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FIRST EXPERIMENTS ON MODULE ASSEMBLY LINE USING BACK-CONTACT SOLAR CELLS

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ABSTRACT: There is a great need for cost-effective high-throughput equipment to assemble thin and high-efficiency solar cells into modules. Single-step assembly using back-contact cells (monolithic module assembly) provides substantial advantages in terms of performance and costs. Progress towards development of a commercial module and assembly process using back-contact cells and monolithic module assembly is described. A fully operational pilot line consisting of dedicated equipment to process back-contact cell modules with the focus on the production of 4 x 9 and up to 6 x 10 cells configuration was build by TTA/Eurotron and ECN. The emphasis is on the production of modules with ultra-thin back-contact cells of mc-Si (156 x 156 mm^2) and only 130 µm in thickness. The design of the equipment is targeting for a throughput rate of 1 cell per second, or equivalently a module production capacity of 100 MWp per year. Processing of the first set of modules shows good results in terms of process reliability and yield. The overall yield for the first series of 23 modules (4 x 9 configuration) built with ECN-MWT cells was 100% while 9 of the 23 modules had a fill factor better than 74%. In addition, a series of 25 modules (6 x 10 configuration) with industrial back-contact cells was built and revealed excellent reproducibility. A standard deviation of the FF of only (σ) 1.44 was observed.

Keywords: module technology, automation, back-contact solar cells

1 INTRODUCTION

The current price of PV systems cannot yet compete with consumer electricity prices. A major further reduction of turn-key system prices is essential and possible. At present, the costs of solar electricity are about € 0.50/kWh in North West Europe to € 0.35/kWh in Southern Europe. To reach competitiveness of solar electricity with consumer electricity (“grid parity”) in Southern Europe by 2015, PV generation costs of 0.15 €/kWh are necessary. This corresponds to a turn-key system price of 2.5 €/Wp. This system price arises from typical manufacturing and installation costs of below 2.0 €/Wp. Back-contact cells allow for fundamentally new approaches to photovoltaic module design and assembly. The integrated optimization of the back-contact cell and module design reduces interconnect resistance, solar cell resistance, solar cell optical, and module packing factor losses compared to modules using conventional silicon solar cells. This optimization not only provides improved module efficiency, but also extracts the most value from the most expensive component in the PV module (solar cell) by minimizing the “encapsulation” loss (module efficiency/cell efficiency). In addition to performance optimization, the new back-contact cell/module design can use new assembly technologies that are inherently more scaleable (i.e., larger and/or thinner cells) with improved cost/throughput compared to current assembly processes using conventional cells. Monolithic module assembly refers to single-step assembly of the module circuit and module encapsulation during the lamination step, and has been demonstrated with back-contact cell and back-sheet with integrated circuit. The planar geometry is more compatible with thinner cells and allows for new assembly techniques (e.g., pick-and-place automation) that have much higher throughputs with smaller floor space requirements when compared to traditional stringer automation.

This paper describes progress towards design and implementation of commercial modules using monolithic module assembly. A pilot production line has been constructed by ECN and TTA/Eurotron that implements this monolithic assembly process. The design and operation of the tool, and initial results, will be described.

2 OBJECTIVES

The continuous drive for reducing cost of PV electricity has led to three main routes of cost savings relative to state-of-the-art module manufacturing with conventional H-pattern type cells: 1. Reducing the amount of materials; 2. High-throughput manufacturing; and 3. Increasing the total-area efficiency of solar modules.

2.1 Reducing the amount of materials

More than 50% of the costs of a state-of-the-art crystalline silicon photovoltaic module are determined by material costs. It is found that the largest potential for cost reduction is by reducing the wafer/cell thickness. In the past years this trend was accelerated by the high Si-feedstock prices due to its limited availability. PV-manufacturers have responded to this by reducing cell thickness from 330 µm in 2002 to 200 µm in 2007, with a further reduction expected to 130-160 µm in 2010.

