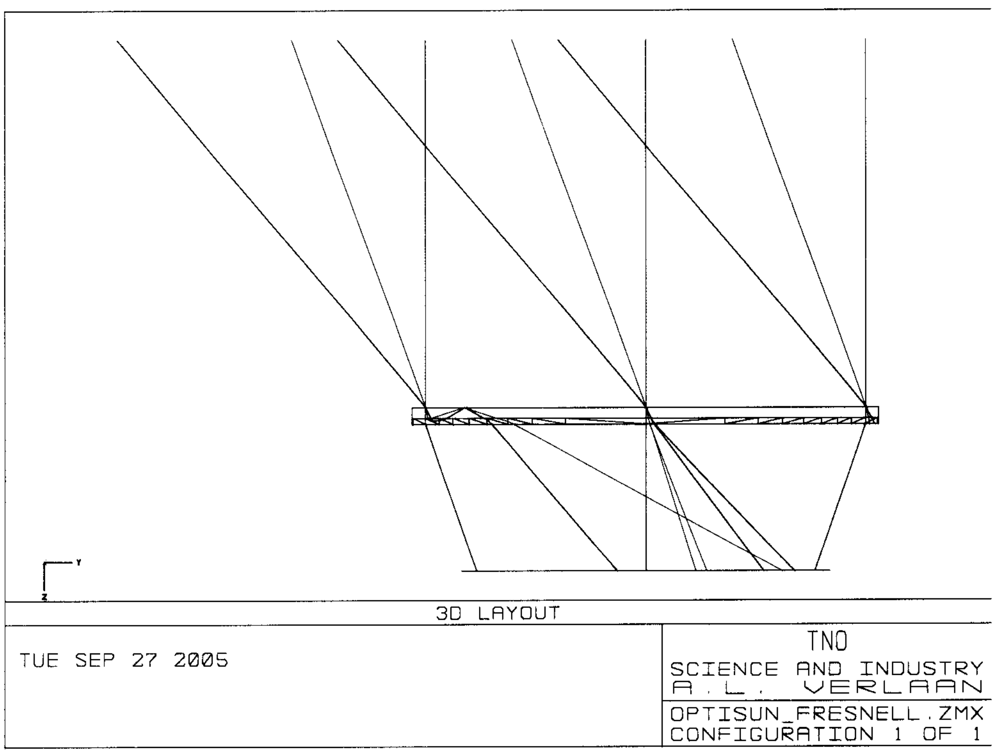


figure 21 Side view of Solar Cell with PMMA Fresnell lens

As can be observed in figure 21 and figure 22 the design works well for perpendicular incidence (Bleu rays and dots). As the angle of incidence increases more light will miss the PV-cell due to the shift of the light spot. Here a balance must be found between the lens focal length and the distance between the PV-cell and the lens. The effects that are regarded are:

- Spot size due to position wrt. Focus. There are two extremes here. Placing the PV-cell against the lens, there's no reduction of spot size, whereas placing the PV-cell in focus will result in a very small light spot. In between the relation is linear.
- Shift of spot position due to variation of angle of incidence (and focal length) By changing the angle of incidence the spot position on the PV-cell will shift. The spot centre is located at the position where a ray through the lens centre hits the PV-cell. This relation means that one would prefer a small distance between the lens and the PV-cell.
- Fresnell lens shading due to light angles at the back side of the lens. As the angles at which the light refracts at the rear side of the lens increases the lens shading will increase. This means a larger part of the light will fall on the lens facets, rather than on the back surface. As a result the lens transmission is reduced and thus the PV-cell efficiency. Consequently one would prefer a large distance between the lens and the PV-cell.

