HIGH-VOLTAGE PV-MODULES WITH CRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT: PV-modules in the power range of 220-240 W with over 250 series connected polycrystalline silicon solar cells are introduced, to obtain operating voltages around 120 V. In one type of module standard cells were cut in four to a format of 156 x 39 mm. In another type specially designed QuarterCells were used. For both types specific cell interconnection technology with overlapping cells was developed. It relies on pressure and needs neither soldering nor gluing. Results of repeated temperature cycling of the different connection technologies are presented.
Keywords: high voltage, silicon solar cell, module manufacturing, cell interconnection, degradation

1 INTRODUCTION

Today, PV-modules made from mono- or poly-crystalline silicon solar cells in the power range of 200-300 W, are "low voltage – high current" devices. They usually employ quadratic solar cells of the 5" or 6" standard yielding module voltages in the range from 30 to 50 V and currents from 5 to 9 A. The high current is a big disadvantage. For example, it requires high cross sections for the cell interconnection, and it poses more stringent requirements on capacitive and inductive components in single-module inverters. If, however, the modules were made from much smaller cells, all connected in series, a single module could give quite a high voltage and a correspondingly low current. A suitable range of operating voltages of such modules might be between 100 and 250 VDC, because it is similar to the various AC-standards, where much experience exists in technological, safety and normative aspects. E.g., thin-film high-DC-voltage modules for single-module inverters have been proposed [1].

Some important technological advantages of such high voltage PV-modules from wafer based silicon would be the following.
At the cell level:
- Smaller cells permit shorter current paths on the cell, so that the amount of metallization on the cells can be reduced.
- Smaller cells make it easier to reduce the thickness to 100 μm or below. (The thinnest cells so far are the very small sliver cells [2-4]).

At the module level:
- The cross section of the cell interconnections can be reduced in proportion to the inverse square of the current. Therefore, much less copper is needed, lowering the mechanical stress on cells, which again makes it easier to go to very thin cells.
- Thin cells can be connected in an overlap fashion, thereby reducing unused area and leading to higher power density of the module.
- Series resistance of the cell interconnection becomes less important, allowing innovative methods like pure mechanical contact.

At the system level:
- Systems can be set up with all modules connected in parallel, thereby adopting a system DC-voltage. A system can start with only one high voltage PV-module plus a standard inverter. Additional PV-modules can be added freely. Also, partial shading or different module orientations play almost no role.
- Single module inverters are technologically simpler and potentially cheaper, if the module generates a low current and a DC-voltage already in the range of the AC-voltage. Here, too, a system can start with a single module.
- Both options lower the economic barrier of PV especially for home owners and building applications in the upcoming era of non-subsidized markets.

Based on these considerations, we have begun a project to develop PV-modules with polycrystalline silicon solar cells whose area is only 1/4, 1/6 or 1/8 of a standard 6" cell, and where all cells in a module are connected in series. The modules have the size of standard modules of 60 cells (982 mm x 1629 mm in our case [5]) with typical power from 220 to 240 W.

The purpose of the present paper is the investigation of cheap but efficient interconnections of the small cells **without soldering and without gluing**. They all have in common that the cells of a string overlap in a shingling fashion and no space is wasted between the cells.

2 EXPERIMENTAL APPROACH

We use two different kinds of polycrystalline silicon solar cells: The first kind are commercial cells of size 156 x 156 mm. They are cut by laser into 4, 6 or 8 pieces of equal size, and then connected in series. The second kind are also solar cells of 156 x 156 mm, but the lay-out of the metallization on the front and back sides takes into account that the cell will later be cut into several pieces. This permits to reduce ohmic losses, and because of the overlap method no busbars are visible. This increases the power density still further.

3 MODULES WITH SMALL CELLS CUT FROM STANDARD 6" CELLS

Standard polycrystalline cells with 2 bus bars and a wafer thickness around 200 μm were used. For the first set of modules the cells were laser cut perpendicular to

the bus bars into 4 pieces of 156 x 39 mm. The nominal current of these cells is only around 2 A. Since the resistive losses along a bus bar increase with the third power of the length, the losses along 39 mm are significantly smaller than along 156 mm. In fact, the screen printed bus bars of 2 mm width and 0.015 mm height had enough conductivity to render additional soldered-on ribbons unnecessary. This made it possible to test new cell interconnection technology, where the cells are overlapped by 2 mm and a connection between two cells is made in the small regions where the back side bus bars of the top cell touch the front side bus bars of the bottom cell. However, direct gluing or soldering is not possible, because in the module the resulting rigid silicon strings of more than 150 cm length would be attached directly to the front glass via the EVA-embedding. Then, due to different thermal expansion coefficients of silicon and glass, the strings would crack within a few months of outdoor operation (we have made such tests). Consequently, the overlapping cells must be allowed to slide against each other. This can be achieved if the contact between the cells is made by pure pressure, which has already been tested successfully in NICE-modules [6].

