RESULTS OF PRESSURE-ONLY CELL INTERCONNECTIONS IN HIGH VOLTAGE PV-MODULES

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ABSTRACT: PV-modules with small rectangular solar cells from polycrystalline silicon were made in which the cell interconnections consist of overlapping the cells and placing contact strips in between. The lamination pressure bends the cells around the contact strips, which ensures good contact by "pressure-only" after the encapsulating material has hardened. Results are presented of rapid aging tests on small modules and of up to one year of outdoor experience with large modules of the 240 W class. In the latter, all cells are connected in series to obtain operating voltages around 120 V and currents around 2 A. Contact strips with coatings of SnPbAg, Ag, and pure Cu were investigated. The Ag-coated "pressure-only" contact strips performed as good as soldered cell interconnections.
Keywords: cell interconnection, silicon solar cell, degradation, module manufacturing, solder free

1 INTRODUCTION

At the EUPVSEC Paris 2013 we presented the first results of interconnecting crystalline silicon solar cells in a PV module without soldering and without gluing [1]. In this new concept, the cells are overlapped by 1 - 2 mm in the fashion of roof shingles and the electrical contact is made at the time of encapsulation by the pressure exerted during lamination. In the overlap region of the cells small contact strips are placed between the bottom bus bar of the upper cell and the front bus bar of the lower cell. During lamination the two cells become slightly bent around the contact strips, because the modules are of the glass – back sheet type. Thereby, a force pressing both cells onto the contact strips is built up and electrical contact is established between the cells. After lamination, the hardened encapsulation material retains the curvature of the cells, but its elasticity permits the cells to exert pressure onto the contact strips.

This concept requires short paths from one cell to the next, because no ribbons which could carry the current are soldered or glued onto the cells. For this reason we used cells with dimensions of 156 x 39 mm (the same width, but only one fourth the length of the currently dominant standard for crystalline silicon solar cells). We made high voltage modules by connecting 252 or more cells in series to obtain modules of the 230 – 250 Watt class. Under standard testing conditions these modules operate at typically 120 – 125 V and around 2 A. As we pointed out in [1], such high-voltage and low-current PV modules have a number of advantages, e.g. simpler and more reliable electronic circuitry in one-module inverters, and the possibility for roof-top and building-integrated systems, where all modules are connected in parallel.

In this paper we report on up to one year outdoor experience with a number of such PV modules, in which we used different materials and thicknesses for the contact strips or different geometries of cell metallization. Furthermore, smaller modules with only 5 cells were made, where additional contact strip materials, different lamination parameters, and different encapsulation materials were tested by subjecting these modules to rapid aging by temperature cycling. Many of them have by now gone through more than 600 cycles.

2 SMALL MODULES

2.1 Module manufacturing

The small modules were of the sandwich-type "glass-EVA-cells-EVA-back sheet". The glass was 2 mm thick. The back sheet was black Tedlar. Aside from the EVA encapsulant also Tectosil (made by Wacker) was tried. The solar cells were from polycrystalline silicon based on p-doped wafers of 200 µm thickness. Two different kinds of cells were used:

1) Rectangular cells of 156 x 39 mm cut from standard cells of 156 x 156 mm.
2) "QuarterCells", these are also rectangular cells of 156 x 39 mm. But they have a special metallization pattern optimized for shingling.

In order to obtain the rectangular cells of the first kind from the large quadratic cells, laser-scribed lines to about half the thickness of the cells were made. Then the cells were broken along these lines. In this way the pn-junction was not damaged. The small modules consisted of five such cells. The method of stringing is shown in Fig.1. The contact strips are pressed between the bus bars (front and back, respectively) of two neighboring cells during lamination. The connections at the ends of the string were made by soldering the SnPbAg-coated solar ribbon of 2.0x0.1 mm² cross section onto the bus bars.