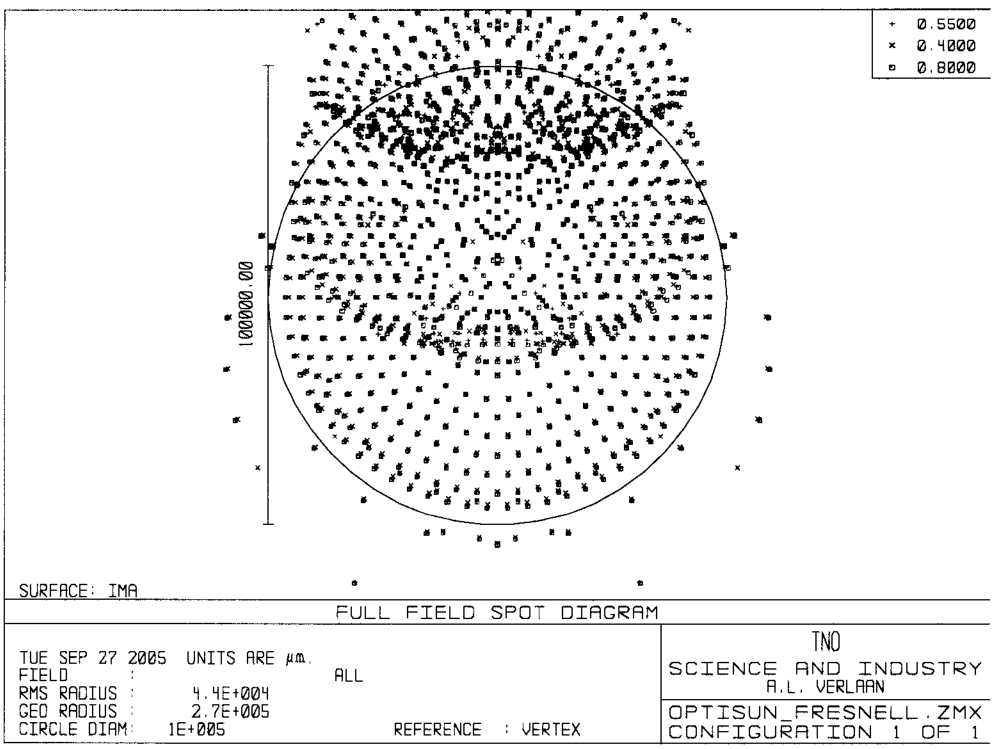


figure 22 Light spot on the solar cell for 0, 20 and 45 degrees angle of incidence

As a result of the counteracting requirements, there is no good configuration possible. Adding a Fresnell lens in front of closely packed PV-cell array that is used for a large range of angles of incidence will not increase the overall efficiency.

Conclusion:
Adding a back reflector results in an increased efficiency of the solar panel with respect to the case where PV-cells with only active front sides are used.

- For orthogonal packing the achievable efficiency gain is about 10% (assuming 6%conversion efficiency for the PV-cell back side)
- For hexagonal packing the achievable gain is about 5.5%
  - Back reflectors can either be hollow or solid
  - Back reflector design is not very critical
  - Back reflector can be optimised somewhat
  - Adding a Fresnell lens in front of a closely packed PV-cell array will not increase the efficiency.
  - Fresnell lenses only work well where the angle of incidence in limited (tracking) or where the lenses can be made large with respect to the PV-cell. (More W/cell but lower W/m^2).

3.1.2 Subtask 3.1.3

Consider the environmental, chemical and thermal conditions that can be experienced by the component and select a material from those identified in task 3.1.1 that will retain its light transmission properties and other required properties for the expected service life of the component.

When building solar panels more practical considerations are introduced. For example the solar panel thickness. In a theoretical case the thickness could be a meter, where practically a few centimetres would be the limit.
Other practical considerations can be:
Dimensions. What is easy to handle in a factory and by a customer? Here the solar cells are assumed to be 4inch discs and the panel thickness should not exceed 5cm.
Materials. Can the materials be handled and what is their price-performance relation? Here plastic optics comes into sight. Although the optical properties might not be as good as those of optical glasses the costs of plastic lenses are substantially lower and they can be made in any required shape (which is not the case for glass optics).
Effect of design change on handling and interfacing. Modification of the design could results in a changed customer interface. Can that be handled?

3.2 Reflector development

Objective: Develop a system for reflecting the light onto the photovoltaic cells.

Sub-task:

3.2.1 Select a coating for the material identified in Task 1.1 that will reflect the maximum amount of light from the transmissive material onto the photovoltaic cells, considering that the reflecting surface will be in contact with the transmissive material.

3.2.2 Develop a method for the application for the selected coating, ensuring that the reflecting surface retains it highly reflective qualities.

3.2.1 *Selection of material of backlight reflector.*

In Task 3.1 it was defined that the backlight reflector is made out of a plastic support with a reflective coating on top of this plastic support. The aim of task 3.2.1 is the selection of the material of the reflector coating.

The two materials mainly used as reflectors are aluminum and silver. Aluminum is used predominantly, because it is relatively cheap, easy to evaporate thermally and has a high reflectivity (92 %). Silver has an even higher reflectivity (96%), but the costs are much higher and the number of coating deposition techniques is limited. Both silver and aluminum are prone to environmental attack, aluminum by water and basic solutions, silver by sulphur containing contaminants. In both cases a protective coating is necessary to prevent degradation. Just to prevent chemical attack very thin layers of transparent material (below 100 nm) produced by plasma polymerization, evaporation or sputtering of metal oxides (SiO_2, TiO_2, Al_2O_3) is sufficient.

Another type of material that is used as reflectors are optical stacks of silica and titania (e.g. SiO_2/TiO_2). By building up 6-8 layers of silica and titania with various thicknesses and alternating diffraction indices a reflectivity of more than 85 % can be obtained.

All the three commercial used reflector materials (SiO_2/TiO_2, Al and Ag) have good reflection properties. Silver (Ag) has the best reflection properties, but the difference with Al is small and additional reflection obtained is outweighed by the additional costs. In close cooperation with the Optisun partners TNO selected Al as reflector material in the back-light module, because it is relatively cheap, easy to deposit on plastic module by PVD and it has a high reflectivity (92%).

