ADVANCED CRYSTALLINE SILICON SOLAR CELL DESIGNS

(ACE Designs)

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CONTENTS

1. Abstract

Keywords: solar cells, crystalline silicon, back-contact, advanced solar cell technology.

The objective of this project is: the development of at least one advanced, crystalline silicon solar cell technology with the following characteristics:

- Better commercialization aspects than the standard technology.
- A design that can be easily used on larger substrates for large scale power production
- Higher efficiencies than standard crystalline silicon solar cells made by the same technology.

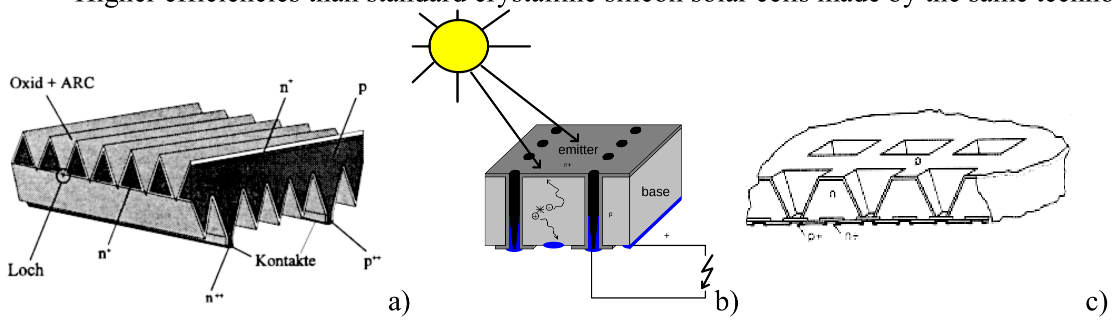

Figure: Prototype back-contact solar cell designs: POWER cell, EWT cell, WAFFLE.

The project was divided into three main tasks. First the different solar cell designs were discussed and simulated by computer programmes. The common problems like increased recombination, shunting as well as series resistance problems were examined. In the second phase the solar cells were manufactured according to the cell designs as defined in phase one. The cell process parameters were optimised to testify the potential of the designs. In the third phase, concepts were developed to improve laboratory-scale methods to a large-scale production level and a description of a complete rear contact, crystalline silicon solar cell technology from starting material up to module design was worked out.

Many different wafer treatment technologies such as laser cutting, plasma etching and mechanical wafer treatments were successfully tested. Sixteen different types of back contact solar cell prototypes were made in the first project phase, from which nine classes of cells were selected for further development in the second phase. At the end of the second phase an assessment task was performed to select the cell type showing the best chances for future commercialisation. As the assessment showed similar results for different technologies, the selection was based upon the interest of one of the industrial partners. The work on other promising rear contacted cell concepts was extended.

After the successful completion of the third phase the overall project resulted in improved crystalline silicon solar cell technologies with the following characteristics: all-back-contact cells with improved efficiency and the prospect for a better cost/Wp compared to ‘standard’ crystalline silicon solar cell technology.

From these cells prototypes of solar modules were produced by module technologies that take into account the special characteristic of the rear side contacts. Based on the competitive cost/Wp ratio and the improved appearance of the modules an exploitation of the results by replacing existing technology in future solar cell production lines is expected.

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3. Objectives and strategic aspects

It is commonly agreed by the European Union member states that the use of renewable energies, and in particular photovoltaics, is one of the most attractive solutions to overcome the problems caused by conventional energy sources.

To improve the position of the European PV industry a strategic action plan with recommendations for the development of PV up to the year 2010 was developed and published by the European Commission, Directorate-General for Energy in 1994. In this action plan the further development of crystalline silicon solar cell technology is seen as the major issue. To meet the desired production efficiency and cost targets a development from the state-of-the-art solar cell with 100 cm^2 (in 1994) to a large area solar cell with improved efficiency was outlined. By looking back at the development the first step going from 100 cm^2 cell area to 156 cm^2 is nowadays common technology on an industrial level. This is mainly due to the effect that this step could be performed without major changes in cell design and production technology.

In comparison with the past, the next step in an advanced solar cell fabrication will lead to an even larger substrate size. This asks for a substantially different technology, if it is to be accomplished in parallel with an efficiency increase. Most probably the standard solar cell concept is not capable to deal with the currents produced in these types of solar cells, which makes the development of a next generation of solar cells necessary. According to the planning, which is outlined in this strategy, a new technology has to be introduced in the year 2001 based on large substrates with the potential of a future steady increase in efficiency.

The development of this new type of advanced crystalline silicon solar cells is the major objective of this proposal.

The need for such a development is felt by all industries and research organisations working in the field of crystalline silicon solar cells, although the individual approach differs. There are a few ideas developed in different places, which all have in common that they leave the standard solar cell structure with a planar p-n junction behind and make use of two- or three-dimensional structures. The consortium of partners as described hereafter clearly sees the needs for this kind of development but also recognises that a co-operation is crucial to speed up the development and to come to a next generation crystalline silicon solar cell technology as fast as possible.

The overall objective therefore is the development of at least one advanced, crystalline silicon solar cell technology with:

- better commercialisation aspects than the standard technology (lower cost/Wp, high level of automation)
- a design that can be easily used on larger substrates for large scale power production
- higher efficiencies than standard crystalline silicon solar cells made by comparable technology.

The achievements of these objectives will directly strengthen the position of the partners in this project by:

- having a highly efficient, high-technology crystalline silicon solar cell available, which is superior to the state-of-the-art cell type
- having a technology with a high level of automation, which assures a future PV production in Europe
- meeting the cost targets as outlined in the strategic action plan for PV in Europe

A successful completion of this project results in a complete next-generation crystalline silicon solar cell technology, with improved commercialisation possibilities. As the extra technology needed for an introduction is limited to a few process steps only, it can be expected that this new technology can be introduced in an industrial production on a short term after completion of the project.

4. Technical description

4.1 The beauty of rear-contacted solar cells

Rear contacted crystalline silicon solar cells are very attractive for multiple reasons:

- In dependence of the concept, the front side metallisation is either completely removed (emitter wrap-through concepts) or almost invisible as the large area busbars are located on the backside (metallisation wrap-through concepts). Both concepts lead to a homogenous appearance of the cell in the module without highly reflective areas.
- The efficiency of rear contacted solar cells is higher than that of comparable standard cells. The shadow loss is lower by the reduced front metal coverage. In the case of rear-side emitters the extra collection on the back is advantageous especially for low diffusion length material. These effects resulted in different cell technologies with efficiencies larger than 16% with thick film, screen printed contacts as well as electroless plated contacts.
- The interconnection can be done on a conducting back plane in the module. This opens the possibility to automate cell interconnection by pick-and-place units.
- As interconnection and busbars of the cells are located on the rear side, larger conductive areas become possible. This allows the development of cell concepts, which are applicable for virtually any wafer size. Such a technology would overcome area and total current limitations existing with today's crystalline silicon solar cells.
- In principle these cell concepts could be implemented in industrial production with no or only minor changes to manufacturing equipment.