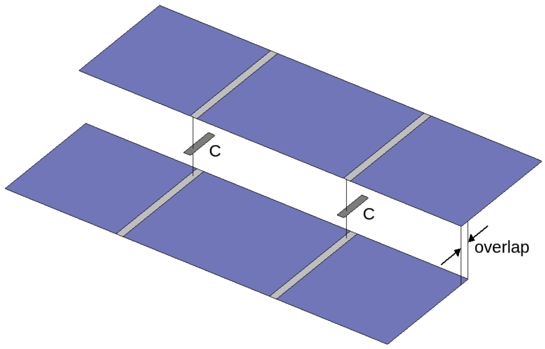

Figure 1: Two cells connected in the fashion of shingles. They overlap by 2 mm. In the overlap region two contact strips "C" of typically 2 x 15 x 0.2 mm are placed on the bus bars of the lower cell. During lamination the two cells become slightly bent around the contact strips. This ensures permanent electrical contact by pressure.

The cells of the second kind, the "QuarterCells", were introduced by us in [2]. Here, the front and back metallization pattern of the original 156 x 156 mm cells is such that, when cutting them to 4 pieces of 156 x 39 mm, one obtains four identical cells. They have a single front side bus bar which disappears under the overlap region. The back side bus bar can have different shapes, and in this work we present results from two types, which are shown in Fig. 2. The type "P" was introduced in [1] and was developed for a project with company Powerquant. Its back side bus bar is a 5 mm wide continuous strip along the edge of the cell. Therefore, when shingling the cells with 2 mm overlap the back bus bar from the upper cell lies exactly over the front bus bar of the lower cell. The type "K" was developed for a project with company Kioto Photovoltaik in which strings were made by shingling *and* soldering. But here, we tested them for non-soldered and non-glued cell interconnection. The back bus bar of these cells consists of 6 pads 3 mm distant from the edge of the cell.

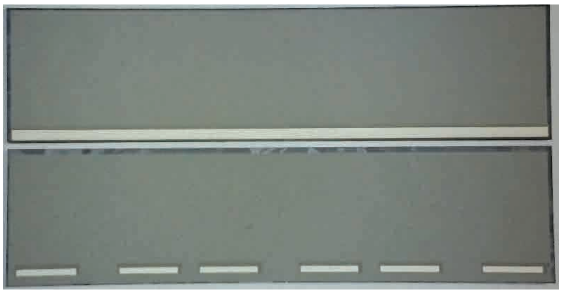

Figure 2: Back side of the QuarterCells of type P (top) and of type K (bottom). The front sides were the same.

For the QuarterCells of type P two "pressure-only" contacting schemes were tried. One was already introduced in [1]. It consisted of a 0.05 mm thick coated copper ribbon (supplied by Schlenk Metallfolien) wrapped around a special adhesive tape (PPI 1040W). The other scheme, with three contact strips, is shown in the photographs of Fig. 3.

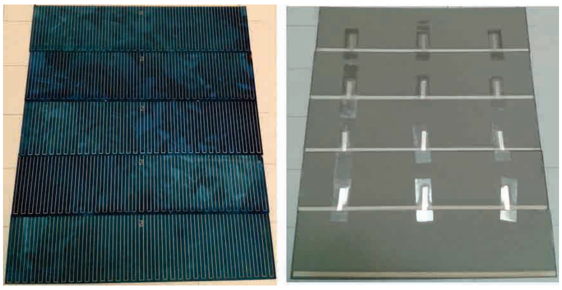

Figure 3: Front and back side of the string for a small module (HA6 in Table I) made from the specially designed QuarterCells of type P. The front side bus bar of each cell is 1 mm wide. It runs directly along the long edge of the cell and is covered by the overlap of the next cell. The back side bus bar is 5mm wide. The three contact strips between the cells are silver coated copper (2 x 20 x 0.19 mm). Cells and contact strips are held together by adhesive tape (PPI 1040W).