3.2.2 *Development of application method of the Al reflector layer.*

After discussing with the Optisun partners two main routes have been selected for the preparation of the back-light module. The first route is the back reflector shaped out of plastic and then an aluminum coating deposited on the surface of the shaped plastic (3D-coating). The second route is a plastic plate coated with aluminum (2-D coating) and then the back light reflector is shaped out of the aluminum coated plastic. The second route is easier and less costly in Al-coating (e.g. packaging laminates, alanod high reflection, Corus protac) but some damage will inevitably happen while shaping, leading to less-reflective spots. Shaping must be done in such a way that extension is minimized. Shaping with the coating inside is preferred for less open spots occur compared to shaping with the coating outside.

Based on the thermal stability of the plastic support, PVD (thermal evaporation or magnetron sputtering) and galvanic wet-chemical processes are the most preferred coating processes. Based on the price, commercial availability and optical quality vacuum metallization by PVD has been selected. Vacuum metallization by PVD (is a line-of-sight process within a specific volume). The objects have to fit inside the equipment, and manipulation is necessary to get optimum exposure to the vapor source. In prototype manufacturing probably the shaping is first, followed by the coating. Thus the prototype will be like a "normal" reflector. Coating is industrially performed in batch reactors and charged per batch. The size of the batch depends on the number of objects that fit the chamber. Price of a batch will vary between 300 and 3000 EUR, depending on the type of coating (single layer by evaporation, multiple layers by sputtering). In addition, fixture tools will have to be manufactured, and some test runs are needed to optimize the processing. Maximum size depends on the mounting in the vacuum equipment. In batch coaters with a chamber diameter around 1 m the maximum width of the object is 20 cm. For chamber diameters above 1.3 m the width is around 30 cm. In 3 m diameter chambers the width may be 50 cm. In al case the maximum height is a bit smaller then the sources length (for targets the target length minus 10 cm). The availability of coaters of Al onto plastic is large. Web coaters are available in all shapes and sizes. Sidrabe (Location:Riga) has designed a web coater for 1 million m^2/yr to coat PET with a stack of sputtered aluminum, evaporated aluminum and a 2 layer optical stack with a coating cost of 3 EUR/ m^2.

For web coating, PET is mostly the preferred substrate. PMMA is a preferred optical material, but because of its UV sensitivity can only be treated by "dark" (without plasma) processes. The Al-coating onto PET (preparation route 1 and 2) will be prepared by Heat & Surface Treatment (H&ST). for the prototype (see task 3.4). Commercial plastic (polystyrene) substrates with an Al reflective coating will also be used in preparation route 2.

3.3 *Design of the backlight reflector*

Objective: Design a backlight system for use with a single photovoltaic cell module.

Sub-task:
3.3.1 Design the light collection portion of the backlight module to capture the maximum amount of incident light that would otherwise be unavailable for conversion into power, taking the environmental conditions and the effects of dirt and water into consideration.
3.3.2 Design the arrangement of photovoltaic cell module, transmissive material and reflective surfaces to facilitate maximum light delivery to the cells, taking the environmental conditions and the effects of dirt and water into consideration.

Hollow and dense back light reflectors
In Figure 17 the principle of the back light reflector is shown. The "empty space" between the round cells is not-used/wasted on the PV module. To utilize as much as possible of the sun-irradiation falling on this "empty space", the space could be filled out by plastic, which should transfer the light to the rear side of the solar cell and here generate additional solar power. The back light module brings light from "the empty space" (plastic between the PV-cells) to the rear-side of the PV-cell.

The shape of the back-light module is discussed in detail in the 12 month report. TNO has defined two main back light module designs: 1) hollow, 2) solid. In figure 23 the both designs are shown.

(a) (b)

figure 23 Hollow (a) and solid (b) backlight modules.

In case of the solid back-light module the solar light passes through the plastic and there is only one air/plastic interface present. In case of the hollow back-light module the solar light passes mainly through the air and there are two air/glass interfaces present. These two interfaces in stead of one interface is the main reason that the optical efficiency of the hollow back-light module is about 10 % lower than that of the solid back light module.
The disadvantages of the solid back light module in comparison to the hollow back light module is the weight of the module and the extra costs of the material. Preliminary calculations show that the economical efficiency of a hollow back light modules is about 10-30 % higher than that of a solid back light modules.

In the Optisun meeting of June 2006 it was decided to prepare hollow and solid back light modules.