In summary the development of cost-efficient, rear contacted solar cell technologies can substantially support the broader use of solar electricity in Europe.

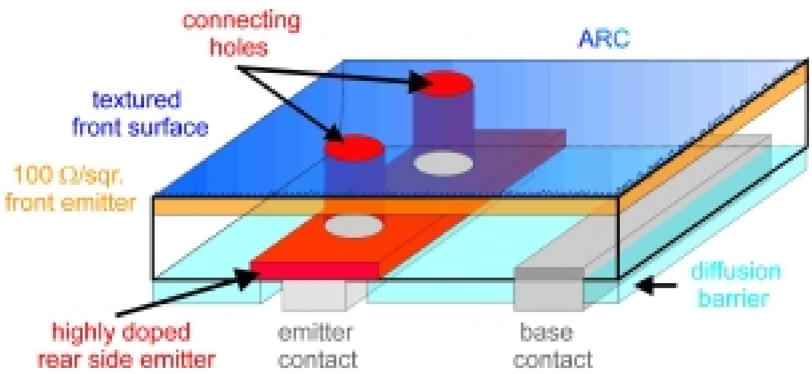


Figure 1: Schematic drawing of a screen printed low-cost EWT cell with the optimised cell design.

Figure 2: Mini modules made of four EWT cells each. Multi-crystalline cells on the left, Cz-Si on the right. The Cz-module was measured at ECN and had an efficiency of 14.0 % (active module area).

4.2 Research approach and methodology

The project was divided into three major tasks. In task 1 different rear contact solar cell designs were discussed and calculated by computer simulations. The common problems like increased recombination, shunting as well as series resistance were examined. Laboratory scale experiments involving parts of the advanced cell designs were done together with the simulation to test the calculation results. In parallel the possibilities of different industrial- and laboratory-scale production facilities were screened considering the individual needs of the different cell types. In the case of lab-scale facilities for cell production their potential to be applied in industrial cell fabrication was estimated. A subtask in task 1 was focussing on the solution inherent to the different back-contact solar cell designs such as the definitions of the p-n junction area and the interconnection in modules.

As a result from task 1, sixteen rear contact cell concepts were described from which nine were selected for further development in task 2.

In task 2 the solar cells were produced according to the cell designs as defined in phase one. The cell process parameters were optimised to testify the potential of the designs. In this phase laboratory-scale technologies were used, as long as they were similar to industrial fabrication. In parallel high efficiency cells were developed with the aim to demonstrate the advantages of different cell concepts and to allow future application in high efficiency modules. By the end of phase two an assessment took place, where the cell technology with the best chance for a future commercialisation was selected. As there were different rear contact solar cell concepts with similar rankings, the selection was rather based upon the interest of the industrial partner than on a clearly superior concept. That was also the reason to continue with the development of multiple cell concepts in the third project year.

In the third phase the research effort was concentrated on solving production bottlenecks caused by the use of laboratory-scale production methods and to make the processing more stable. Concepts were developed to translate laboratory-scale methods to large-scale production level and a complete technology from starting material up to module design was described. In parallel a larger number of this type of solar cells was made to demonstrate its potential in prototype modules inclusive the advantages of new possibilities for a highly automated module production line.

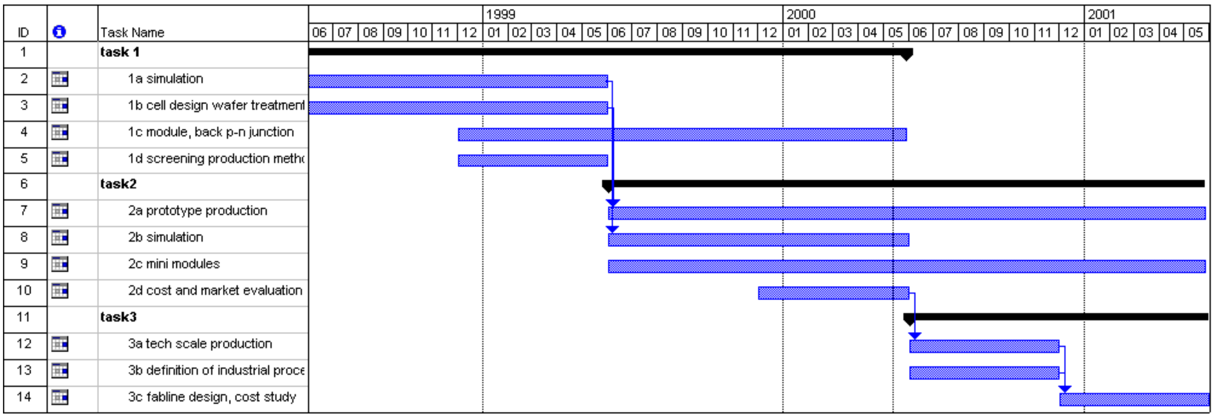


Figure 3: Task overview and time schedule of the project.

5. Results and Conclusions

The set-up of this project with its emphasis on covering the complete range of rear contact crystalline silicon solar cell development from fundamental research to industry related applications resulted in expected but also in unexpected results. The following chapter gives an overview starting with the more fundamental results, device simulation and p-n diffused area definition followed by a brief description of the main rear contacted cell designs. The chapter closes with an overview of the assessments made in the project and the planned exploitation.
The results are far from being complete and are meant to demonstrate what the main expertise gained during this project is. Partners performing the main part of the work are reported as contact points for further details.