When shingling the QuarterCells of type K two schemes were possible. In one scheme the overlap was 5 mm, so that the front bus bar of the lower cell did lie directly below the back bus bar pads of the upper cell and simple contact strips could be placed in between (modules HA3, HA4 in Table I). In the other scheme the overlap was only 2 mm and specially embossed contact strips had to be made to ensure good electrical contact at the back bus bar pads, because the pressure came from the cell on one side, but from the EVA and the back sheet on the other side (modules HA9, HA11, SU2 in Table I).

Fig. 4 shows this scheme.

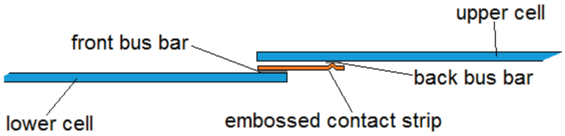

Figure 4: Shingling of QuarterCells of type K with 2 mm overlap when front and back bus bars of the two cells are not on top of each other.

2.2 Elastic deformation of cells and contact pressure

In order to obtain the bending of the cells around the contacts strips the lamination pressure was kept high until the end of the cooling phase at around 70 – 80°C. The modules MeAg1 and MeSn1 were laminated with 600 mbar, all others with 800 mbar. Fig. 5 shows the height profiles of the edges of two overlapped standard cells with contact strips of 0.2 mm thickness. Here, the "lower cell", shown in red, is the one closer to the glass, because the profile was taken from the back side. (The module for profiling had no back side EVA and no back sheet, so that the back side of the cells was free for profiling.) In the vicinity of the contact strips the data points were extrapolated (dashed lines), because the profiler did not reach the cells there. Note that the cell closer to the glass gets bent downwards by about 50 µm, while the other cell gets bent upwards by about 150 µm. The bent region around the contact strips is typically 20 mm wide. Although polycrystalline silicon is a brittle material, this amount of curvature does not seem to be a problem, as we observed cell breakages only when the width of the bent region at 0.2 mm height was well below 10 mm.

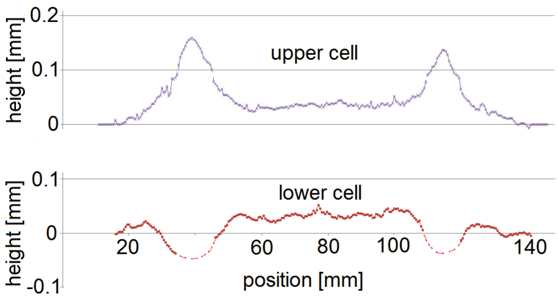

Figure 5: Height profiles of two overlapped cells along the edges of the overlap region.

2.3 Results of temperature cycling

The small modules were exposed to temperature cycling between -26° and +85°C (after about 400 cycles with the first modules this was changed to -24°C to +87°C). Each cycle takes about 8 hours. The modules were left open circuited. At least after every 50 cycles, but sometimes more often, the current-voltage curve of the modules was measured under standard testing conditions. Table I gives a list of the investigated modules, the type of cells used, and the properties of their contact strips.

The figures 6 to 8 show the results for the decline in output power as a function of the number of temperature cycles. At the time of writing not all modules had completed the same number of cycles. Each curve is labelled with the coating material of the contact strips and the module name as listed in Table I. Independent of the type of cell used, one can observe that modules whose contact strips are Ag coated have little degradation of maximum power. Those, where the coating was the solder alloy SnPbAg (63/36/1), show very heavy degradation, and those of pure copper show medium to heavy degradation.