3.4 *Development of prototype backlight module.*

Objective: Build a prototype backlight system

Sub-task:
3.4.1 Design and manufacture an injection moulding tool to produce the transmission component. Mould components that have the required optical properties.
3.4.2 Using the application method designed in Task 1.2, apply the reflective coating to the required surfaces of the transmissive material to produce surfaces that reflect at least 90% of the transmitted light.
3.4.3 Using the design developed in Task 3.3, assemble a prototype backlight module to enable further testing of its properties in Task 4.5

This paragraph is divided in two parts. In the first part of the paragraph the single-cell unit of the solid back light module is discussed, in the second part the upscaled four-cell unit of the hollow and solid backlight module are discussed.

One-cell unit
Solid
Based on the information of Task 3.2 (Materials and Manufacture) and Task 3.3 (design) a single-cell prototype solid back light module was prepared by moulding with polyurethane. After preparation of the back light module the polyurethane shape was

coated with an aluminum coating by PVD. The preparation of this single-cell prototype solid backlight module was successful and in close cooperation with the Optisun partners it was decided to upscale to a four-cell unit.

Hollow
The hollow single-cell prototype back light module has not been prepared. In close cooperation with the Optisun partners it was decided to prepare directly four-cell hollow prototype backlight modules.

Four-cell unit

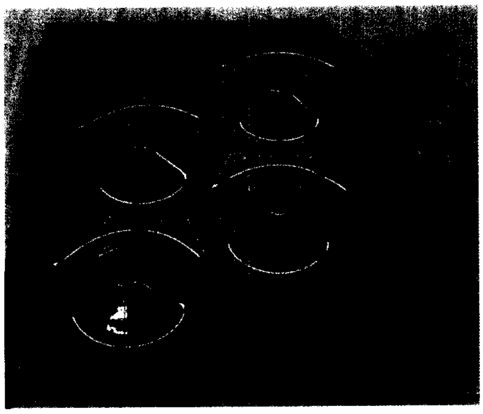
Solid
Four single-cell solid prototype backlight modules have been prepared (see above) and have been stuck together. The mould of the single cell module has been used for the preparation of the four-cell unit. A picture of this four-cell prototype solid back light module is shown in figure 24.

figure 24 Photo of four-cell prototype solid backlight module.

A four-cell solid backlight module has been delivered to optisun partners Pera. A second four-cell solid unit has been used for the development for the hollow four-cell back light module and a third one has been coated with an aluminum coating by PVD.
In the Optisun meeting of September 2006 (Denmark) it was decided to stop the work on the dense back light modules, due to the weight and the material costs of the module in comparison to the hollow back light module.

Hollow
After discussing with the Optisun partners two preparation routes have been selected for the preparation of the hollow back-light module. The first route is the back reflector shaped out of plastic and then an aluminum coating deposited on the surface of the shaped plastic (3D-coating). The second route is a plastic plate coated with aluminum (2-D coating) and then the back light reflector is shaped out of the aluminum coated plastic. For both routes the form of the four unit proto type dense back light module has been used as mould/negative.

Route I
In the first step a PET plate (Bayer Sheet Europe) was vacuum formed in the desired shape (figure 25a). The shaped PET plate was coated with an aluminum coating by PVD at Heat & Surface Treatment (H&ST). (figure 25b).



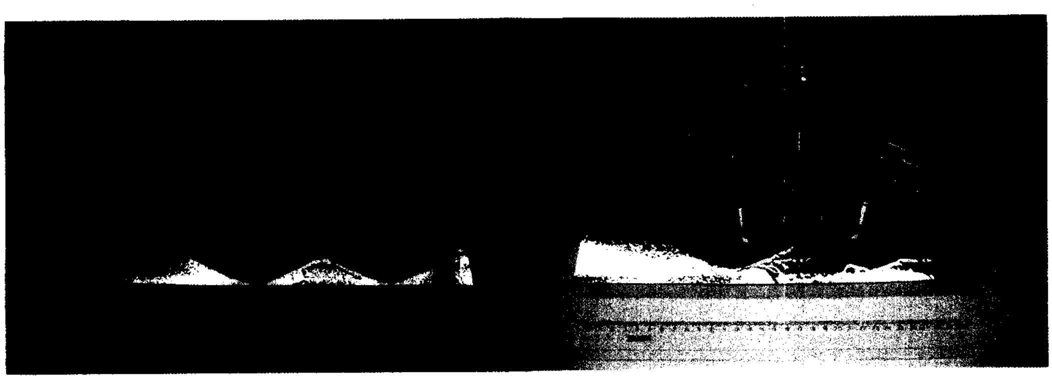
(a)

(b)

figure 25 Uncoated (a) and Al-coated (b) four-unit prototype hollow backlight module by routeI

In total six four-cell route 1 modules have been prepared. Four four-cell route I backlight modules have been sent to Pera, Allsun and Solartec for further testing (see Task 3.5).

