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ABSTRACT

This paper presents an outline of the work done in the EC co-funded project ACE Designs. The objective of this project was to develop rear contact solar cell designs and to demonstrate their applicability as an alternative crystalline silicon technology for industrial module production. An overview of the results is given with links to the most relevant publications for further details. The most important result of this project was that rear contact solar cells are a feasible, attractive and cost effective alternative to the well-known front contacted solar cell.

INTRODUCTION

ACE Designs was a European Commission co-funded project (1998-2001) with the objective to develop advanced, crystalline silicon rear contacted solar cells and to demonstrate their advantages in the manufacturing of silicon based PV modules especially in the building integrated PV market.

The main motivation for the project was the promise of higher efficiency of rear contacted solar cells, the homogeneous appearance without busbars and the advantageous interconnection of the cells in the modules. Making optimum usage of these advantages while minimizing the drawbacks of a more complex solar cell process was the challenge of the ACE Designs project.

APPROACH

The project was set-up in three phases: In the first phase, advanced crystalline silicon solar cell concepts were developed practically, with support of cell design calculations [1]. In parallel solar cell manufacturing technologies were examined such as how to drill vias through wafers and how to define local p-n junction areas on the rear side of the cell [2].

A selection of cell designs was worked out to demonstrate their technical feasibility in the second phase. In parallel, concepts for rear contact cell interconnections were developed. The results were used in an economical assessment of the different technologies.

In the last project phase, large number of solar cells of the most promising cell designs were made in order to get more insight into the different aspects that are important for industrial implementation such as production yield, product quality and product lifetime. These cells were also used to manufacture demonstration modules.

RESULTS

The rear contacted solar cells that were developed during this project can be classified as metallisation wrap-around (MWA), metallisation wrap-through (MWT) and emitter wrap through concepts (EWT). While MWT and MWA solar cells are still using metal fingers on the front of the cell, there is no front metallisation for EWT cells. All three solar cell concepts were developed in two versions using either screen-printing technology or laser grooved buried grid (LGBG) technology in combination with electroless plated contacts.

For all rear contact solar cell designs, certain cell manufacturing steps turned out to be crucial. A rear contact cell design implies that at least part of the emitter area is located on the rear. Therefore technologies had to be developed, which allowed the application of local n- and p-type areas on the same side of the cell. Different technologies such as local removal of the rear emitter by laser ablation, local diffusion by diffusion masks (LPCVD SiN, screen-printable pastes) or local compensation by Al-P co-diffusion [2] were applied successfully.

Another technological challenge was the application of the cell metallisation in the 3rd dimension. For all cell designs, metal had to be applied to either vias through the wafer or around the edges. The challenge was to achieve a highly conductive connection from the front emitter to the rear, without shunts to the base of the solar cell. For screen-printed metallisation, problems such as insufficient filling of vias or different sintering behavior in vertical areas had to be solved. Although from a first view apparently easier, the reliable and shunt-free application of electroless plating technology turned out to be similarly challenging.

In addition to the cell technology development, the interconnection technology of rear contact cells formed the third major challenge in the project. Soldering as well as conductive adhesive technologies were examined to connect rear contact solar cells to foils with interconnection patterns.

In general, most problems could be solved effectively during the duration of the project, which will be shown in more detail per solar cell type.

Screen-printed, rear contact solar cells

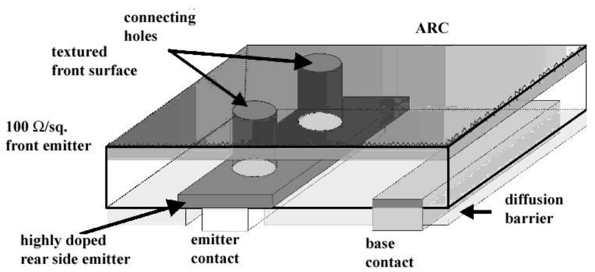

Fig. 1: Schematic drawing of a screen-printed EWT cell.

The first challenge for a screen-printed EWT solar cell design was the geometrical definition of the cell geometry (number of holes, finger-finger distance). The large positional tolerance and the minimum finger-width of screen-printed contacts had to be taken into account. With the support of 2D and 3D simulations, a screen-printing compatible EWT cell design was described that could be realized on 1 Ωcm silicon wafers.

The next important point was the passivation of the open p-n junction area at the rear. In difference to planar p-n junction cells the large p-n junction area at the highly recombining crystal surface was clearly limiting open circuit voltage and filling factor. The solution to this was the application of a surface passivating SiN layer on the rear covering the p-n junction area. This was an important step to reach efficiencies beyond the 16% limit (see Table 1).