Table I: List of small modules

Cell type	Module name	Contact strips		
		Coating, µm	TxW[mm]	#
Standard	HA1	SnPbAg, 15	0.15 x 2.5	2
	HA2	SnPbAg, 15	0.20 x 2.0	2
	HA5	Cu	0.20 x 2.5	2
	HA8[a]	Ag, ~1	0.30 x 2.2	2
QuarterCell “K”	HA3[b]	Ag, 6.5	0.19 x 5.0	4
	HA4[b]	Ag, 6.5	0.19 x 5.0	4
	HA9[c]	Ag, ~1	0.30 x 2.2	3
	HA11[c]	Ag, 6.5	0.25 x 5.0	3
	SU2[c]	Cu	0.20 x 5.0	3
QuarterCell “P”	MeSn1[d]	SnPb, 6.5	0.05 x 3.5	7
	MeSn2[d]	SnPb, 6.5	0.05 x 3.5	7
	MeAg1[d]	Ag, 6.5	0.05 x 5.0	7
	MeAg2[d]	Ag, 6.5	0.05 x 5.0	7
	HA6	Ag, 6.5	0.19 x 2.5	3

a…encapsulated by Tectosil (Wacker), not EVA
b…cell overlap of 5 mm to put front bus bar and back bus bar pads on top of each other
c…overlap and contacting as in Fig.4
d…wrapped contacts as introduced in [1]

SnPbAg: These contact strips were actually normal solder ribbons with a copper core, but here they were not soldered, but only pressed between the overlapping cells. We expected that the soft material of the SnPbAg-coating would penetrate a little into the rather rough surface of the screen printed bus bars on the cells, thereby forming a large contact area. This may have been true during the first 100 cycles (see Fig.6 and bottom of Fig.8), but then the repeated thermal expansion and contraction seems to lead to an abrasion and hence strongly fluctuating contact resistance.

Cu: The pure copper contact strips (HA5 in Fig. 6 and SU2 in Fig. 7) were cut from rolled sheets of soft copper. Interestingly, already the initial fill factor of these modules was lower than that of the modules with SnPbAg- or Ag-coated contact strips. And very soon they develop a high resistance. Both observations are somewhat surprising, because with NICE-modules, which also use pressure for contacting the cells, it was found that copper makes very reliable contact to screen printed bus bars [3,4]. Presumably traces of acid, originating from reaction with the EVA encapsulant, lead to some oxidation of the copper surface. This problem might be avoided by using, e.g. Tectosil, or a similar silicone-based encapsulant. But in unpublished tests with Tectosil we noticed that, since it becomes very liquid during lamination, it does not convey the lamination pressure fully onto the cells, so that the cells become less bent around the contact strips, which results in weaker contact pressure. The low viscosity may also lead to an insulating layer around the contact strips.

Ag: With the silver coated contact strips one notices in several cases an initial decrease in series resistance and hence an increase in power output. And then only a very slow degradation follows. One can also observe that larger contact area means less contact resistance, but also less degradation, if one looks at the modules MeAg1, MeAg2 (top of Fig.8). They had the largest contact area between the cell bus bars and the contact strips and they showed the highest initial fill factors of all small modules. This is partly owed to their cells being of type QuarterCell P, whose metallization grid has lower internal series resistance than that of standard cells with two or three bus bars. They showed a power loss of less than 1% after almost 700 temperature cycles, despite some fluctuations between 300 and 400 temperature cycles, which went as far as 2.9% power loss with module MeAg1. (This may have been due to some abrasion, as already noticed with SnPbAg-coated contacts before. The lower lamination pressure of MeAg1 compared to MeAg2 may also have been a cause.) The importance of high pressure can be seen with module HA9 (Fig. 7): It shows a strong increase of power after the first 100 temperature cycles, despite its very small contact area, but it had 0.3 mm thick contact strips (Cu-ribbon with thin galvanic Ag-coating supplied by the company Ulbrich of Austria), and thus the cells were more strongly bent around them.

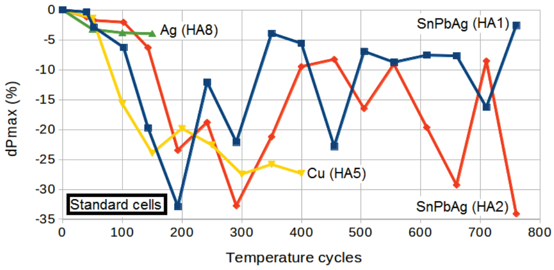

Figure 6: Degradation of maximum power for small modules made from rectangular cells cut from standard cells with two bus bars.

