RECENT PROGRESS WITH APOLLONSOLAR’S NICE MODULE TECHNOLOGY

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ABSTRACT: APOLLON SOLAR’s NICE (New Industrial Solar Cell Encapsulation) technology aims at drastically reducing the manufacturing costs of PV modules, while at the same time increasing the total module lifetime. It makes use of a sealing technology which is well established in the insulating glass industry to replace the state-of-the-art lamination technology for PV modules. An additional feature is the soldering free electrical series connection of the solar cell busbars with the metal interconnectors, thanks to an under-pressure inside the module. Thanks to these features, the NICE process is completely in-line and easy to automate. Modules with 36 silicon solar cells have been produced with the NICE technology and evaluated, including by tests according to the IEC 61215 standard. Although the power degradation of the tested modules remained largely in the acceptable range, the evaluation revealed two areas onto which additional work was necessary to increase the overall performance and reliability of the NICE modules: (i) mechanical aspects concerning the stability of cells and migration of cells and interconnectors during thermo-cycling tests, (ii) performance losses due to a lack of optical continuity between front glass and solar cell. This work reports on solutions to overcome both performance limiting factors.

Keywords: Module Manufacturing, Cost Reduction, Encapsulation

1 INTRODUCTION

A detailed presentation of the NICE technology has been presented earlier [1]. In summary, the key elements, compared to the state-of-the-art EVA based lamination technology for the manufacturing of PV modules [2], are:

(i) Implementation of an air- and humidity tight sealing technology based on a thermo-plastic spacer (TPS) an organic material from the family of poly iso-buthylene [3], that is deposited in form of a narrow ribbon around the perimeter of the module’s supporting sheets (glass/glass, or glass/metal) of the module, creating a strongly adhesive contact between these two sheets.
(ii) Fixation of metal interconnectors and solar cells, by an adhesive material (TPS) on one of the supporting sheets.
(iii) Solder free, low resistivity series interconnection of the cells by creating an under pressure within the delimited space between the two supporting sheets of the module, which establishes a pressure contact between metal interconnectors and the conducting paths of the solar cells.
(iv) Inert gas inside the module to avoid corrosion of cells and connectors.

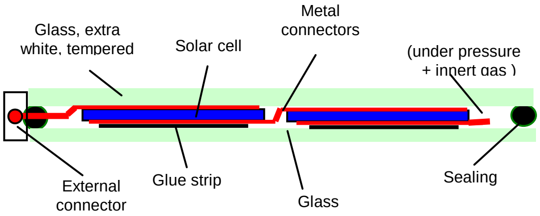

Figure 1: Schematic view of the cross section of a NICE module (not to scale, only 2 solar cells shown).

Other important features of the NICE technology are a newly developed simplified external connector that provides the electrical contact from the solar cell network inside the module to the outside. Metal sheets as rear support (instead of a second glass sheet) represent another new optional feature of the NICE module technology. The metal sheets, e.g. from stainless steel, are coated with an electrically insulating layer, allow for a series weight reduction of the module, while providing mechanical reinforcement for the modules.

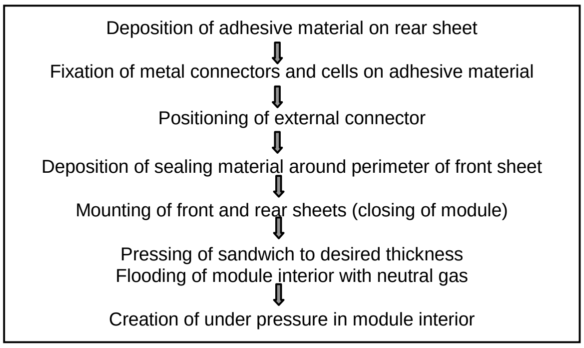

Figure 2: Generic process flow of the NICE module process.

The motivation behind the development of the NICE technology was to arrive at a drastic reduction of direct manufacturing costs for PV modules. Looking at the process sequence as shown in Figure 2, the simplicity of the NICE technology becomes obvious. Compared to the state-of-the-art, the total number of process steps has been largely reduced and simplified, especially since the entire process takes place at normal atmosphere and ambient temperature.

In consequence, the NICE process can be entirely organized as an in-line operation, requires little surface space and allows for a complete and easy automation.