In general it was found, that the open-circuit voltage of EWT cells was lower than that of cells with planar p-n junction. However, this loss was more than compensated by the short-circuit current increase [3].

Table 1: Solar cell parameters of screen-printed EWT solar cells and a conventional cell (italics). Different process scenarios were applied. (Texture: alk.=Alkaline; V=mechanically textured V-grooves. Emitters: 35 Ω/sq. homogeneous; 80/10 Ω/sq: selective emitter. P-n junction definition: LPCVD SiN diffusion barriers with laser ablation; screen-printable paste).

Material	texture	Emitter	barrier	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
CZ	no	35	SiN	586	34.0	66	13.1
CZ	alk.	35	SiN	594	36.2	64	13.8
CZ	alk.	80/10	SiN	599	37.8	72	16.1
CZ	alk.	80/10	paste	600	37.9	70	15.8
mx	V	80/10	paste	585	35.7	68	14.2
CZ	*no*	*35*	-	*614*	*32.5*	*76*	*15.2*

In parallel to the EWT concept two other commercially very interesting screen-printed rear contact cell concepts were successfully developed. In the case of MWT and MWA the wafer processing is simpler, which results in an economically more feasible cell concept. The major challenge in this case was the connection of the front- and rear metallisation by screen printing through the vias (MWT) or along the edges (MWA). Also the shunt free firing of the metal in the vertical cell surfaces was not without problems [4]. After solwing thes technological challenges, both screen-printed MWA and MWT cells were produced with high efficiencies up to 17% (see Table 2).

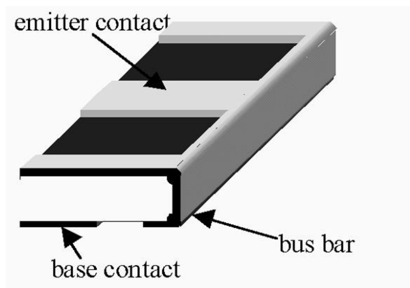

Fig. 2: Basic design of a screenprinted MWA cell.

Table 2: Results of screen-printed MWA cells on 1Ωcm Cz-Si and mc-Si. Cell area is 10x10cm^2

Cell type	Material	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
MWA	Cz-Si	613	37.6	74	17.0
MWA	Mc-Si	611	35.1	74	15.9

Electroless plated, rear contact solar cells

Compared to the above described screen-printed technology, a rear contact solar cell design making use of the laser grooved buried grid (LGBG) technology in combination with self aligning electroless plated contacts seems more appropriate for rear contact cell designs. In the project processing schemes were developed for all three cell concepts, LGBG EWT, MWT, and MWA. From all of them solar cells were produced with very good efficiencies (see Table 3). [5]

Among the three concepts the LGBG MWA cell (see Fig. 3) is the cell design, which is most promising for commercialization. Its processing is very close to the existing LGBG solar cell process. It also allows the optimum use of the wafer surface by having the p-n area isolation on the rear instead of on the edge. During the economical assessment, this rear side solar cell concept turned out to be most attractive and was therefore tested intensively in large numbers in the last phase of the project.

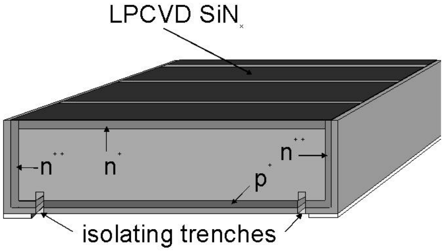

Fig. 3: Schematic drawing of a metallisation wrap-around, rear contact solar cell made by electroless plating. The external p- and n-contacts on the rear of the cell are separated by mechanical abrasion.

Table 3: IV-results for three LGBG rear contact solar cells in comparison to a conventional LGBG solar cell. Alkaline etching surface texturing was used for Cz-Si, mechanical V-grooving was applied on mc-Si solar cells. Cell area was 5x5 cm^2.

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

High-efficiency rear contacted solar cells

In parallel to the above mentioned low-cost, industrial cell technologies, high efficiency technologies were applied to rear contact solar cell concepts. By doing this much could be learned about the advantages of rear contact cell concepts and about the limit of the cell technologies.

Tab. 4: Maximum efficiencies of high-efficiency EWT and RCC cells on FZ silicon (1.25 Ωcm material, cell size 6 cm^2).