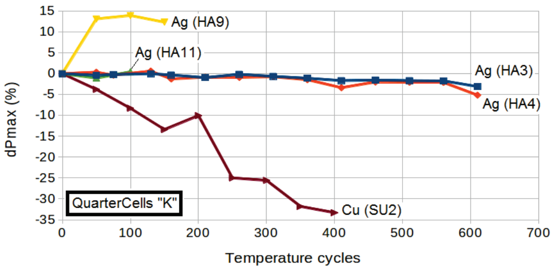

Figure 7: Degradation of maximum power for small modules made from QuarterCells of type K.

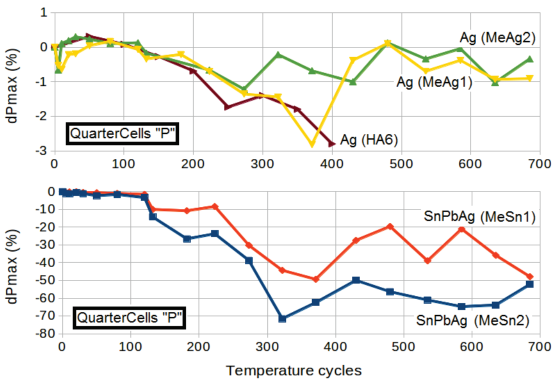

Figure 8: Degradation of maximum power for small modules from QuarterCells of type Q. Top: Ag-coated contact strips. Bottom: SnPbAg-coated contact strips.

3 LARGE MODULES

3.1 Manufacturing

Eight large modules were produced manually and mounted on an outdoor test site at the Atominstitut in Vienna, at an angle of about 10° from vertical, facing south west (Fig. 9). They were encapsulated by EVA. The back sheet was PE-based, except for module 8, which had a Tedlar back sheet. The lamination pressure was 800 mbar. All modules had 6 strings connected in series and mostly 42 cells per string. Module 8 had 41 cells per string. The cell overlap was 2 mm, except in module 5, where it was 5 mm, and where each string had 46 cells. Table II gives an overview.

Figure 9: Outdoor test site at Atominstitut, Vienna

Table II: Properties of large outdoor modules

Nr.	Cell type	Contact strips		
		coating	thickness in mm	#
1	standard	SnPbAg	0.22	2
2	standard	Ag	0.19	2
3	standard	Ag	0.24	2
4[a]	standard	soldered		2
5[b]	Qu.Cell K	Ag	0.19	4
6[c]	standard 3BB	Ag	0.24	3
7	standard	Cu	0.20	2
8[d]	Qu.Cell K	Ag	0.25	3

a…Used as reference. Cells connected by usual soldering with ribbon, but still with 2 mm overlap
b…Cells overlapped 5 mm, as in small module HA4
c…Cut from standard 156 x 156 mm cells with 3 bus bars
d…Embossed contact strips, as in small module HA11 and shown in Fig.4

3.2 Outdoor results

The modules were mounted as soon as they were available and until now some had more than one year of outdoor exposure, while others had only a few months. During the tests a phase of measuring the IV-curves every 2 minutes and leaving the modules in open circuit condition in between, alternated with a phase of short circuited modules to have maximum current and maximum load on the cell interconnections. Each phase typically lasted from a few days to a few weeks.

Figure 10 shows outdoor IV-curves of modules 1 and 2 at the beginning, and just recently. For each module the two curves were chosen for the same short circuit current. Due to different temperatures, the open circuit voltages differ slightly. As expected from experience with the small modules, the SnPbAg coated contact strips of module 1 show a large decline of power due to increasing series resistance, while the Ag-coated contact strips of module 2 show hardly any decline.

