Electrically Conductive Adhesives as Cell Interconnection Material in Shingled Module Technology

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Abstract. Shingled modules, in which pre-cut crystalline silicon solar cells are assembled into solar modules by placing them one by one on top of each other, have gained a lot of market attention in the last year. The shingling approach has as main advantage increased module output due to more efficient packing without inactive space between cells. An additional benefit is that no important modifications to the cell production process are needed. The first commercial market-available modules are use electrically conductive adhesives (ECAs) to connect the pre-cut cells – or shingles – into strings. This paper will demonstrate that using ECAs with optimized properties will result in reliable solar modules. Adhesive properties such as adhesion strength, Young's modulus, volume resistivity and contact resistance are shown in combination with the reliability data of ECA-assembled modules. Application techniques suitable for high-volume manufacturing are demonstrated.

PURPOSE

Most solar modules currently on the market are built up from ribbon-attached crystalline H-pattern cells in which the ribbons are interconnected to the cells via soldering. The advantage of this approach is the low-cost interconnection and the robustness of the technology. Some disavantages, however, such as high resistive losses and the incompatibility with very thin wafers. One of the new, promising advances for module assembly is shingled modules technique whereby pre-cut crystalline cells are placed like roof tiles on top of each other (FIG 1). Interconnection of the different pre-cut crystalline cells is achieved via electrically conductive adhesives (ECAs), which have an advantage over soldering in that they can absorb stresses due to CTE mismatches in the module. Commercially available, higher-power density modules based on this technology are the Sunpower® Performance Series solar panels [1] and Solaria PowerXT® solar panels [2]. The most important drivers for introducing this alternative module design are increased power output, reduced ohmic losses due to smaller currents in strings, no residual stress between the silicon and metal, compatibility with thinner cells and other cell technologies, and, finally and most importantly, optimized cell to module active area due to the tighter cell packing with no important modification to the cell production process.

Currently, there is market available equipment capable of mass producing shingled modules [3] and with the work presented in this paper, it is demonstrated that by using the correct electrically conductive adhesives in combination with an accurate stringing assembly tool, there is a great potential for shingled module technology in terms of module power out-put and reliability performance at reduced cost.

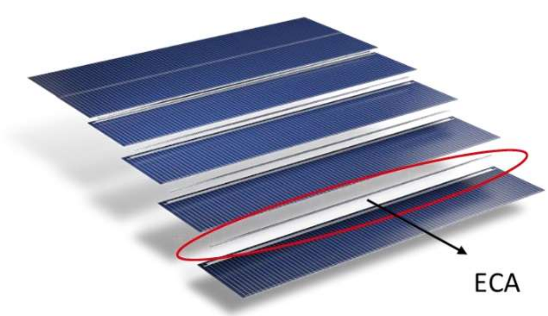


FIGURE 1. Assembly scheme of pre-cut cells with electrically conductive adhesives

MATERIAL PROPERTIES

The two materials studied in this paper are both acrylate based ECAs which are highly reactive and for which full cure can be achieved in 15 seconds at 150°C. The material properties of ECA-A and ECA-B are presented in Table 1. In order to have a good shingle module performance, the ECAs need to have good and stable electrical performance combined with strong adhesion and the capability to absorb stress. The reliability data in Table 1 shows the contact resistance of the different ECAs to Ag-coated Cu-ribbon and Sn-coated-Cu ribbon. The Ag-coated ribbons are used to mimic the electrical contacts in the module between the silver busbar and the conductive adhesive. The ribbons used are the same as the ribbons used in the modules for bussing different strings to each other.

ECA-A is a high-density electrically conductive adhesive with reliable electrical performance on Sn-, SnPb- and Ag-coated Cu-ribbon after thermocycling between -40°C to 85°C open conditions and after storage at 85°C and 85% humidity open conditions. The second material presented is ECA-B, which is a low density electrically conductive adhesive with stable electrical properties on Ag-coated Cu-ribbon after thermocycling between -40°C to 85°C open conditions and after storage at 85°C and 85% humidity open conditions. Due to the low density of this adhesive lower weight amounts are needed to bond the shingles. The adhesion strength of the two materials is very comparable and a bond strength of aluminum to aluminum of above 10 MPa is reached for both materials.