2.2 High throughput manufacturing

The most important bottleneck arises during the module assembly process where individual cells are interconnected by soldering technology. Many of the yield losses occur during this cell interconnection step. Reducing the cell thickness below 180µm might have the consequence that state-of-the-art module manufacturing technologies with H-pattern cells are no longer feasible. This necessitates the need for new module processes and equipment.

For many of the processing steps it holds that the throughput is determined by the amount of wafers per hour that can be processed. So, increasing the surface area of cells and modules automatically leads to an increase of production capacity while the additional material and manpower costs are limited. In the past years the surface area of solar cells has increased from 125 x 125 mm² to 156 x 156 mm², with experimental cells of 210 x 210 mm². Also, module configurations are growing in size. In 2002, a typical module area was 1m² which was composed of 4 x 9 cells. Nowadays, module areas are 1.5 to 1.6 m² and available in 5 x 10, 6 x 9 and 6 x 10 cell matrix configurations. The increasing size of the wafers, in combination with thinner wafers, leads to several processing difficulties. Processing these large and thin wafers to H-pattern solar cells and modules has several drawbacks which result in efficiency losses and/or yield losses:

- Larger cells suffer from increased series resistance as a result of longer metallization fingers on the front side, or will result in increased shading losses, when three bus-bars are applied.
- Larger cells will generate higher currents that will give higher series resistance losses in the interconnection material.
- Using traditional tabbing material might lead to breakage of the thin and fragile cells.
- Soldering tabs will account for highly stressed surface area because of differences in thermal expansion, and so reducing the production yield.
- Using a full aluminum rear-side metallization will result in cell bowing, which may lead to cell breakage during service life.

To overcome these drawbacks, innovative cell designs that have low-cost high-throughput potential are necessary, as well as module assembly equipment to interconnect these cells.

2.3 Increasing the total-area efficiency of solar modules

Due to the module assembly process, electrical and optical losses will be introduced, resulting in lower module efficiency then the acquired cell efficiency. State-of-the-art multi-crystalline H-pattern cells with 16.5% cell efficiency will generally lead to a total area module efficiency of only 14.0%. Therefore it is necessary to optimize the total area module efficiency.

Developments towards increasing the total-area efficiency of solar modules have mainly led to further investigating the physics of solar cells. However, it is equally important to reconsider the module concept. Developing modules efficiencies beyond 18% will require further integral development of alternative cell- and module technologies. This necessitates the need for new module processes and equipment.

The developing of new module technologies is to narrow the efficiency gap between the solar cell efficiency and module efficiency. Strategy is to drain the current from the cell as quickly as possible into a current carrying conductor which is part of the back sheet foil. This leads to a shift of relatively expensive metallization on the cell to relatively cheap metallization in the module. By proper design, resistive losses can be much smaller then with (smart) tabbing which results in module efficiencies that approach the efficiency of the cell. One example is the ECN busbarless MWT cell.

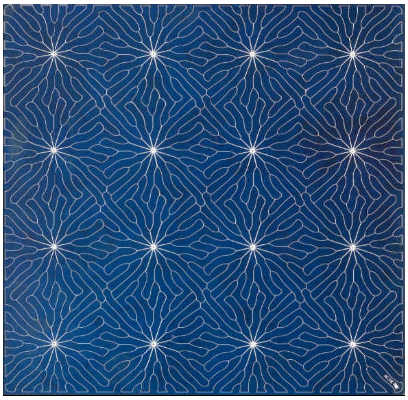

Figure 1: Metallization Wrap Through solar cell, developed at ECN

3 MODULE ASSEMBLY LINE

It is essential that a module technology will be developed to enable to work with extremely thin and fragile cells. A novel module assembly process, developed by ECN, has the potential to fulfill this requirement containing the following steps: 1) Conductive back-sheet foil comprising an electrical pattern for interconnection of solar cells. 2) Conductive paste deposition on the conductive tracks of the interconnection foil. 3) Placing of a pre-processed sheet of EVA. 4) Solar-cell pick and placement onto the conductive paste. 5) Lay-up of an additional EVA sheet and a cover glass plate. Finally, the module assembly will be laminated in a vacuum laminator while simultaneously forming the interconnections. In this context, a pilot module assembly line was built by TTA/Eurotron under ECN supervision to demonstrate the feasibility of the concept. This equipment is capable of assembling modules configured into matrices of 4 x 9 and 6 x 10 using 156 x 156 mm² cells. The module assembly line is designed to support existing back-contact cell types such as Interdigitated Back Contact (IBC), Heterojunction cells, Emitter Wrap Through (EWT), Metallization Wrap Around (MWA) and Metallization Wrap Through (MWT) solar cells.