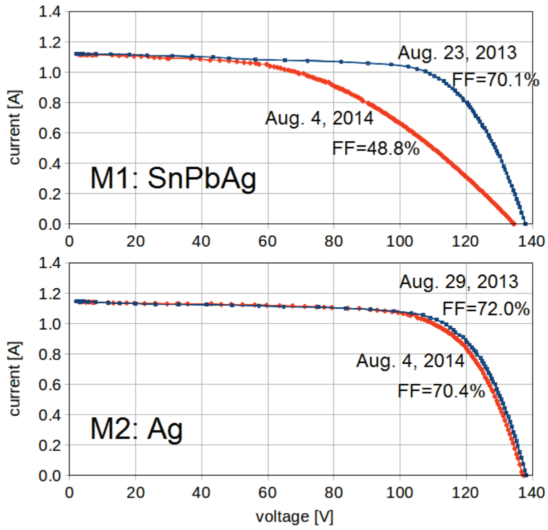

Figure 10: Modules 1 and 2 initially and more than 11 months later. (FF = fill factor.)

For modules 1-7 the decrease in output power under STC since the date of mounting is shown in Table III (Module 8 does not yet have enough data.) These are extrapolations from outdoor IV-curves, which practically never conform to standard testing conditions. Therefore, IV-curves with short circuit currents between 1.10 and 1.15 A and with open circuit voltages at the two dates as similar as possible were selected. These were then fitted with the two- diodes model, and then extrapolated to STC. ΔP was then obtained as the relative difference between the most recent data and those of the first day. The values have a typical absolute error of ±0.60 %.

Table III: Decrease of output power of large modules

Nr.	First day	Last day	ΔP [%]
1	Aug.23, 2013	Aug.4, 2014	-41.41
2	Aug.29, 2013	Aug.4, 2014	-1.82
3	Feb.13, 2014	Aug.4, 2014	-2.08
4	Feb.13, 2014	Aug.4, 2014	-2.54
5	Feb.13, 2014	Aug.3, 2014	-2.40
6	May 2, 2014	Aug.4, 2014	-1.58
7	May 2, 2014	Aug.4, 2014	-6.46

The overall result conforms to that of the small modules: The SnPbAg-coated contact strips (module 1) show the strongest deterioration. The pure copper contact strips (module 7) perform insufficiently, too. This module also had a noticeably lower initial fill factor, just as the corresponding small modules HA5 and SU2. But the Ag-coated contact strips in modules 2, 3 and 5, 6 are clearly as good as the soldered connections of module 4. So far, it is not possible to say whether their deterioration is caused by an increase of series resistance of the cell interconnections or by other factors playing a role in the first few months of outdoor operation of a module. In fact, one might consider that this initial degradation is due to other factors, as it is known that temperature cycling over hundreds of cycles puts more severe mechanical and thermal stress on a module than years of outdoor exposure in moderate climates [5]. An interesting observation can be made when comparing the soldered module 4 with those other modules which also used standard cells with bus bars: The fill factor of the soldered module is not higher! This can be explained by the fact that the current of the cells is reduced by a factor of four compared to the original quadratic cells, so that the conductivity of typical screen printed bus bars is sufficient.

CONCLUSION

Of the three types of contact strips we have currently investigated for pressure-only cell interconnections, only Ag-coated contact strips have the potential to become a real alternative for the traditional cell interconnection methods of soldering or gluing. Our results suggest that pressure-only interconnections in overlapped cells work very reliably for PV-modules made from many small cells for low current and high voltage. This opens a path to cheaper manufacturing of modules as well as to very thin crystalline silicon solar cells, because the problems of thermal stress of soldered or glued connections do not exist. Since the cells must overlap to form the connection, they can be designed without visible bus bars, thus raising the power density of the modules by several percent as was shown earlier with our QuarterCell concept. Furthermore, the amount of copper in the modules is easily reduced by more than 70%, and perhaps by as much as 90%, compared to traditional modules of similar power.

References

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