Route II
Commercial Al coated polystyrene (Bayer Sheet Europe) plates have been vacuum formed in one-step in the desired shape. In figure 26a and figure 26b samples of batch 1 and 2 are shown. In the first batch we were not successful to obtain the desired shape. In the second batch after a few optimizations in the vacuum forming we were successful by obtaining the desired and designed shape. In total nine modules by route II have been prepared. Four-cell route II backlight modules have been sent to Pera, Allsun and Solartec for further testing (see Task 3.5).



(a) (b)

figure 26 Four-cell prototype hollow backlight module by route II.

3.5 *Test of backlight module efficiency*

Objective: Design a backlight system for use with a single photovoltaic cell module

Sub tasks:

3.5.1 Perform simultaneous comparative tests between the developed systems using the backlight module and the same photovoltaic system without the backlight module to access the improved efficiency under real external conditions for periods up to 4 days.

3.5.2 Optimise backlight module to meet target operational performance of 1-2% improvement in efficiency without overheating the micro inverter.

As mentioned in task 3.4 the 5 four-cell prototype hollow backlight module prepared by TNO have been sent to Pera, Allsun and Solartec for further testing. There was not enough time and capacity in the project for further testing of the four-cell prototype hollow backlight modules.

4 WP4 Integration and industrial trials

4.1 Task 4.1 Integration Bonding of Micro Inverter and Solar Cell

Objective: Integration bonding of micro-inverter and subdivided solar cells.

Sub tasks:
4.1.1 Investigate methods of integration based on adhesives and soldering interconnection and select most suitable method.
4.1.2 Develop thermal mechanical modelling of the inverter / solar cell interconnection structure to predict the reliability of the bonding.
4.1.3 Optimise the interconnection process between the inverter and the solar cell with the total module interconnection system.
4.1.4 Construct prototype module on lab-scale with the chosen interconnection structure to prove its performance and reliability.

4.1.1 *Sub-task 4.1.1 Investigate methods of integration based on adhesives and soldering interconnection and select most suitable method.*

In work package 4 the separate modules of segmented solar cell, micro inverter and backlight module were to be combined to form a prototype of the OPTISUN solar module.
In sub task 4.1.1 the interconnection of the separate solar cell parts was studied and an interconnection type was chosen.

The two interconnection methods investigated are soldering (using a lead free solder) and gluing (using electrical conductive adhesives).
First of all the final design of the cell was chosen as described in task 1.3. As a result of the investigation on the cell dividing two possible solutions were defined:
1. using etching paste,
2. using a water laser jet or laser sublimation to divide the cell in eight separate parts.

The interconnection solution had to be compatible with both options.

The common way to interconnect solar cells nowadays is (lead)soldering, a well known interconnection method with a large service record. Due to the lead free legislation, lead containing soldered interconnections will finally have to be excluded from being used in solar modules. Many lead free alternatives have a much higher melting point an will therefore be not applicable in solar applications. There are alternatives with a lower melting point, even as low as the laminating temperature, like SnBi-alloys. But since the interconnection is made on silver contacts, the silver on the contact will dissolve within the solder alloy and thus creating bare copper surfaces to be oxidized. Adding silver to the solder alloy would prevent the silver on the contacts to dissolve into the alloy but would also raise the melting temperature of the solder. The lifetime of lead free soldered interconnections within a solar module are not known yet. Also in other application there is not much knowledge on the behaviour of lead free soldered interconnects in time.

The alternative could be the use of electrical conductive adhesives. This type of adhesives consists for 80wt% of silver flakes. It has already been stated that, if the conducting surface is sufficient, the electrical properties of the silver filled adhesive will be comparable to that of soldered interconnects. In the present lay out, designed by Solartec, the interconnection areas on both front- and rear side of the cell (for they are equal) will be more than sufficient (figure 27). Introducing isotropic conductive adhesive (ICA) within the solar module manufacture will be fairly easy. The soldering equipment can be removed from the production line. An extra print step will be necessary to deliver the ICA on the contacts but this is a well known process. For curing the adhesive the (final) lamination step is used. Thus no new process step and corresponding equipment has to be implemented in the production line.
As with lead free soldered interconnects, also for these ICA interconnections the lifetime behavior is not known yet.

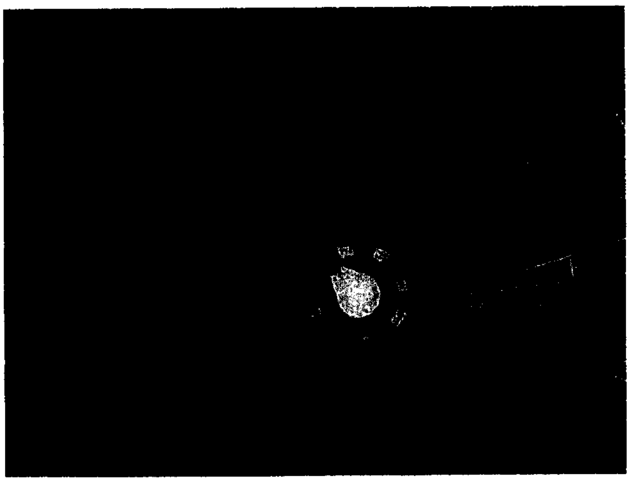


figure 27 Contacts on an Optisun solar cell, collected around the hole in the centre of the cell.