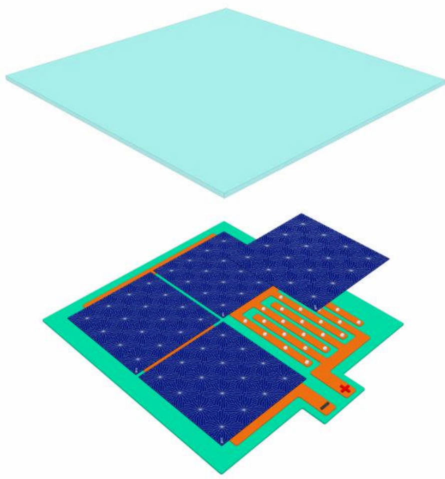

Figure 2: Back-contact module assembly using MWT solar cells

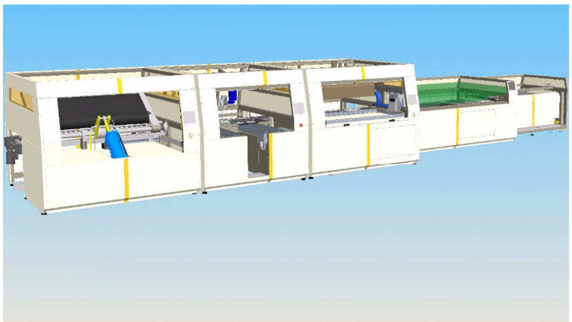

Figure 3: Outline of the module assembly line using back-contact solar cells and conductive back-sheet interconnection foils

Based on the module assembly process a full-scale pilotline, able to process back-contacted solar cells according to PV-industry standards, comprises five stations as will be explained in the following sub-sections.

3.1 Foil lay-up and transport system

The first station consists of the transport carrier system moving the back-sheet foil through all sub-stations. The back-sheet foil is lined-out and will be held in place by a vacuum support.

Figure 4: Substation for foil lay-up

3.2 Deposition of conductive paste

Figure 5: Interconnection, deposition of conductive adhesive

After the foil lay-up, the solar cells need to be interconnected. This interconnection between the conductive back-sheet foil and the back-contact cells is established by means of deposition of conductive paste. It is of utmost importance that the interconnection yields low-stress to avoid cell breakage after the interconnection process. These stresses are the result of differences in thermal expansion which necessitates the use of interconnection materials that cure at a relatively low temperature and yet be tough during service life.

3.3 Encapsulant placement

After the deposition of the conductive paste, the encapsulant will be placed. The encapsulant requires machining to fit the design of the back-sheet foil, i.e., holes need to be punched to establish contact of the conductive adhesive previously placed.

Figure 6: Substations for EVA encapsulant lay-down

3.4 Solar cell pick-and-place

The thin and fragile cells must be picked from a stack. Accurate positioning of the cells relative to the conductive back-sheet foil is realized with a dedicated handling and vision system. The vision achieves precise alignment between the actual position of the bonding area on the back sheet foil and the contact points of the cell.