5.1 Simulations (UKN, IMEC, FhG-ISE)

The most fundamental parts of the project were the simulation tasks and the high efficiency cell processing. In the simulation and modelling task, cell geometries were developed for the actual processing work but also fundamental questions were solved. The principal question whether a rear side emitter region improves the cell efficiency overall was positively answered. An efficiency increase of 4 % (relative) in the case where the diffusion length is less than the wafer thickness was found. From these results it can be concluded that back-contact cells have the potential for larger efficiencies beyond the efficiency improvements caused by the avoided front-side shadow loss.
The second modelling result was that it is possible to make emitter wrap-through cells with unit cell dimensions in the 2 mm to 3 mm range at least in cases where highly doped base material is used. This allows to process cells by screen printing with realistic accuracy requirements.
Another important question is for which material quality the EWT concept is superior compared to a rear contact cell (RCC) concept. The RCC structure has interdigitated rear contacts and a floating (= uncontacted) emitter on the front side. This simulation was carried out for different surface recombination velocities in the connecting emitter hole of the EWT cell as a function of bulk diffusion length. The result is quite evident: the efficiency and the open circuit voltage are better for an EWT cell if the diffusion length becomes small. The short circuit current is better in the EWT case, even for very large diffusion lengths.
Although only the main results are mentioned it clearly demonstrates the usefulness of the modelling task both in understanding of the fundamentals of back-contacted cells and also in supporting the prototype cell tasks with valuable design parameters.
At the partners the experience is available to simulate complex 2D and 3D solar cell structures to support the design of a cell.

5.2 Specialties: p-n junction definition by co-diffusion compensation

5.2.1 Al-P co-diffusion

The common properties of bifacial POWER and EWT solar cells are the interdigitated contact pattern of p- and n-contacts on the rear of the solar cells. Currently there are additional process steps necessary for the formation of rectifying junctions (deposition of a diffusion barrier; removal of Si by plasma etching or mechanical abrasion) of the interdigitated contact structure. The purpose of this task was the investigation of new approaches leading to rectifying junctions by overcompensation methods.
Starting point by the selection of the doping materials was the usage of the standard materials P and Al, since diffusion processes are already present in current industrial processing sequences using these two materials (emitter and BSF formation). Three different process flows were investigated in the first set of experiments by processing test solar cells with evaporated contacts. P-diffusion was done using a $POCl_3$ source, whereas Al was deposited by electron beam evaporation.

Method 1: Optimisation of the conventional overcompensation method
This approach was based on the sequence of diffusion processes as it is currently used in conventional solar cell processing. First, front and rear surface obtained a P-diffusion using a $POCl_3$-source, which was followed by Al-evaporation and alloying. The basic idea was to obtain a smooth, homogenous p^+n^+-interface with rectifying properties by slow cooling. However, the obtained shunt values R_{sh} were limited below 600 Ωcm^2.

Method 2: Removal of the Al-Si eutectic
This approach is very similar to the previous one but involves one additional process step: the removal of the Al-Si eutectic after Al-alloying. In this case the rectifying properties were enhanced with shunt values comparable to those with the co-diffusion process (Method 3), yet this process involves the additional wet-chemical etching step.

Method 3: Al-P co-diffusion
In the previous two methods the two dopants were diffused in two adjacent high temperature furnace steps whereas in this method the simultaneous diffusion of Al and P was investigated in one thermal cycle. The obtained shunt resistance values were high and independent of the metal-emitter contact length and of the applied parameter set (e.g. temperature and duration). By using co-diffusion three processing steps of the standard sequence (emitter formation, BSF formation, junction isolation) were successfully combined in one single high temperature step.

Processing of EWT solar cells using P-Al co-diffusion
Method 3 was applied to EWT solar cells on different crystalline Si materials. The process was based upon Al deposition using electron beam evaporation and the formation of the metal contacts by vacuum deposition of Ti/Pd/Ag on front and Al on rear. The process was successfully applied to Cz-Si, cast multi-crystalline Si and EFG-Si. The cell parameters of the illuminated IV-measurement are given in the table below, indicating the high potential of this method for the formation of rectifying junctions for the new solar cell designs as EWT and POWER.

Table 1: Illuminated IV-parameters of planar co-diffused EWT solar cells without anti-reflection coating.

Si material	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
Cz-Si	593	23.9	71.1	10.1
mc-Si	575	24.7	67.4	9.6

5.2.2 P-B co-diffusion in high efficiency processes (ISE)

In order to verify the feasibility for a rear pn-junction definition by overcompensation, rear contacted cells with overcompensation using gas phase diffusion were manufactured. First a locally defined heavy boron BSF was diffused (peak concentration approx. $3x10^{19}$ cm^{-3}), followed by a phosphorus diffusion (peak concentration ca. $3x10^{18}$ cm^{-3}) over the whole rear side of the cell.
The best efficiency obtained for cells fabricated in such a way is 21.3% (V_{oc} = 690.2 mV, J_{sc} = 40.02 mA/cm^2, FF = 0.772), if illuminated from the front side. This is already an excellent result which compares to 22.1% (V_{oc} = 697.6 mV, J_{sc} = 39.84 mA/cm^2, FF = 0.794) on a RCC with rear diffusions separated by an undiffused gap and additional n^{++} diffusion under the n-contacts.

5.3 Rear contact solar cells: prototype development

5.3.1 Screen-printed solar cells (UKN, IMEC, ECN)

5.3.1.1 EWT solar cells (ECN, UKN, IMEC).

The screen-printed EWT solar cells developed in this project followed the concept of a low cost solar cell, using an industrially applicable processes. For the fabrication of EWT the following problems were found to be especially crucial:

- formation of connecting holes
- p and n-area definition at the rear surface
- determination of the optimal grid design

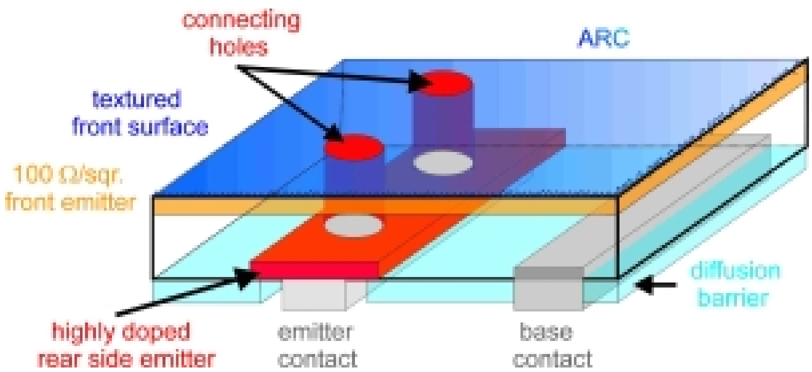


Figure 4: Schematic drawing of a screen printed low-cost EWT cell with the optimised cell design.