	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 high efficiency cell concepts under development in the ACE Designs project were the waffle cell, the rear contact cell (RCC) and a high efficiency EWT cell concept. As results, world record efficiencies [6] were achieved, but also simulation results were verified such as the superiority of an EWT cell to an RCC concept in case of lower diffusion lengths [6].

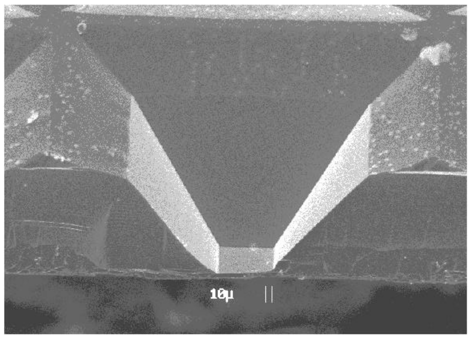

Fig. 4:SEM photograph showing a typical waffle solar cell structure. With this structures efficiencies up to 21% were reached.

Demonstration modules

An important advantage of rear contact solar cells lies in the new possibilities for interconnection of cells in the module. To show this potential, demonstration modules with advanced interconnection schemes were made [7].

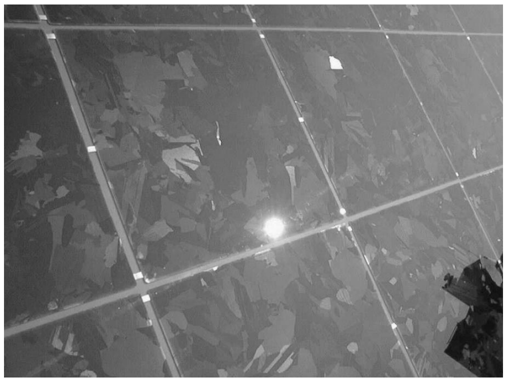

Fig. 5: Front surface of a 36 cells EWT module showing the homogeneous appearance without front metallisation.

Such an advanced design was realized with the busbarless EWT module. There, instead of using current collecting busbars, the backside module interconnection foil was used to connect the metal fingers directly [8]. This resulted in an EWT cell design with 100% active cell area.

Furthermore new interconnection techniques based on the application of conductive adhesives were examined. Very low contact resistances were achieved that are certainly sufficient to replace soldered contacts. Together with excellent first results on long term stability in accelerated aging tests and the possibility of a one step contact curing and lamination process, this makes conductive adhesives a promising candidate for a next generation module.

Manufacturing costs

In order to assess the potential of the different rear contact solar cell technologies, four different processes were 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 labor, depreciation and yield, based on a factory with 10 MWp/a throughput. Wafer costs are not included. Input parameters for each process are cell area and efficiency.

Table 5: Fully built-up costs in $/Wp for standard, MWA and MWT solar cell using LGBG technology.

BURIED CONTACT			
Input Parameters	Standard LGBG	MWA	MWT
	CZ	CZ	CZ
Cell area [cm^2]	147.3	151	147.3
Cell efficiency [%]	16.5	16.9	16.9
P_{max} 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**

Table 6: Fully built-up costs in $/Wp for screen-printed standard, MWT and EWT solar cells.

SCREEN PRINTED				
	Std	Std	MWT	EWT
Input parameters	CZ	mx	mx	CZ
Cell area [cm^2]	148.6	156.25	156.25	147.3
Cell efficiency [%]	14.5	13	13	14.2
P_{max} 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
Total	**1.81**	**1.92**	**1.82**	**2.24**

The following conclusions were drawn from the cost calculations above.

Laser grooved buried grid processes:

- The LGBG-MWA process has potentially the lowest cost of all rear contacted solar cell concepts.
- 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. This is more than compensated by the potential cut in labor cost, which can be achieved by the easier assembly of back contact cells.
- The costs for the screen-printed EWT process on today's laser manufacturing equipment are clearly prohibitive.

Note that the benefits of rear 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.

CONCLUSIONS

The ACE Designs project clearly demonstrated that rear contact solar cell concepts are a viable alternative to today's crystalline silicon solar cells. Their appearance, their cost competitiveness and their compatibility with existing cell processing equipment make them a candidate for a next generation solar cell. What is needed in order to harvest the potential of these cell concepts is a module manufacturing line, which makes optimal use of the possibilities of rear contacted cells. These technologies are under development in the EU co-funded projects Advantage and Afrodite.

ACKNOWLEDGEMENT

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