In order to obtain a permanent force to press the bus bars of the top cell onto those of the bottom cell, short strips of coated copper ribbon ("contact strips") were placed between the top and bottom bus bars. During lamination of the module in the usual sandwich of glass-EVA-solar cells-EVA-back sheet, the bottom cell would be bent as shown in Fig.1. This bend becomes permanent, if during the final cooling phase of the lamination process the pressure is kept high until the EVA has solidified. Such bends in solar cells are also known in NICE-modules [7].
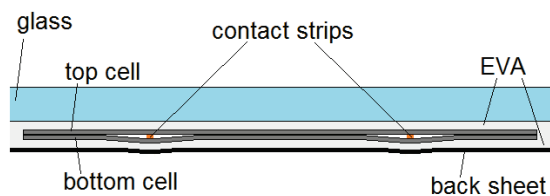

Fig.1: Cross section of a string within a module at a position where cells overlap. The bottom cell forms a bend around each contact strip resulting in good contact between the cells.

3.1 Tests with mini-modules

A demonstration that thicker contact strips leads to better contact was made by means of small modules of 5 cells each ("mini-modules"), which were exposed to accelerated degradation by temperature cycling between -26°C and +85°C. The IV-curves of the modules were measured under standard test conditions at intervals between 12 and 50 cycles and analyzed by means of the two-diode model to extract the value of the series resistance. The results for two mini-modules are shown in Fig.2. The contact strips in module HA1 consisted of SnPbAg-coated solar cell soldering ribbon with a cross section of 2.5 mm x 0.15 mm. In module HA2 the same kind of ribbon was used, but it had a cross section of 2.0 mm x 0.20 mm. (Note however, that the ribbons were only laid between the cells and were NOT soldered to

the bus bars.) In both cases the length of the contact strips was about 20 mm. As expected, the thicker contact strips of module HA2 exhibit lower series resistance in the beginning, because the force from the bends of the cells is higher. With repeated temperature cycles the series resistance increases strongly and it looks as if both types tend towards a similar, but very high value. (Data taking continues at present.)

Tests with mini-modules were also made with contact strips made of copper ribbon of similar cross sections but coated with silver. It turned out that with Ag-coating the increase of series resistance with the number of temperature cycles is very much slower. The causes still have to be clarified, because the expectation was that the soft SnPbAg-coating would get rubbed into the porous screen printed bus bars during the sliding of the cells and thereby establish better contact, while the relatively hard Ag-coating would contact only the surfaces of the screen printed particles. But possibly an increase of contact area by smearing of SnPbAg occurs between 200 and 250 cycles.

A general concern with the overlap-technology was that the 0.5 mm thick EVA-sheet between the glass and the solar cells might show bubbles after lamination or delamination after degradation tests. But this was not observed (lamination was at 800 mbar).
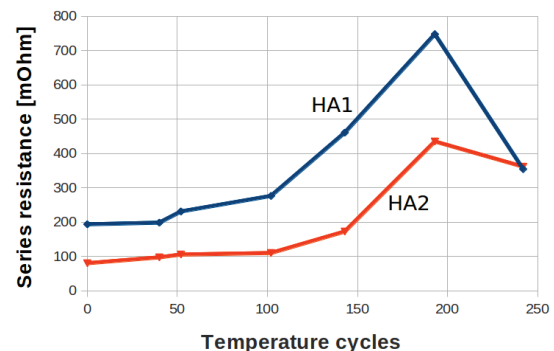

Fig.2: Series resistance of mini-modules HA1 and HA2 as a function of temperature cycles. Thicker contact strips in HA2 give higher pressure and lower series resistance.