Table2: Solar cell parameters of different EWT solar cells and conventional cell (italics) with different investigated solar cell processes (UKN).

material	texture	Emitter	barrier	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]	R_{serie} [Ωcm^2]
Cz-Si	no	35	SiN	586	34.0	66	13.1	2.1
Cz-Si	alk.	35	SiN	594	36.2	64	13.8	2.0
Cz-Si	**alk.**	**80/10**	**SiN**	**599**	**37.8**	**72**	**16.1**	**1.3**
Cz-Si	**alk.**	**80/10**	**paste**	**600**	**37.9**	**70**	**15.8**	**1.5**
mc-Si	V-text	80/10	paste	585	35.7	68	14.2	1.9
Cz-Si, conv.	*no*	*35*	-	*614*	*32.5*	*76*	*15.2*	*0.7*

From simulation results it appeared that in the case of EWT cells the busbar area forms a cell region with lower efficiency. Thus in order to test the ultimate module concepts EWT solar cells without busbars were produced at ECN in co-operation with UKN and BP (see also chapter 5.3.4). By using a screen printer with automatic alignment these cells can be easily produced with sufficient accuracy. Nevertheless the development was hindered by the fact that these cells could not directly be measured under the solar simulator due to the large number of unconnected contacts on the rear side. A special measurement chuck was developed and applied for the tests, but temperature control of the device was difficult to be accomplished. Therefore most cells were characterised after fabrication of a laminate.

Cell results measured in a single cell laminate were in the 15.5 to 16% range.

5.3.1.2 Metallisation wrap-through solar cells (IMEC).

In opposite to the emitter wrap-through concepts where the emitter is used as conductive path to the rear, metallisation wrap-through concepts use of the front metal contacts as conductive paths. That means that a part of the front side metallisation remains and is connected via a small number of holes to the back. These concepts result in solar cells, where the busbars on the front side can be omitted, which means that from a small distance the front side metallisation is no longer visible. Compared to EWT concepts the number of holes is strongly reduced, which means faster and cheaper wafer processing, but there still remains a metal covered part of the cell limiting, which lowers the photon collection.

The MWT prototype cells developed under this task make use of laser drilling to produce the conductive vias through the wafer and screen printing technology to connect the front metallisation to the rear. This resulted in a process flow similar to the standard solar cell process with hole drilling and rear side emitter contact printing as extra steps.

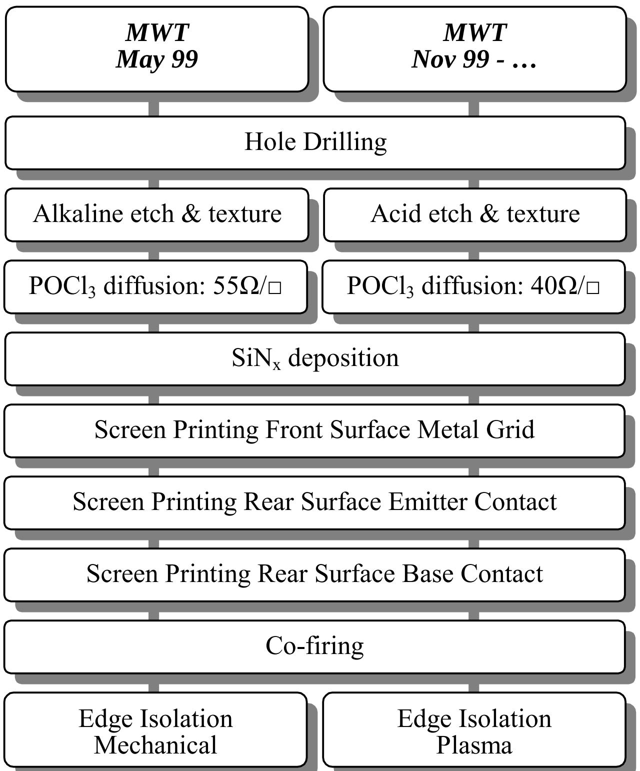


Figure 5: Intermediate and final process flow for the experimental MWTstructures realised in the frame of this work

After hole diameter optimisation and after the development of a reliable screen printed contact through the wafer consistent and repeatable cell efficiencies were obtained, which were demonstrated by the building of a 36 cells module. The results of the electrical characterisation of the experimental module are represented in the next table together with the derived parameters of an 'average cell'. These cell parameters are calculated assuming 36 identical devices in the module.

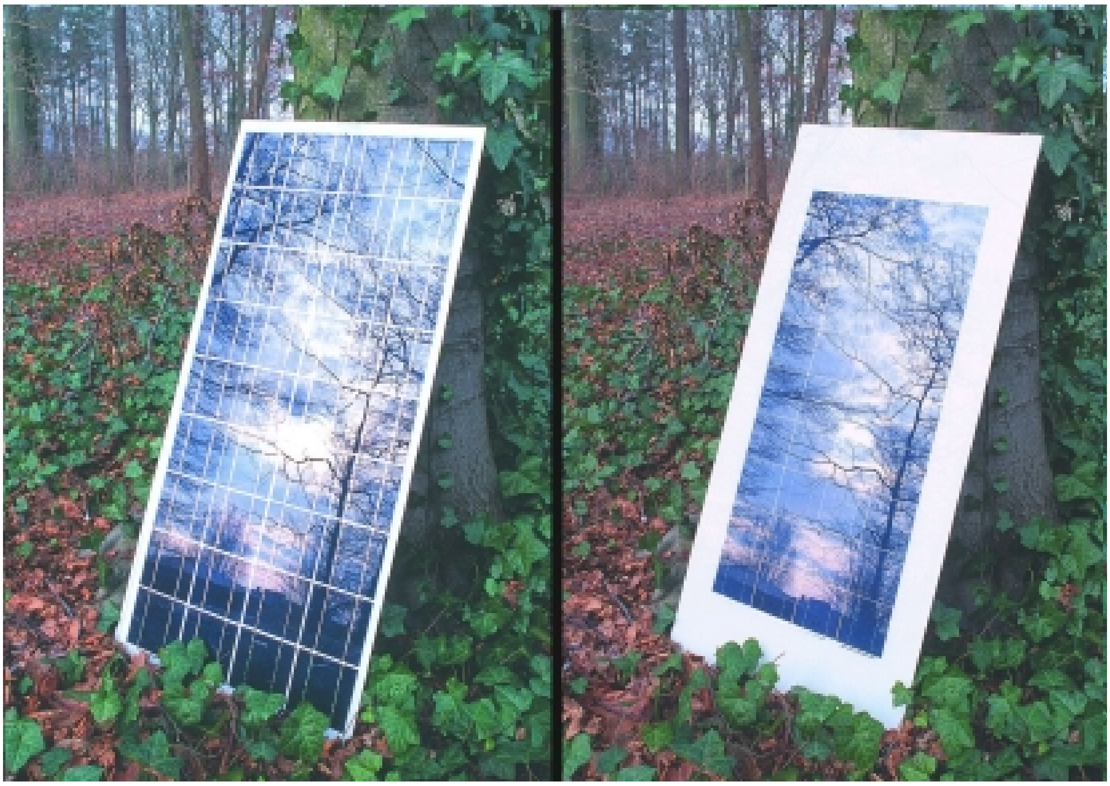
Table 3: Results of 36 MWT-cells module and derived efficiency of average cell performance in the module (Baysix multi-c, 10x10cm^2)

	I_{sc} [A]	V_{oc} [V]	FF [%]	P_{max} [W_p]
Module	3.44	21.9	71.5	54

	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]
average cell	34.4	608	71.5	15.0

The performance excels mainly through the high value of the current density obtained. Both the determined open circuit voltage and the fill factor underline the difficulty of reliably characterising individual cells without the construction of a dedicated measurement set-up. Through the reproducible cell efficiency of 15%, a 54W_p module could be realised. This is not only the highest reported performance for a large area module based on rear contacted cells but furthermore it outperforms the similar sized industrially manufactured conventional modules.