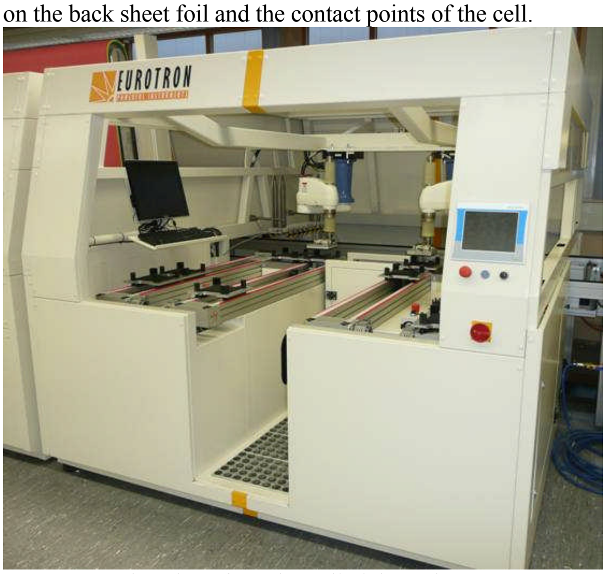

Figure 7: Substations for solar cell pick & place

The subsequent placement of EVA and glass sheet is combined with station 3 (see figure 6). The EVA and glass plate are accurately placed in position. The construction of the pilot line allows for combining stations to realize a compact automation tool.

3.5 Turning unit

The assembly needs to be turned and placed into a vacuum laminator. A clamping system was developed to deal with the required force and to avoid shifting or breakage of solar cells.

Figure 8: Turning unit station that transports the module assembly into a vacuum laminator.

4 RESULTS

During the course of finalizing the module assembly line the capability of the installation was experimentally tested. In accordance with the assembly line objectives three topics were selected.

- Processing of ultra-thin solar cells of 130 µm on the assembly line without cell breakage.
- Manufacturing of 24 modules with 4 x 9 MWT cells of 156 x 156 mm^2 comprising conductive back-sheet foil and conductive adhesive as interconnect.
- Reproducibility analysis of 25 manufactured 6 x 10 modules containing industrial back-contact solar cells

4.1 Handling of ultra thin solar cells (130 µm)

Several 36-cell modules were manufactured on the module assembly line comprising ECN MWT mc-Si solar cells based on 130 µm as-cut wafers. The emphasis for manufacturing modules with theses fragile cells was to prove the capability of the assembly line to demonstrate the cell handling and the low-stress interconnection with conductive adhesive. These cells experienced no breakage during the module manufacturing process. This proves the strength of the pick-and-place concept, i.e., the handling of the solar cells is only a single action over a short distance without introducing external stresses. Temperature effects on the cell are non-existing as the interconnection is based on low temperature curing conductive adhesive. A flexible bond between contact pads of the back sheet foil and contact points of the solar cells is established. The curing of the conductive adhesive takes place during the lamination cycle.

4.2 Module reproducibility testing on the assembly line

The reproducibility of the pilot-line process was tested by processing 23 modules in one run. For this reason ECN mc-Si, MWT cells 156 x 156 mm^2 with a thickness of 220 µm were used. The distribution of FF for the 23 modules is shown in figure 9. An overall yield of 100% was reached without any cell breakage. In table I, the average values of the I-V parameters together with the deviations are presented.

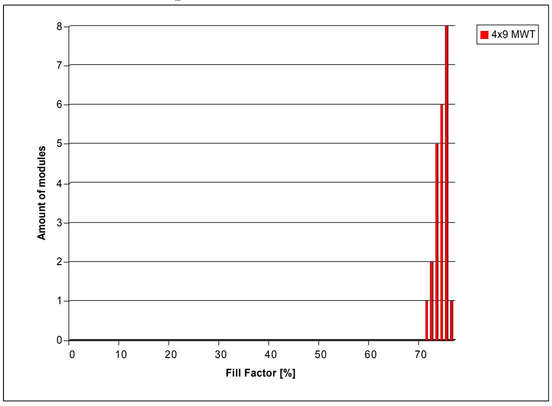

Figure 9: Fill factor deviation of manufactured 4x9 modules

Table I: Variations of average I-V parameters for 23 modules (4x9) MWT mc-Si cells of 156 x 156 mm^2

FF	**$\eta_{encaps\ cell}$ [%]**
72.9	14.8
Deviation FF [%]	**Deviation $\eta_{encaps\ cell}$ [%]**
1 module: <4 3 modules: 2.6 to 2.8 13 modules: 1.2 to 1.5 6 modules: 0	2 modules: 3.3 to 3.4 5 modules: 2.7 4 modules: 2.0 8 modules: 1.3 2 modules: 0.67 2 modules: 0