TABLE 1. Material properties of ECA-A and ECA-B

Property	Units	ECA-A	ECA-B
Bulk resistivity	Ohm·cm	$2{\cdot}10^{-4}$	$2{\cdot}10^{-3}$
Tensile Lap Shear Strength (Al/Al)	MPa	11.5	10
E‘-modulus at -50°C	MPa	12000	6645
E‘-modulus at 25°C	MPa	4900	1388
Cr-Ag ribbon	mOhm	2	6
Cr-Ag ribbon after 3000 hours 85°C/85%RH	mOhm	2	12
Cr-Ag ribbon after 300c -40°C/85°C	mOhm	3	6
Cr-Sn ribbon	mOhm	16	NA
Cr-Sn ribbon after 3000 hours 85°C/85%RH	mOhm	15	NA
Cr-Sn ribbon after 300c -40°C/85°C	mOhm	20	NA

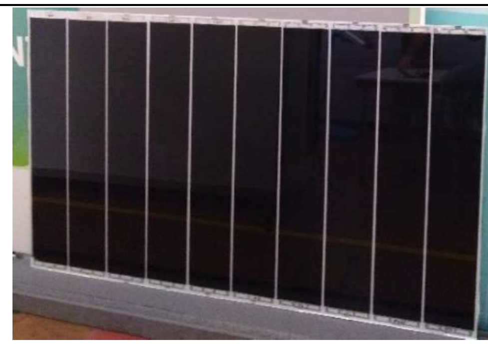
MODULE ASSEMBLY

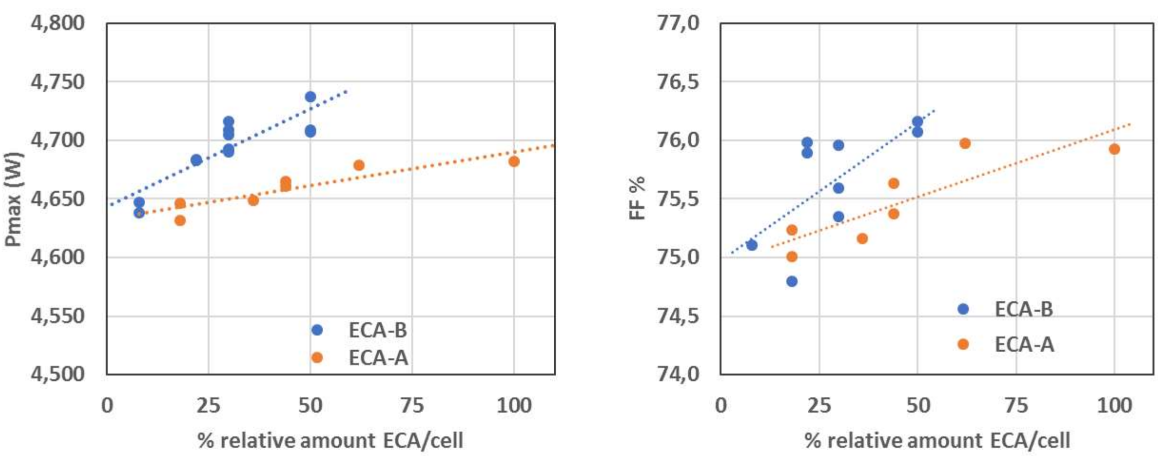
To better understand the performance of the ECAs in full modules, one cell-shingled modules (mini-modules) and 1-meter long string modules were assembled. With the mini-modules, a study was conducted to determine the amount of material needed to obtain a high-efficiency module. Assembly of the modules and mini-modules were carried out with the Applied Materials tool [3]. The application of the ECA to the silver busbar of the cell was achieved via screen-printing. This is in comparison to reference mini-modules for the two ECAs where the material was applied via dispensing. Details of the assembly are described in Table 2.