2 EVALUATION OF NICE MODULES

As part of the evaluation of NICE modules process, the IV characteristics were determined; modules were subjected to reliability tests according to the IEC 61215 standard and verified for mechanical degradation.

2.1 Performance of the TPS sealing material

The reliability of the TPS sealing material itself has been validated by the insulating glass industry, where it is used as a replacement for the traditional aluminum spacer. The reliability testing procedures of the glass industry and the building sector are very similar to the IEC 61215 standard and include exposure to different environmental conditions (heat, cold, humidity, UV-exposure) and mechanical impact. Apart from its major component poly-isobutylene, TPS also contains a desiccant that is capable of absorbing residual humidity, which is an important requirement of the insulating glass industry.

2.2 IV characteristics of NICE modules

Two 36 cells modules, as shown in Figure 3, have been characterized at Fraunhofer-ISE according to standard conditions, see Table 1.

Table 1: IV data of 2 NICE modules as measured at FHG-ISE.

	V_{oc} [V]	I_{sc} [A]	FF [%]	P [W]
No 1	**21.5**	**4.38**	**75.8**	**71.3**
No 2	**21.5**	**4.38**	**76.0**	**71.4**

Compared to state-of-the-art modules with EVA lamination, using the same type of multi-crystalline silicon solar cells, the NICE modules show open circuit voltages in the same order and slightly higher fill factors. However, the short circuit currents of the NICE modules is by approximately 10% lower, that what is normally obtained on standard EVA modules. This decrease in short circuit current directly translates into a lower power output of NICE modules compared standard EVA modules.

The reason for the strong decrease of short circuit current and module power is related to the optical discontinuity, looking at the succession of optical layers of a NICE module: the presence of a neutral gas gap in between solar cell front surface and internal surface of the front glass and the related discontinuity of refractive indices of the respective layers gives rise to reflective losses compared to the standard EVA module technology.. This point is discussed in more detail in the following section 3.

2.3. Degradation test results of NICE modules

NICE modules were tested according to the different degradation tests required for the PV module certification according to the IEC 61215 standard.

As already reported in [1], NICE modules do not show any degradation after the damp heat test (1000 hours at 85°C and a relative humidity of 85%). Even after an extended testing time of 3500 hours the decrease of module power remained below 1%, which clearly demonstrates the long term sealing quality of the TPS material. A first series of thermal cycle tests (exposure to 200 cycles from -40°C to +85°C) on small 12 cells NICE modules did not show any power degradation below 1%, as also reported in [1]. A second series of thermal cycle tests, realised at ISE on the two 36 cells modules whose IV data are presented in Table 1, however, showed a degradation of the fill factor and the short circuit current as can be seen from Table 2.

Table 2: Results of thermo-cycling test of 36 cells modules, carried out at FHG-ISE.

	V_{oc} [V]	I_{sc} [A]	FF [%]	P [W]
No 1	**21.5**	**4.38**	**75.8**	**71.3**
No 2	**21.5**	**4.38**	**76.0**	**71.4**
After 132 thermo-cycles:				
No 1	**21.5**	**4.30**	**74.5**	**68.9**
No 2	**21.5**	**4.28**	**71.1**	**65.2**
After 202 thermo-cycles:				
No 1	**21.5**	**4.43**	**73.2**	**69.6**
No 2	**21.4**	**4.15**	**66.8**	**59.5**

Both modules show a more or less strong decrease in fill factor during thermo-cycling and in case of module 2 an additional decrease in short circuit current. The total power loss in case of module 1 with 2.4% stays within the 5% margin of the testing standard, whereas module 2 has experienced as serious power loss of 16.6%. A visual inspection of the modules revealed two major mechanical problems that occurred during the thermo cycle test which explain these degradations, see also Figure 3.

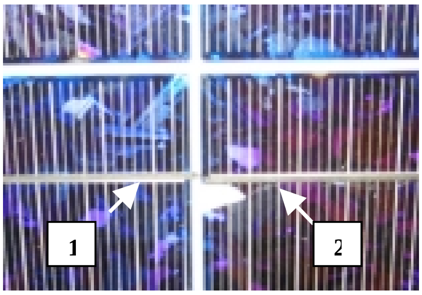

Figure 3: Detailed view on a NICE module after thermo-cycle testing, with a metal connector migration – away from the cell busbar (1) and a solar cell crack along the metal connector (2) clearly visible.