3.2 Tests with large modules

The strings for large modules were made from 42 cells. A module contained 6 strings. All 252 cells were connected in series. Cells were selected from the same current class of 100 mA width. Since neither gluing nor soldering was employed for connecting the cells, strings were made in the following way in a semi-automated
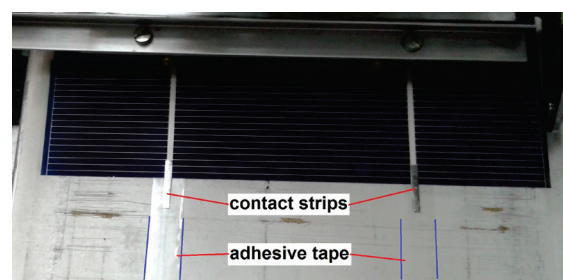

Fig.3: Method of string-making without soldering for cells of size 156 x 39 mm cut from standard solar cells.

fashion (Fig.3). Two strips of high-temperature one-sided adhesive tape (PPI 1040 W, width 10 mm, thickness 50 μm) were laid out in parallel with the sticky side up in a distance corresponding to the distance of the bus bars. Then a cell was put onto them and stuck to the tapes. In the next step the contact strips were put over the bus bars to extend into the cell for about 4 mm and onto the adhesive tape for about 16 mm, and stuck to it. Then the next cell was put on top so that it overlapped with the first cell by 2 mm. And then again the next contact strips were laid out, etc. Only at the back side of the first cell and at the front side of the last cell of a string solar ribbon was soldered on, in order to facilitate the series connection of the strings.

So far, two types of modules were made in this manner. In the first type, the contact strips were the same as in the mini-module HA2, i.e. copper strips made from solar ribbon with a cross section of 2.0 mm x 0.20 mm coated with SnPbAg. The contact strips in the other type consisted of an Ag-coated copper ribbon of a cross section of 2.5 mm x 0.19 mm.

Fig.4: High voltage module with 252 series-connected cells in 6 strings. The overlap technique avoids unused space between the cells of a string.

Figure 4 shows the mounting of one module of the type with Ag-covered contact strips on a vertical test stand facing south in a location near Vienna. The back sheet is black. In this case the standard junction box is used, with a bypass diode for every two strings, thus one diode per 84 cells. This cannot render full protection if only a single cell is shaded, because the other 83 cells generate a voltage far beyond the reverse break down of a single cell. Therefore, such high voltage modules must be connected either to single module inverters which stop drawing current below a certain voltage, or to a DC-grid via a diode, so each module is forced to operate at the

Pmax [W]: 160.6143
Upmax [V]: 119.3077
Ipmax [A]: 1.3462
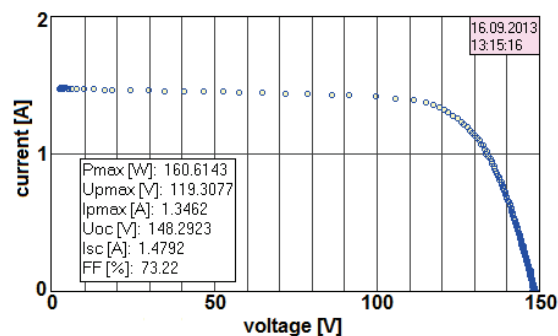Uoc [V]: 148.2923
Isc [A]: 1.4792
FF [%]: 73.22

Fig.5: Typical IV-curve of the module of Fig.4. The contact strips between the cells are Ag-coated Cu.

system voltage. A typical outdoor IV-curve of such a module is shown in figure 5. At a module temperature around 35°C the open circuit voltage is 148.3 V.

4 MODULES WITH SMALL CELLS CUT FROM SPECIALLY MADE 6" CELLS

Here we adapted the concept of QuarterCell, whose first version we introduced in [8], to allow for non-soldered and non-glued strings with overlapping cells. The screen-printed metallization of the 156 x 156 mm polycrystalline cells was modified to obtain four identical cells of 156 x 39 mm (Fig.6). The interconnection was made by means of 2 strips of 5 mm wide one-sided adhesive tape (PPI 1040 W , 50 μm thick) which were laid over each other with the sticky sides on the outside, and then pieces of coated Cu-ribbon of 50 μm thickness were wrapped around in the forms of "V" as shown in Fig.7. This connector was then put in the overlap region of two cells and the two cells were pressed together. Since the sticky sides of the two tapes stuck to the back side bus bar of the top cell and the front side bus bar of the bottom cell, respectively, the two cells became electrically connected. The cells could also move against each other as much as permitted by the bends of the "V" of the Cu-pieces, because the two adhesive tapes could slide against each other. In the
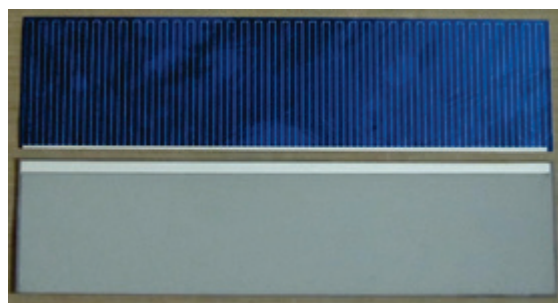

Fig.6: Front and back side of a QuarterCell. The bus bars on front and back side are on the opposite long edges to enable overlapping.