The mini-modules (single cell-modules) were build up out of five shingles (single cell module). For the single-cell modules, monocrystalline PERC solar cells of engineering grade quality were used. These cells were sorted by efficiency in 0,1% bins to relate the observed changes to the varied parameters and not to the cell variances. For bussing the string, a SnPb/Cu-ribbon was used, and the ribbon attach was done with ECA-A. For comparison, ribbons for two mini-modules were also soldered. Shingle attach was carried out with ECA-A or ECA-B. The amount of ECA was varied between the different mini-modules by the number of printed pads. All pads were 350 µm wide by 5 mm long and the different pads were evenly distributed over the full length of the shingle. Overlap of the shingles was 1.8 mm. The ECA curing temperature was 150°C.

Modules built up out of 1-meter long strings of 40 shingles (string modules) were assembled in the same manner as the single-cell modules, but different PERC solar cells were printed and cut in six shingles. For bussing these strings, the SnPb/Cu-ribbons were not interconnected by means of a conductive adhesive but were soldered. For the cell-to-cell attachment, twelve pads per shingle were printed in groups of four close to each other. The pads were 750 µm wide by 4mm long.

TABLE 2. Details of shingle cell modules and 1-meter long string modules.

	Mini-Module	Module
Picture		
Cell type	mono-crystalline PERC 5 shingles/cell	mono-crystalline PERC 6 shingles/cell
Shingle overlay	1.8mm	1.5mm
Pad dimensions	Varied number of pads of 5 mm by 0.35 mm or full line	11 pads of 4 mm by 0.75 mm
Shingle attach	ECA-A or ECA-B	ECA-A or ECA-B
Ribbon attach	ECA-A or Solder	Solder
Application method	Print or Dispense	Print



(a) (b)

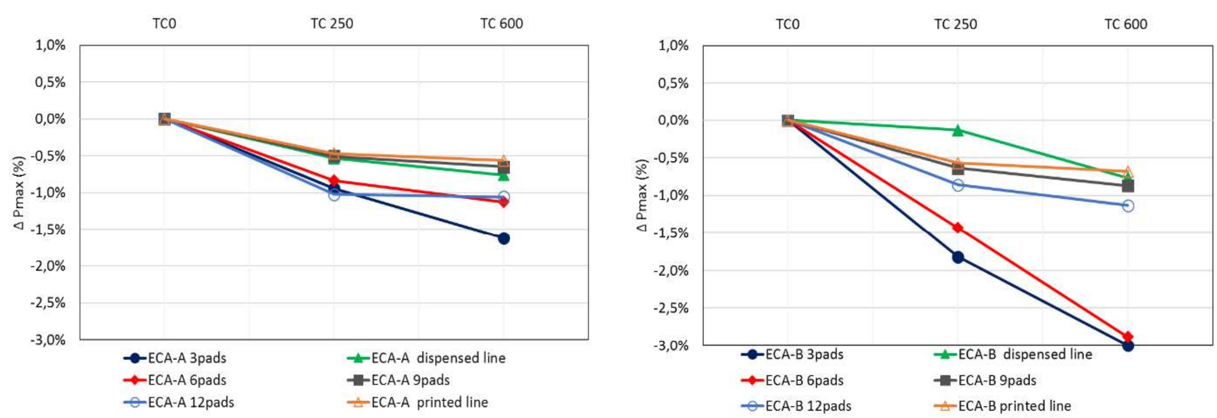
FIGURE 2. a) Influence of amount of ECA on the power output and b) on the fill factor of these single cell module.