(i) The metal interconnectors which covered the entire surface of the cell busbars directly after the sealing of the module started to migrate away from the cell busbars during the thermo-cycling test, leading to a smaller contact area and, in consequence, to a higher series resistance and lower fill factor.

(ii) Solar cell cracks were observed along the cell busbar, or the metal interconnectors, leading to an insulation of certain surface areas which do not contribute to the light generated current any more. These typical cell cracks were mainly observed on module 2.

Strategies to overcome these mechanical problems and first results are presented in the following section 3. Other mechanical tests, like a simulated wind load of 2400N/m^2 did not lead to any degradation of 36 cells NICE modules.

2.4 Operating temperature in NICE modules.

An important performance degrading factor is the operating temperature of the encapsulated solar cell under direct irradiation. A thermocouple was placed inside a fully operational NICE module, to get the necessary information about the operating temperature of the solar cells. The module was exposed to direct sun irradiation on different days and the temperature inside the module as well as the ambient temperature was monitored. The maximum operating temperature that was determined during these tests was 60°C at an ambient temperature of 23°C, thus resulting in a maximum temperature difference of 37°C. It has to be noted that these measurements were not carried out under standard conditions for the determination of the NOCT (0.8 kW/m^2, 20°C and 1m/s wind speed), since the illumination intensity was not monitored, the ambient temperature higher and the experimental set-up was completely wind shielded.

3 SOLUTIONS TO IDENTIFIED PROBLEMS

3.1 Optical problems

Figure 1 shows a schematic view on the succession of different optical layers of NICE and standard EVA modules, starting with the outside (air) to the solar cells inside the module. The corresponding refractive indices of each layer are also given.

NICE	
Layer:	**n:**
Air	**1.0**
Glass	**1.5**
Gas	**1.0**
SiN	**2.3**
Silicon	**3.5**

Standard	
Layer:	**n:**
Air	**1.0**
Glass	**1.5**
EVA	**1.47**
SiN	**2.3**
Silicon	**3.5**

Figure 4: Refractive indices of different optical layers in NICE modules and standard EVA modules.

The gas layer between front glass and solar cell anti-reflective coating (ARC) in the case of the NICE module gives rise to important reflective losses, due to the important jump of refractive indices between gas layer and its neighboring layers. This optical discontinuity is not found on a standard module, since the refractive index of EVA much better matches the indices of its adjacent layers. The optical performance of NICE modules can be enhanced by the introduction of additional anti reflective coatings, as shown in Figure 5. A similar approach can be found in literature [4].

NICE +	
Layer:	**n:**
Air	**1.0**
SiO	***1.25***
Glass	**1.5**
SiO	***1.25***
Gas	**1.0**
SiO2	***1.5***
SiN	**2.3**
Silicon	**3.5**

Figure 5: Addition of ARC layers (in italics) to increase optical continuity of NICE modules.

AR coated glasses, for example with a porous SiO layer (n=1.25 to 1.3), reduces the reflective losses at the two glass/air and glass/neutral gas boundary layers. The same holds for solar cells with a double ARC, for example an additional SiO_2 layer (n=1.5) on top of the SiN layer, which gradually enhances the optical continuity between the silicon surface and the neutral gas layer of the NICE module.

Collaborative experiments with the CEA-GENEC have been carried out, to verify the beneficial effect of additional ARC layers. Multi-crystalline silicon solar cells both, with single SiN coatings and double SiO_2/SiN coatings have been produced on neighboring wafers with in-house developed processes [5]. Glass manufacturers provided small 150x150mm^2 samples of extra white PV glass with and without ARC. Different combinations of solar cells and glasses were placed under the IV tester at the CEA and the IV characteristics, especially the short circuit current density, of each combination were measured. The NICE module technology was simulated by placing metal connectors on the cell busbars followed by a sample glass sheet that was mechanically presses to assure electrical contacts between cell busbars and metal connectors. The rear surface of the cell was in direct contact with the IV tester chuck and the integrated probes for the electrical contacts.

Table 3: Comparison of the short circuit current density of different combinations of AR coated glasses and cells with single and double ARC. The combination marked with (*) corresponds to the actual NICE technology. The percentage differences Δ are related to this reference.