An additional topic addressed through the developments in this work is harder to quantify. As *beauty is in the eyes of the beholder*, only through time an indication can be expected whether the quest for improved aesthetics has ended in satisfying results. However, from the pictures of both a conventional module and the experimental counterpart represented in the following pictures, the potential of improved uniformity can clearly be seen.



5.3.1.3 Metallisation wrap around solar cells (IMEC).

In this subtask, the feasibility of a screen-printed design for large-area MWA solar cells was studied both on 100cm^2 1Ωcm Baysix Cz-Si and 100cm^2 1Ωcm Baysix mc-Si.

For the emitter-metallisation, the busbar- and finger-metallisations are separated from each other. The fingers are screen-printed in a standard way with an altered screen (no busbars and fingers slightly longer than the wafer-width to cover partially the sides of the substrate), whereafter the busbars are printed from the rear through a stencil, ensuring contact with the fingers on the front. To avoid shunt-losses on the sides of the cell, the busbars were printed with a paste that cannot fire through the junction existing on the sides.

Secondly, for the junction separation, a plasma-etching technique was employed. Since the rear-metallisation patterns show self-masking properties, only the emitter had to be masked for this type of

etching. Compared to junction-separation by mechanical grooving (about 30µm deep) with a dicing saw, this technique shows a reproducible high shunt-resistance (well above 1000Ωcm^2), which is comparable to that obtained in a standard processing flow. Other advantages of the plasma etching technique are the fact the mechanical stability of the substrate is not attacked and the batch-type possibilities of the process.
The best results obtained this far with the described technique are given in the next table, showing efficiencies of respectively 16.95% for Cz-Si solar cells and 15.93% for multi-crystalline Si solar cells.

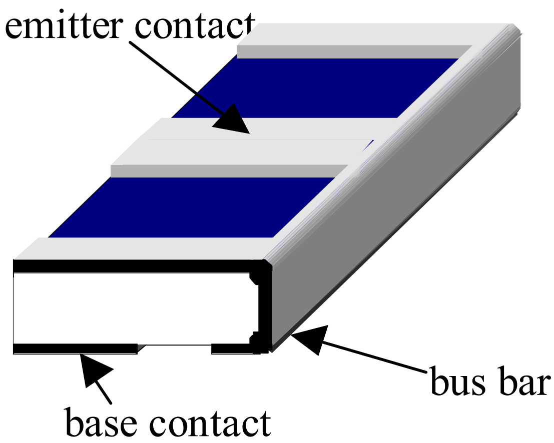


Figure 6 : Basic design of a screenprinted MWA cell

Table 4: Comparison of the standard IMEC screen-printed process and the applied MWA screenprinted processing sequence.

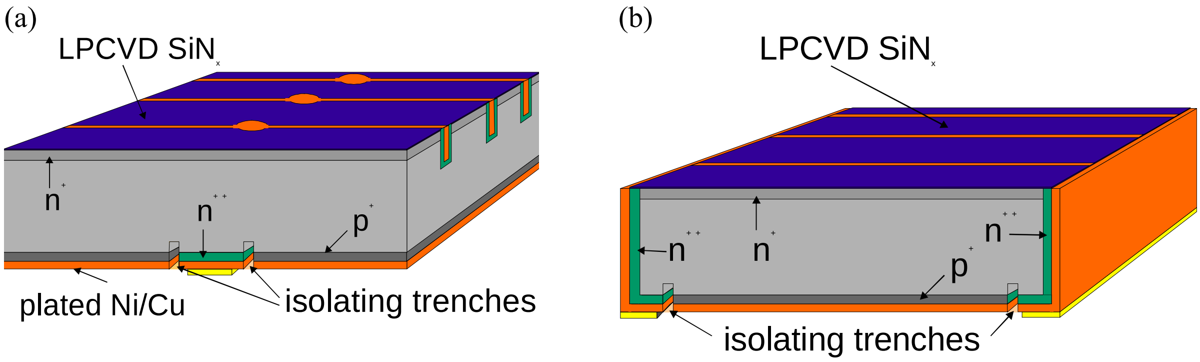
Standard	MWA
Saw damage removal and texturing	Saw damage removal and texturing
$POCl_3$ emitter diffusion	$POCl_3$ emitter diffusion
Parasitic junction removal	
SiN_x:H deposition	SiN_x:H deposition
Emitter metallisation	Emitter *finger*-metallisation
	Emitter *busbar*-metallisation
Base metallisation	Base metallisation
	Masking and junction separation
Co-firing of the contacts	Co-firing of the contacts

Table 5: Results of screen-printed MWA cells on 1Ωcm Baysix Cz-Si and 1Ωcm Baysix mc-Si. Cell area is 10x10cm²

Parameter	Cz-Si	mc-Si
V_{oc} [mV]	612.7	610.7
J_{sc} [mA/cm²]	37.59	35.10
FF [%]	73.61	74.30
η [%]	16.95	15.93

5.3.2 Electroless plated solar cells (BP, UKN)

This subtask deals with the processing, characterisation and simulation of back contact solar cells made by electroless plating metallisation. Due to the selective character of the metal deposition, this kind of metallisation is very advantageous for the fabrication of rear contact solar cells i.e. the interconnection between front side emitter/contact and rear side emitter contact get metallised during the electroless plating step. Since the chemical reaction of the metal deposition occurs on semiconductor and metal surfaces, this is done without further effort.
Therefore the buried contact technique was used for fabrication of three different back contact solar cell designs: the Metallisation Wrap Around MWA, the Metallisation Wrap Through and the Emitter Wrap hrough. Schematic diagrams of the obtained solar cells are given in the figure below.