4.1.2 *Sub-task 4.1.2 Develop thermal mechanical modeling of the inverter / solar cell interconnection structure to predict the reliability of the bonding.*

One of the main advantages of using electrical conductive adhesives is that the final curing step needed for the ICA can be combined with the already implemented lamination step to cure the EVA (Ethylene-Vinyl Acetate). The ICA will have to be tuned to fit to the specific lamination parameters. The only heating step throughout the module-production will be the lamination process.
The thermal mechanical stresses introduced to the cell by the interconnection between cell and inverter through this temperature step will be low. Since each cell will be connected to one micro-inverter, no extreme thermal mechanical stresses are expected. Each cell will be glued to a carrier plate (e.g. glass) using EVA, but this will not induce stress either for the cells are not connected to each other by means of tabs and therefore will be able to move freely with the extending glass plate.
Depending on the way the back reflector will be mounted to the OPTISUN solar module thermal mechanical stresses might become an issue. Thermal mechanical modelling will directly give insight into the possible effects on stress in the total module.

4.1.3 Sub-task 4.1.3 Optimise the interconnection process between the inverter and the solar cell with the total module interconnection system.

Dividing a cell in eight equal pie-parts is only possible by removing the centre of the cell first. The stress on the "central" edge of a pie-piece would very easily cause it to undefined breaking, leaving an unknown active cell surface. To prevent the cell pie part from this undefined breaking, the centre of the round cell was removed first. By removing the middle of the cell, an extra interconnection possibility is created. This centre hole can easily be used to position the inverter and to make the interconnection between the separate cell parts on one end and the interconnection between cell parts and inverter on the other.

An interconnection foil was designed as shown in figure 28. On the left one of the first designs is shown. The length of the contacts in the middle were not sufficient to cover the distance between front side foil and back side foil with in between the solar cell parts. Those contacts were lengthened and the final result is shown in the right drawing in figure 28.

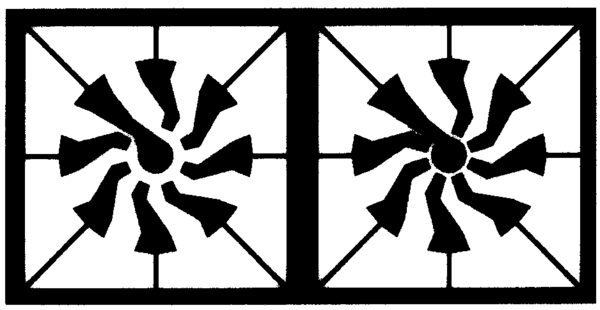


figure 28 Layout of the interconnection foil to make the electrical connection between all cell parts and inverter.

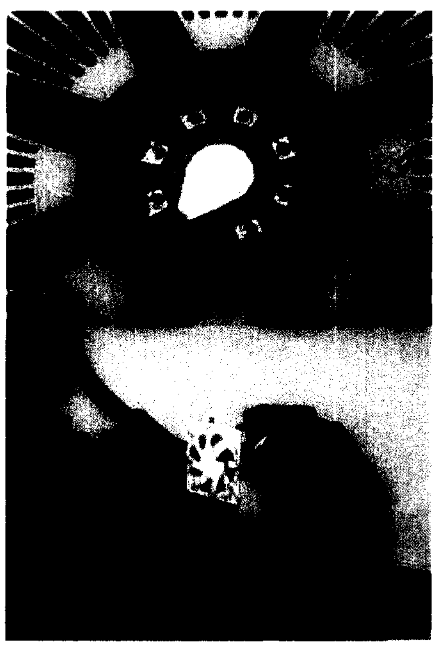
To prevent the foil from short-circuiting the cell, an isolating lacquer was used on both foils as shown in figure 29. The inner circle of the cell was also isolated using the same lacquer. The centre contact, used for interconnecting the inverter, was partly cut loose from the back contact foil. This part has to be fold back to make the interconnection between front side foil, back side foil and inverter possible.

figure 29 Interconnection foil without and with UV cured isolating lac.

Two possible solutions in overcoming the distance between both interconnection foils due to the cell-thickness were presented:

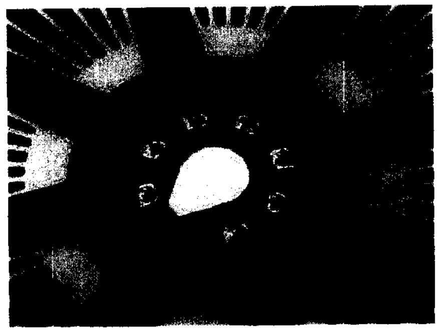
a) use of spacers
b) pre-formed foils

a) Use of spacers,
   spacers are often used in soldered interconnections to overcome a certain distance in height and for the same reason they were applied here. In figure 30 this principle is shown.