Cell type	**S-ARC**		**D-ARC**	
Combination	**Jsc** [mA/cm^2]	**Δ** [%]	**Jsc** [mA/cm^2]	**Δ** [%]
Cell only	31.6		32.5	
Cell + Glass	**29.2 ***		29.9	+2.4
Cell + AR Glass	30.4	+4.1	31.4	+7.5

Results of all combination of solar cells and glasses are summarized in Table 3. Only the measured short circuit current densities are indicated, which are directly proportional to the light entering the solar cells. It can be concluded that by a careful selection of additional ARC coatings the performance losses related to the NICE technology can be strongly reduced. In order to carry out a direct comparison between the NICE technology and standard EVA modules, a single cell with S-ARC from the same series as above has been laminated, using a standard glass without ARC. The short circuit current density of this EVA module has been compared to NICE assemblies: The NICE module with D-ARC cells and ARC glass showed only a 2% lower Jsc than the EVA module, whereas the NICE module without additional ARC layers had a 10.8% lower Jsc compared to the EVA module. It has to be noted that the optical properties of the single ARC SiN layer on the used cells was optimised for use in standard EVA modules. Taking this into account as well as the measurement uncertainty, the gap between NICE modules and EVA modules in terms of optical performance could be closed.

3.2 Mechanical problems

The encountered mechanical problems after thermo-cycle testing – connector migration and cell breakage have been analysed by modeling of the pressure evolution inside the module in function of a varying temperature. During the sealing process an under pressure inside the module with regard to the atmospheric pressure outside is established. If the temperature is lowered this pressure difference increases, since the volume of the module does not change. At the lowest extreme point of -40°C during thermo cycling, the under pressure increased by less than a factor of 2, leading to a strong mechanical impact on the solar cells inside the module. At the other extreme, +85°C the opposite takes place: the under pressure decreases, giving rise even to a slight volume expansion that is supported by the elasticity of the TPS sealing. In this case the metal connectors are no longer in close contact with the cell busbars and risk to move away from the busbars. If the metal connectors on the front and rear surface of the cell are no longer perfectly in line with the cell busbars the cell risks to break when the pressure inside the module is increased, and explains the typical cell breakages along the busbars. This effect was supported or multiplied by two other phenomena: (i) all modules so far realised were manually assembled, which did not always result in the necessary precision of alignment of the metal connectors with respect to the cell busbars, leading thus to potential breaking points when the under pressure is established.
(ii) the metal connector ribbons when delivered on a spool, unrolled and shaped for integration in a module accumulate mechanical stress that releases inside a NICE module when the under pressure decreases and thus supports a movement away from the cell busbar.

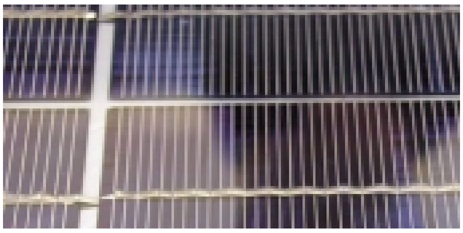

Figure 6: Undulated metal connector profile.

Based on this analysis the mechanical aspects of the NICE technology could be step by step improved and experimentally verified: (i) the under pressure at the moment of the sealing of the module was modified, in order to relief the maximum pressure impact at the temperature extremes during thermo-cycling. (ii) the composition and the mechanical profiling of the metal connectors was optimized. In parallel, automatic equipment was developed by Vincent Industries to pre-shape the metal connectors and to relief the residual mechanical stress at the same time. In addition, an undulated profile was given to the metal connectors, as shown in Figure 6 to absorb pressure peaks. First test modules could be realised, incorporating these mechanical improvements. After 150 thermo cycles that were achieved at the time of writing this article, no cell cracks and connector movements could be observed.

4 CONCLUSIONS

The potential of the NICE technology in terms of a drastic process simplification, an increased module reliability and a related reduction of manufacturing costs could be demonstrated. Solutions to identified optical and mechanical problems that have led to a performance loss of NICE modules could be presented. Further work is directed towards the realisation of a pilot line that comprises all automated assembly and processing stations to have the necessary mechanical precision and reproducibility for the manufacturing of NICE modules. This represents an important step towards the demonstration of the industrial feasibility of the NICE technology. The pilot line will be realised by Vincent Industries.

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