The I-V measurements have been carried out with the aid of a class-A flash tester. As can be seen from the table, the deviations in the single I-V parameters FF and encapsulated cell efficiencies are small. The FF deviations of the modules are < 2.8 % for at least 22 modules (95% of total). The deviations add up in the efficiency values as is indicated by somewhat larger deviations in η_{encaps_cell}. The majority of the group of 23 modules (21 modules 91% of total) shows a maximum deviation of 2.7% from the average η_{encaps_cell} value of 14.8%. From this it can be concluded that the reproducibility of the pilot-line is excellent. A fill factor loss of 2% between cells and modules was observed.

IV parameters of the best performing module of this series are displayed in table II . The averaged fill factor of the cells was 77%.

Table II: IV parameters of a 36 (156 x 156 mm²) cells module comprising electrical back sheet foil.

V_{OC}/V_{MP} [V]	I_{OC}/I_{MP} [A]	FF [%]	η_{encaps_cell} [%]
21.7 / 17.4	8.21 / 7.65	75.0	15.2

4.3 Reproducibility of 6 x10 modules

Recently, a production run of 25 modules with a 6 x 10 cell matrix was executed on the assembly line. These modules comprise industrial back contact cells of 156 x 156 mm^2 with a thickness of 220 µm. In table III the averaged fill factors for the 25 modules are displayed. In accordance with the fill factor measurements for the 4 x 9 modules the majority of 23 (92% of total) were less then 2%. The derived fill factors were normalized to 100% for comparison of the 4 x 9 and 6 x 10 case (see figure 10).

Table III: Variations of average FF parameters for 25 modules (6 x 10) mc-Si cells of 156 x 156 mm^2

FF (6x10)
Deviation FF [%]
3 modules: 3.6
2 modules: 1.94
15 modules: 0,63
5 modules: 0,5

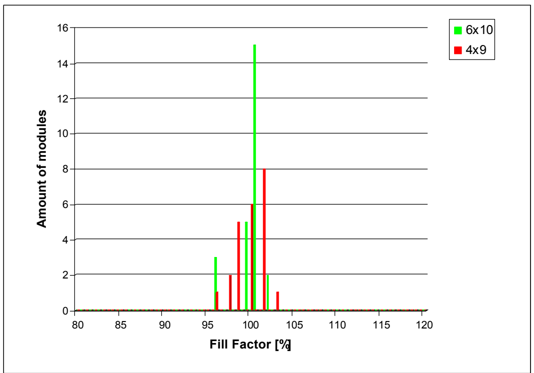

Figure 10: Comparison of fill factor variation for 4 x 9 and 6 x 10 cells modules

5 CONCLUSIONS

The concept of a fully-automated module assembly line for back-contact solar cells has been realized and demonstrated. A firm basis has been established to achieve the manufacturing of modules comprising back sheet foil, back contact solar cells and conductive adhesive. Functional modules have been manufactured on the module assembly line. Ultra thin solar cells of 130 µm were manufactured into 4 x 9 matrices without cell breakage during assembly and lamination.

First manufacturing of 4 x 9 and 6 x 10 test modules on the assembly line sub stations revealed excellent performance of the module efficiency and fill factor.

Processing of 23 modules has been successful in terms of yield and reproducibility. The mechanical yield was 100% while the electrical performance of 21 out of 23 modules showed an encapsulated cell efficiency with less than 2.7% power loss from individual cell measurements. A fill factor loss between cells and module of 2% was measured.

Recently, 25 modules comprising a 6 x 10 cell matrix revealed equal reproducibility of the fill factors compared to the 4 x 9 cell configuration. Electrical loss between the solar cells with the best performing module was 1.1% only. These results indicate stable and reproducible process conditions for the module manufacturing process. It is expected that this novel module technology will furnish the route towards drastic cost reduction enabling the assembly of ultra thin solar cells into modules.

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