Apply ICA on both foils.

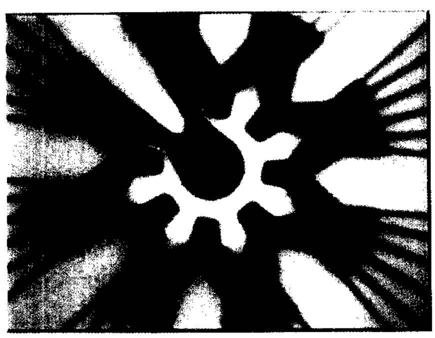
Position and place foil on front side of cell and turn cell over.



Place spacers in the ICA on foil to foil contacts.

Place opposite foil with ICA.

Put a little pressure on the heap.



Cure adhesive in oven: X-ray view on final interconnection.

figure 30 Process of using spacers to overcome distance between interconnection foils due to cell thickness.

b) pre-formed foils with notched contacts so they can cover the cell thickness.
In figure 31 the foil to foil contacts are notched. The separate contact fingers can now be bent towards each other during the interconnection process whereas the isolating lacquer will prevent the foil from short circuiting with the solar cell parts in the middle of the cell.

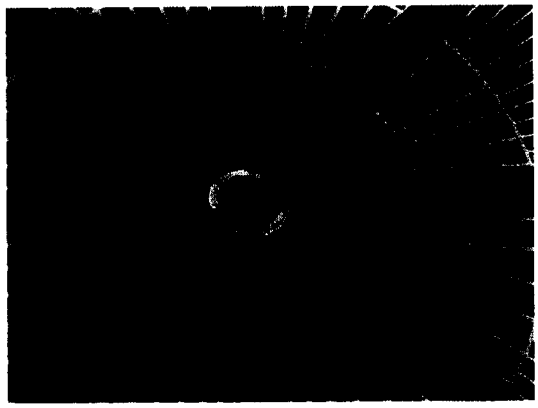


figure 31 A back contact interconnection foil with notched foil to foil contacts.

The foil with isolating lacquer can also be pre-formed using a template before the ICA is applied (figure 32). The pre-formed foil with the adhesive on the foil contacts will be positioned on both sides of the cell. The foil to foil contacts will directly put the cell segments in series.

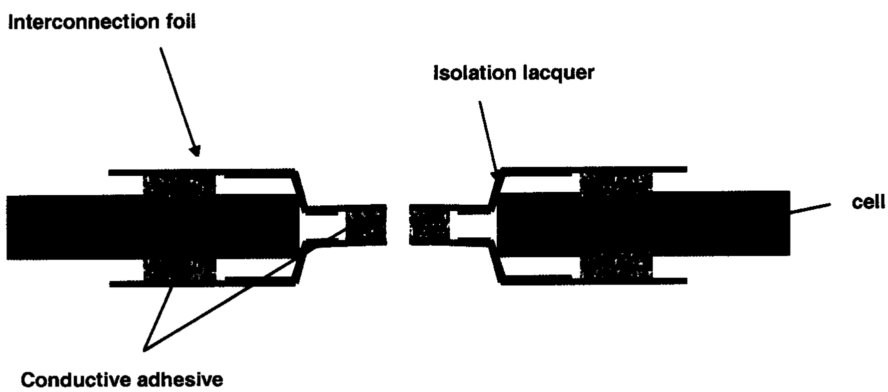


figure 32 Cross-section of interconnection using preformed interconnection foils.

In both ways, the final electrical interconnection between the cell segments (whether they are separated by laser or by a chemical etching process) will be made.

Conclusion:
The preformed interconnection foils will cover the problems we encountered using 2D foils which could not overcome the height of the solar cell. Unfortunately it was not tested within the Optisun project.

4.2 Construction of Prototype PV Module

Objective: To develop schematic concept designs integrating, subdivided solar cells, cell integrated micro inverter and backlight module to form a fully functioning PV system prototype.

Sub tasks:

4.2.1 Manufacturing concept designs will be prepared based on a detailed understanding of the process developed in the initial work packages.

4.2.2 An integrated OPTISUN system will be constructed integrating the subdivided solar cells, cell integrated micro inverter and backlight module for real applications and industrial trials.

4.2.1 *Sub-task 4.2.1: Manufacturing concept designs will be prepared based on a detailed understanding of the process developed in the initial work packages.*

The interconnection of segmented solar cells by using electrical conductive adhesive can be realized without subsequently changing the production process. The curing of the silver filled adhesives is done during the lamination cycle at which the EVA within the module is laminated and cured (step 4 in figure 34). The optimal adhesive has to be chosen, or even fitted, after the process parameters of the specific lamination process. A within TNO developed and well known procedure

A point of attention will be the covering of the inverter-contacts (also step 4 in figure 33). The inverter will either be mounted on the solar cell or will also be covered in EVA after lamination. The electrical interconnections will have to be free of EVA material. If the inverter is not connected to the cell before the laminating process, the inverter contacts on the interconnection foil will have to be protected.