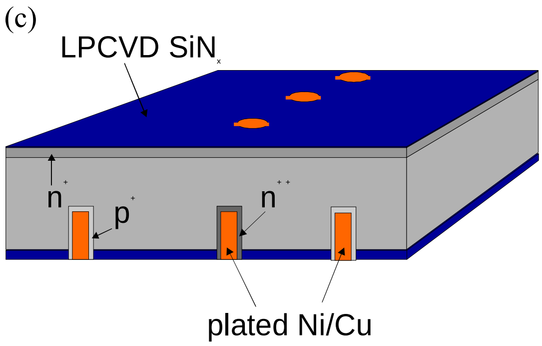


Figure 7: Schematic drawing of three different rear contact solar cells made by electroless plating (a) Metallisation Wrap Through MWT, (b) Metallisation Wrap Around, (c) Emitter Wrap Through. The external p- and n-contacts on the rear of the MWA and MWT cells are separated by mechanical abrasion. In the case of the EWT solar cell, they are defined by LPCVD-SiNx between the contacts.

The major problems for the fabrication of back contact solar cells are:

- Formation of the electrical connection between front side emitter (EWT) or emitter-contact (MWA/MWT) and n-contact on the rear
- Electrical isolation of p- and n-type regions on the rear

The first task is easy to realise if the technique of electroless plating is used, since the interconnections get metallised due to the selective character of this technique.

Simulations performed as well as experimental results showed that the removal of Si for p/n-junction isolation (e.g. by plasma etching or mechanical abrasion) is reducing the cell efficiency. This is due to a highly damaged region and is depending on the emitter/p-type contact length of the interdigitated pattern. Junction separation by mechanical abrasion can therefore be used for MWA and MWT solar cells, but seems not to be appropriate for EWT solar cells. Therefore, the second task was done by mechanical abrasion for MWA/MWT solar cells, and a diffusion/plating mask of LPCVD-SiN_x was used for EWT solar cells.
To show the feasibility of the cell concepts and the suggested processing sequences first devices with an area of 25 cm^2 were processed. For the MWA solar cell an efficiency of η=17.5 % was measured, whereas for the MWT solar cell an efficiency of 17.2 % was reached. Both back contact solar cells led to a higher efficiency than the conventional BCSC processed from a parallel wafer. The EWT solar cell with an efficiency of 16.6 % was processed in a different batch, therefore no direct comparison can be made. Yet the obtained efficiencies and fill factor for all three cell types indicate that the two tasks of metallising the interconnection and p/n-junction definition are successfully realised within the applied processing sequence. From the obtained IV-results the following conclusions can be drawn:

- MWT and MWA solar cell have about 1 mA/cm^2 higher J_{sc} as compared to conventional burried contact solar cell. This can be explained by the non-existing shadowing loss of the front busbar.
- Fill factor and shunt values R_{sh} of MWA/MWT above 1000 Ωcm^2 indicate the effectiveness of mechanical abrasion for p/n contact isolation
- Good series resistances of around 0.5 Ωcm^2 for MWA/MWT solar cells show a good interconnection between front grid and rear side busbar
- EWT solar cells show a lower V_{oc}, which is due to a higher J_{01}. This effect can not be avoided for EWT with a low ratio of diffusion length to cell thickness.
- The series resistance as well as shunt resistance also indicate the effectiveness of the applied processing sequence for EWT solar cells

Table 6: Illuminated IV-results for three back contact solar cell designs and a conventional buried contact solar cell. Surface texturing was done by alkaline etching for Cz-Si and by mechanical V-grooving for mc-Si solar cells. Cell area 5x5 cm^2.

Cell type	Material	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
MWA	Cz-Si	611	37.2	77.2	17.5
MWA	mc-Si	598	35.1	74.9	15.7
MWT	Cz-Si	611	37.2	75.8	17.2
EWT	Cz-Si	591	37.4	75.1	16.6
Conv.	Cz-Si	612	36.2	76.2	16.9

As consequence of this developments the electroless plated MWA solar cell concept was worked out as the rear contact solar cell concept with the highest interest for short-term industrial application (see also chapter 5.4).

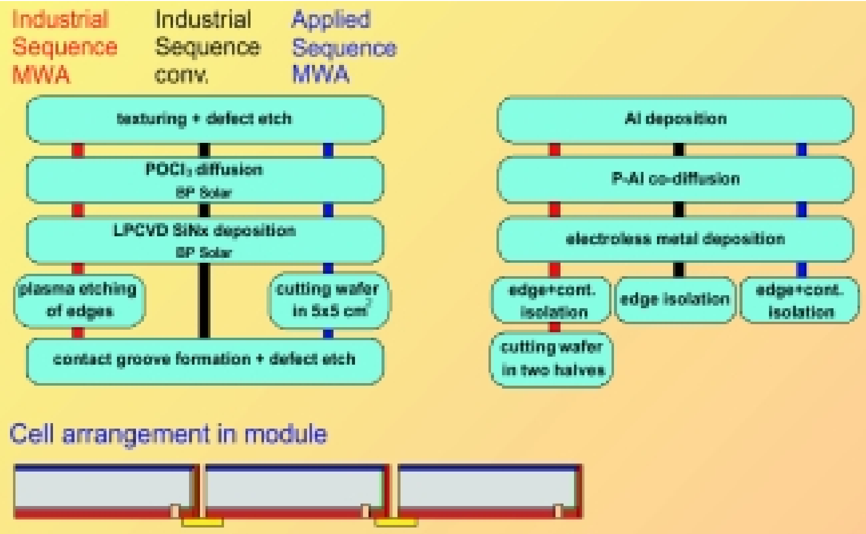


Figure 8: Industrial MWA cell processing sequence.

5.3.3 High efficiency concepts (ISE, MIC)

5.3.3.1 High efficiency EWT cells (ISE)

In order to demonstrate the possible performance of the rear side contact solar cell structures, high efficiency concepts were examined. The processing for these cells makes use of photolithography, metal evaporation and conventional diffusion processes.

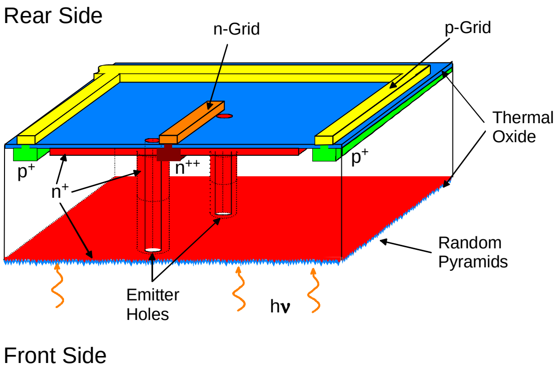


Figure 9: High-efficiency EWT cell.