Fig.7: Back side of a cell with adhesive tape connector.

finished module the cells must be able to move a few 10 μm relative two each other to compensate the different expansion of solar glass and silicon between -40° and +90°C. This is accommodated by the bends in the Cu-ribbon, even within the EVA-encapsulant.

As may be inferred from Fig.7, the adhesive tapes receive a slight bend around the Cu-ribbon when the cells are pressed together during lamination Then the natural tendency of the tape material to straighten itself presses the coated Cu-ribbon to the bus bars of the cells. This strengthens the contact. Additionally, the contact ribbon is pressed onto the cells by the bend around it, which the cells receive during the lamination.
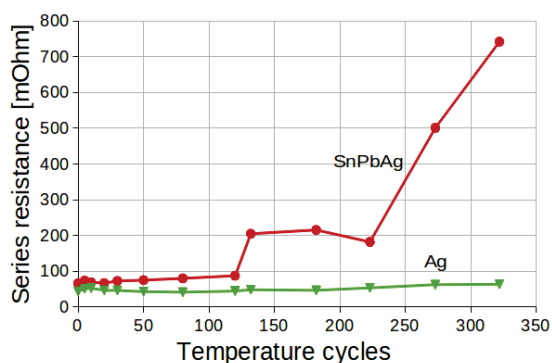

Fig.8: Series resistance of two mini-modules with QuarterCells with connector as shown in Fig.7, but with two different coatings of the Cu-ribbon.

4.1 Tests with mini-modules

Mini-modules of 5 cells each were made with two different types of coated Cu-ribbon. One had a cross section of 3.5 x 0.05 mm including a coating of 6.5 μm of SnPbAg on each side. The other had a cross section of 5.0 x 0.05 mm including a coating of 2.5 μm of Ag on each side. (Both from Schlenk Metallfolien.) Some typical results for the evolution of the series resistance as a function of the number of temperature cycles are shown in Fig.8. Clearly, the Ag-coated contact ribbon is much superior, as it shows very little increase in contact
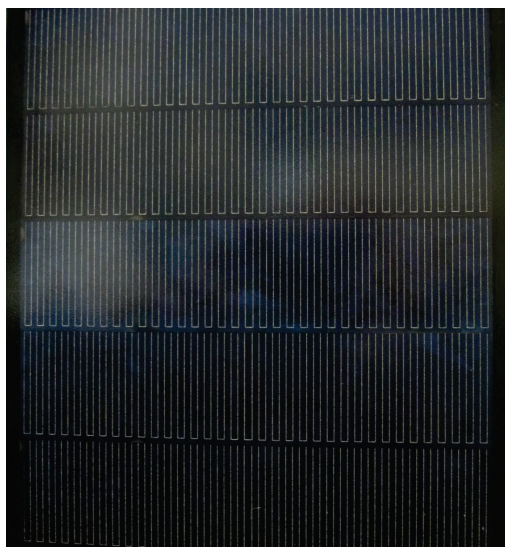

Fig.9: String section in a module with cells of Fig.6 in overlapped connection with connector of Fig.7.

resistance. With the SnPbAg-coated ribbon a similar deterioration as in Fig.2 can be observed, and interestingly, with the same temporary improvement between 200 and 250 cycles.

4.2 Tests with large modules

Tests with large modules with this type of cells have not yet started. Fig.9 shows a section of a string of such a module. No bus bars are visible. This gives higher current and 6% more STC-power than strings of the same length with standard 6" square solar cells.

5 SUMMARY AND OUTLOOK

We have tested first modules consisting of many small silicon solar cells of size 156 x 39 mm connected in series to obtain DC-voltages above 100 V for easier implementation of single module inverters or for parallel connection of the modules to a system DC-grid with a common inverter. The lower cell current permits simplified connection technology between the cells. We have introduced concepts which rely on pressure and need neither soldering nor gluing. The cells are overlapped by 1 to 2 mm and the connection is made in the overlap region. Especially Ag-coated connectors showed little degradation in accelerated aging tests. We have tested modules with cells cut from standard 2-bus bar 6"- cells and with specially designed "QuarterCells" which we introduced earlier. In the latter case resistive losses and shading are strongly reduced, yielding a 6% higher power density than standard modules of equal string size. Our tests used polycrystalline cells, but can be transferred to monocrystalline cells, too.

The currently tested modules have operating voltages between 100 and 120 V. In the next step we will produce modules of the same size but with still smaller cells and correspondingly higher voltages.

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