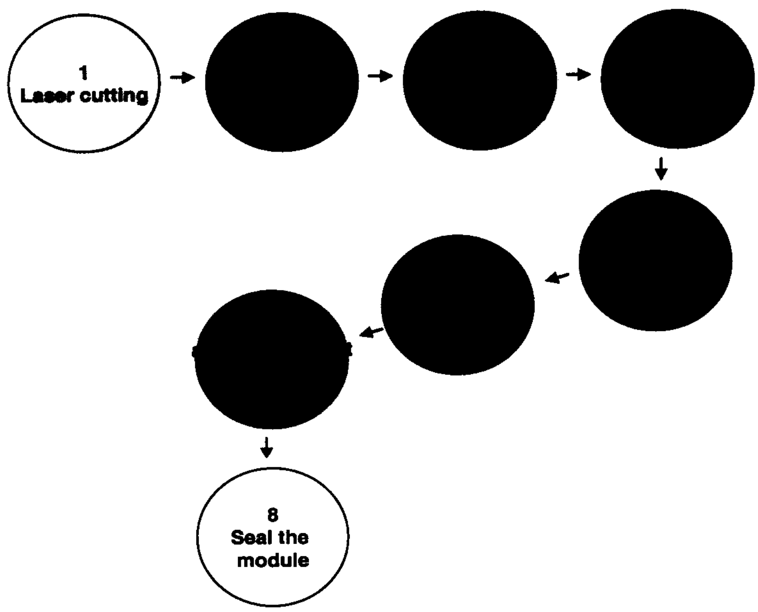


figure 33 Schematic of possible production process steps (from cell to module).

Conclusion:

The interconnection between the contacts on the foil and the contacts on the cell segments is made in the centre of the solar cell using conductive adhesive which can be cured within the lamination cycle. This lamination cycle is part of the module production process and does not need any additional steps or machinery. Lead free solder alloys have also been tested, but not optimised. The idea was to use again the lamination step in the module production process to melt the solder and make the interconnection.

4.2.2 *Sub-task 4.2.2 An integrated OPTISUN system will be constructed integrating the subdivided solar cells, cell integrated micro inverter and backlight module for real applications and industrial trials.*

The separate parts of the modules were manufactured. The total module however was not completely tested.

Conclusion:
A prototype off all separate modules has been made, but the final integration of all modules has not been build. There was not enough time in the project.

5 Conclusions

Subdivided solar cells.

1. The following laser-types have been tested: Water jet Technology from TrennTek (Germany), Abrasive Water jet Technology from TrennTek (Germany), Laser cutting Technology from TNO (the Netherlands), Laser sublimating Technology from TRUMPF laser (Germany) and Laser Microjet® Technology from SYNOVA (Switzerland). Based on the research of the Optisun project, it is decided to use the laser jet to subdivide the cells.

Development backlight reflector

2. The EU Optisun project has shown that the usage of the backside of the PV cell and so more efficient use of Si/efficiency of the solar cell can be obtained by a back light module.
3. Optical studies show that a "dense" back-light module has a higher optical efficiency than a hollow back light module. The disadvantage of the dense back light module in comparison to the hollow back light module is the weight of the module and the extra costs for the material. Back light modules (dense and hollow) have been prepared based on this optimal shape. Based on the research in Optisun the hollow back-light modules were selected for the high efficiency PV module of Optisun.
4. All three commercial used reflector materials (SiO_2/TiO_2, Al and Ag) have good reflection properties. Silver (Ag) has the best reflection properties, but the difference with Aluminium (Al) is small and additional reflection obtained is out weighed by the additional costs. TNO selected Al as reflector material in the back-light module, because it is relatively cheap, easy to deposit on plastic module by PVD and has a high reflectivity (92%).
5. In total six four-unit proto type hollow back light modules by route 1 and nine four-unit proto type hollow back light modules by route 2 have been prepared and sent to the Optisun partners. In the Optisun project there was not enough time and capacity to test the back light modules prepared by TNO.
6. During the project the one-unit proto type hollow back light module has been up scaled to a four-unit proto type hollow back light module.

Intergration (serial/parallel connection)

7. The segmentation of the round solar cells led to the mechanical need of a hole in the middle of the cell. This hole is used to lead the collected current of each individual cell segment through an interconnection foil to the micro inverter. The interconnection between the contacts on the foil and the contacts on the cell segments is made using conductive adhesive which can be cured within the lamination cycle. This is part of the module production process and does not need any additional steps or machinery.

6 Signature

Eindhoven, April 2007

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