Tab. 7: Maximum efficiencies of high-efficiency EWT and RCC cells on FZ silicon (1.25 Ω cm).

Structure	**V_{oc} [mV]**	**J_{sc} [mA/cm^2]**	**FF**	**η [%]**
RCC	683.0	40.82	0.773	**21.6**
EWT	684.6	40.91	0.764	**21.4**

The efficiency of 21.4% is the highest efficiency for EWT cells reported so far.

5.3.3.2 WAFFLE cell (MIC)

A different approach to a high-efficiency rear contact cell is the “WAFFLE”, solar cell concept. It has deep inverted pyramids etched into the silicon. In this device some of the many possibilities of anisotropic etching have been exploited.

To make this more explicit the following advantages can be named:

1) The deep inverted pyramids etched into the front surface act as an antireflection layer and

2) also make it possible to bring the front side emitter to the backside of the wafer, further,
3) the removal of silicon material in the pyramid regions also has the effect of increasing the surface area, while at the same time
4) reducing the volume of the cell.
Finally, it should be mentioned that the waffle structure has a certain light trapping effect. Efficiencies ranging from 16 – 21% have been achieved in various devices having the Waffle structure.

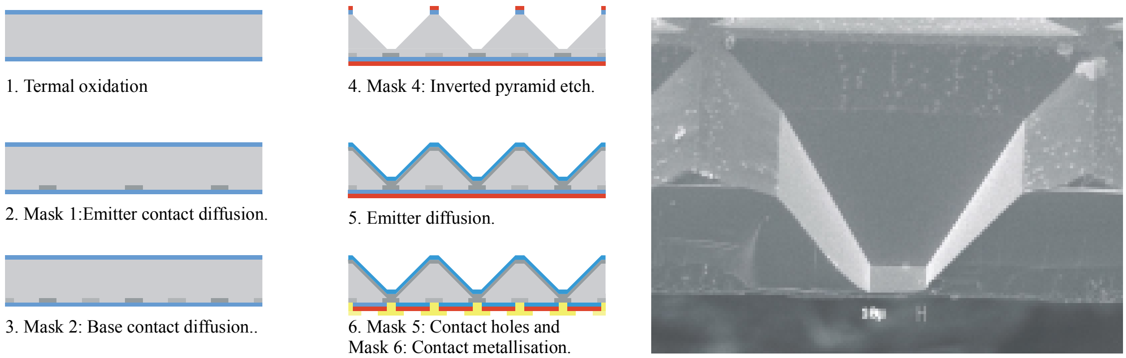


Figure 10: Main process steps of the WAFFLE cell and SEM picture of the structure.

Table 8: Parameters of a high efficiency WAFFLE solar cell.

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF	η [%]
WAFFLE	630	41	78	21

5.3.4 Module concepts (ECN, EUS)

All rear contact solar cell concepts have the possibility to apply them in combination with conducting adhesives to a conductive back plane in the module by pick-and-place technology. Depending upon the conductive adhesive curing can be done during a conventional lamination process.
The promises of this technology form part of the motivation for rear contact solar cell development. The ultimate module would have no connecting busbars on the cell. Each finger is locally connected to the connecting back plane, which means that 100% of the solar cell surface is electronically active.
The figure below demonstrates the concept idea, which was used to test a number of conducting adhesives and screen-printable isolating materials.

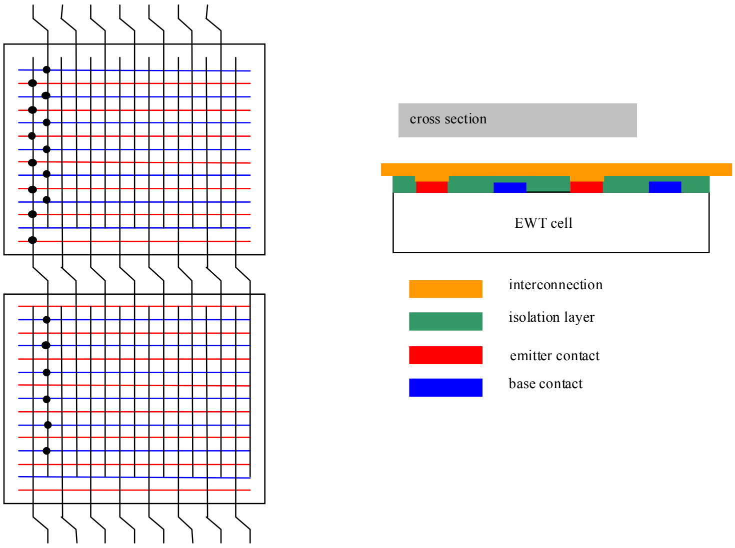


Figure 11: Busbarless EWT cell concept. The interconnection of the fingers is done via the connecting rear foil in the module.

The results of rear contact solar cell developments using conductive epoxies are:

- Contact resistances between cell and interconnection plane are excellent
- Best results are obtained with a combination of Ag pastes and Ag filled conductive epoxies.
- First accelerated ageing tests show good stability.

The major problem which still must be solved, is that it is rather unknown how the long term behaviour of the interconnection is under outdoor conditions. This prohibits the use of conductive adhesives in module technology for the time being.

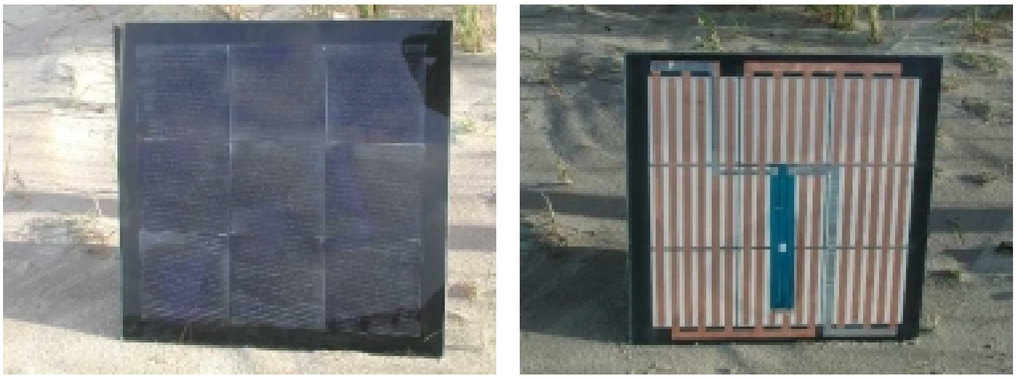


Figure 12: Rear- and front side of an EWT minimodule. The solar cells are manufactured without busbar. The interconnection of the fingers is made with conductive adhesive to the copper strips. The white isolation layer is a screen printable ceramic.

5.4 Industry relevant topics (assessments)

5.4.1 Solar cell production cost assessment

Four different processes where chosen for a detailed cost assessment: The LGBG-MWA, the LGBG-MWT, the screen-printed MWT and the screen-printed EWT process. The costs are fully built up costs in $/Wp, including labour, 10 years depreciation and yield, based on a factory with 10MW throughput. Wafer costs are not included. Input parameters for each process are cell area and efficiency.

Table 9: Cost comparison of buried contact and screen printed rear contact solar cells.

BURIED CONTACT			
costs in $/Wp			
Input Parameters	Standard LGBG	MWA	MWT
Cell area [cm2]	147.3	151	147.3
Cell efficiency [%]	16.5	16.9	16.9
Pmax per cell [W]	2.43	2.55	2.49
Total Costs (without wafer)			
Fixed Costs	0.43	0.43	0.43
Wafer to Cell Costs	0.70	0.71	0.78
Cell to Module Costs	0.81	0.67	0.68
Sum	**1.94**	**1.81**	**1.90**

SCREEN PRINTED				
costs in $/Wp				
Input Parameters	Standard Mono	Standard Multi	Multi MWT	EWT Mono
Cell area [cm2]	148.6	156.25	156.25	147.3
Cell efficiency [%]	14.5	13	13	14.2
Pmax per cell [W]	2.15	2.03	2.03	2.09
Total Costs (without wafer)				
Fixed Costs	0.39	0.39	0.39	0.43
Wafer to Cell Costs	0.50	0.55	0.59	0.99
Cell to Module Costs	0.92	0.98	0.84	0.82
Sum	**1.81**	**1.92**	**1.82**	**2.24**

The following conclusions can be drawn from the cost calculations above.

1. Buried Grid Processes:

- The LGBG-MWA process has potentially the lowest cost of all three buried grid processes compared. This is mainly due to the P_{max} gain caused by higher efficiency and larger cell area using the same wafers.
- Due to additional process steps the wafer-to-cell conversion costs of the back contact MWA and MWT processes are higher than the standard process. But this is more than overcompensated by the potential cut in labour cost, which can be achieved by the easier assembly of back contact cells.

2. Screen-Printed Processes:

- The same argument as above holds for the screen-printed MWT process. The wafer to cell conversion cost is slightly higher compared to the standard process, but due to the potentially higher degree of automation in module assembly the overall cost is slightly lower.
- The screen-printed EWT process is more difficult to judge since there are more uncertainties in this process as it stands right now. First of all to get accurate cost data on drilling thousands of holes per wafer is rather difficult, but on today's laser manufacturing equipment the costs are clearly prohibitive. On the other hand, once a next generation laser technology is developed the basis for the comparison will have changed since all LGBG processes will benefit from such a development. The improvement of EWT cell efficiencies to above 16% is not going to change the results of the cost assessment significantly.

Note that the benefits of back contact cells are not only in cost but also in the potentially high market penetration especially in the BIPV market. This marketing advantage is not accounted for in the cost calculations but has been investigated in detail in the "Bimode" project (JOR3-CT97-0175).

5.4.2 Design of a LGBG-MWA solar cell production line

The total cost of the cell process equipment for a LGBG-MWA production line is slightly higher than for a conventional LGBG solar cell production. However, as a proportion of the total cost of building a solar cell production plant, this small difference in production equipment cost is not significant. The processes used for module assembly are essentially the same for MWA cells as for conventional LGBG cells. The only difference is that in the case of MWA cells, the tabbing and stringing operations are carried out in the same operation. The separate tabbing and stringing machines used for conventional cells are replaced by a single soldering machine. A small reduction in equipment cost is expected.

Table 10: LGBG MWA solar cell process equipment – cost breakdown by process step

Equipment	**Process**	**Cost (%)**
Chemical etching system	Saw damage and texture etch	3
Tube furnace	Emitter diffusion and ARC deposition	14
Laser	Silicon nitride removal	19
Laser	Contact groove formation	19
Chemical etching system	Contact groove etching	2
Vacuum deposition system	Al deposition	17
Tube furnace	Contact diffusion	7
Plating system	Ni deposition	3
Conveyor belt furnace	Ni sintering	2
Plating system	Cu deposition	4
Laser	Edge isolation	10

6. Exploitation

In principle there are two slightly different markets for back-contact solar cells. On the one side it is the market of large scale, reliable power production in grid connected as well as remote systems. In this market the expected cost advantages play the most important role. On the other side there is a market of PV systems in buildings, where PV replaces facade elements such as marble. In this segment the appearance and not the price is the most important key factor for success. For this market segment semitransparent cells are further developed in the project such as the POWER cell (University of Konstanz) or the one IMEC is testing. All back contact cells have typical advantages because of their homogeneous appearance and the possibility to manufacture high efficiency modules.

6.1 Advantages for large scale electric power production

In this market cost reduction of PV module manufacturing is the most important factor. Back-contact solar cells have the potential for improved cost per Wp ratio in a next generation manufacturing line for the following reasons:

Comparable costs:

- Negligible extra investments compared to standard cell lines.
- Improved perspective for automated module fabrication.
- Increased process costs are in relation to the increased efficiency resulting in competitive costs per Wp.

Higher efficiency

- No or reduce front side metallisation
- Improved carrier collection by rear side emitter

6.2 Advantages of building integrated backside contact solar cells

The development of backside contact solar cells has some obvious advantages in the case of building integration. The front side without or with only little metallised area has a homogeneous appearance. It is further also possible to produce these cells in a semitransparent way, which means that in the case of replacing windows by PV modules daylight can enter a building. These cell types are typically implemented in small and medium sized enterprises (such as the POWER cell at Sunways as an example), because the production volume is smaller than for power generation and the profit gain per product is larger. These SME's can normally react quite fast to customer wishes, which also gives them the flexibility to introduce new products in short cycles. For these fields back-contact solar cells will be developed which can be produced by standard equipment but not necessarily at the high production rates needed for multi-MW manufacturing lines.

Rear side contacted solar cells were developed for all relevant industrial solar cell processes. The different partners in the project can assist in setting-up production lines. Interest is expressed by the industrial partner to consider the implementation of an LGBG MWA solar cell.

Obstacles for a broad implementation are formed by the lack of a module technology, which makes optimum use of back contact cells and in the case of EWT cells by the lack of a cost efficient laser system to do the via hole drilling.

7. Photographs