MODULE PERFORMANCE

The mini-module performance was tested with the Meyer Burger 'Pasan Spot^{LIGHT} cell tester. In Fig. 2a and 2b respectively, the fill factor (FF) and the power output (Pmax) of a five-shingle single-cell module are shown. Only the mini-modules, which were printed on the Applied Materials' tool, are shown in Fig. 2. For ECA-A, the amount of adhesive on one cell, was varied from 18% to 100% relative weight/cell and for ECA-B, the amounts of adhesive on one cell, was varied from 8% to 50 relative weight/cell. Varying the applied amounts on the cells was facilitated via specially designed screens with 3, 6, 9, or 12 pads or a full line design.

FF and Pmax increase upon higher volumes for both ECA's. Power output increases with 2% per cell from 8% to 50% relative weight/cell for ECA-B. This indicates that a strong reduction of the ECA deposit is possible without significantly affecting the electrical performance of the module. ECA-B, in particular, allows extremely low deposits with only a small effect on power output of the mini-module.

To mimic the effect of outdoor conditions, the mini-modules and 1-meter long string modules were cycled between -40°C and 85°C, according to IEC 61215:2005 standard. In Fig. 3 a and 3b, ΔPmax in function of the number of thermocycles is shown for ECA-A and ECA-B. The data shown in Fig. 3 are an average of two mini-modules for each condition. All mini-modules have a decrease in power output of less than 3% after 600 cycles from -40°C to 85°C. Some stronger losses for Pmax for ECA-B are seen when lower ECA amounts are applied. For example, the mini-modules with only 8% relative weight/cell of ECA-B had an average decrease in ΔPmax of 2.9% versus an average decrease of 1.1% for the mini-modules with 22% relative weight/cell. This same trend can be observed for ECA-A, though less pronounced and with lower losses in power output. For example, a ΔPmax of 1.5% versus 1.1% for respectively 18% relative weight/cell versus 44% relative weight/cell of ECA-A. This may indicate that very low amounts of ECAs per cell could reduce the long-life performance of the modules, though the cause could be attributed to the fact that only three or six connection points were used and were likely too low a quantity to manage the module stresses during cycling; a more evenly distributed pattern may need to be applied. Therefore, it is important to optimize the size, quantity and distribution over the cell to optimize the ECA usage in the module. In addition to mini-modules in which the ECA was printed, reference mini-modules were made in which the ECA was dispensed on the bus-bar of the cell. For both ECAs the same 0.7% loss in power output is found for all mini-modules, regardless of whether the material was dispensed or printed. This, of course, can be related to the amount of material that is applied, which was identical in both cases. However, based on tests that were preformed, printing provided the simples approach to reducing the amount of material applied due the ease of changing the screen design to reduce the quantity and size of the pads. In addition, with printing at 200mm/s a complete cell can be printed in one stroke, whereas with dispensing at 200mm/s only one shingle is prepared. So, based on the busbar design of the solar cell, printing is a much faster application technique by a factor of four or six as compared to dispensing.



(a) (b)

FIGURE 3. Thermal cycle performance of single cell modules with (a) ECA-A and (b) ECA-B

Bussing the ribbons in standard modules is normally done via soldering, in this work for almost all mini-modules the ribbons were attached with ECA-A. To study if the connection with ECAs had some effect on the performance of the mini-modules, the ECA process was benchmarked against standard bussing with soldering. The data are shown in Fig. 4 and are an average of two mini-modules for each condition: mini-modules with 44% relative weight/cell of ECA-A bussed with ECA-A or with solder are evaluated in function of cycling times from -40°C to 85°C. Based on the results, it appears that attaching the ribbon to the string with ECA produces better mini-module reliability performance, see Fig 4. The mini-modules with ECA attachment of the ribbon show only a decrease of 0.65% in power output, whereas with soldering we found a decrease of 2.04% in power output. This may be related to the strong warping of the cell observed after cooling down from the soldering temperature. Cell warpage is much higher upon cool-down from the elevated temperatures of around 270°C needed for soldering, compared to the cell warpage from the relative low temperatures of 120°C-160°C needed for curing ECAs.

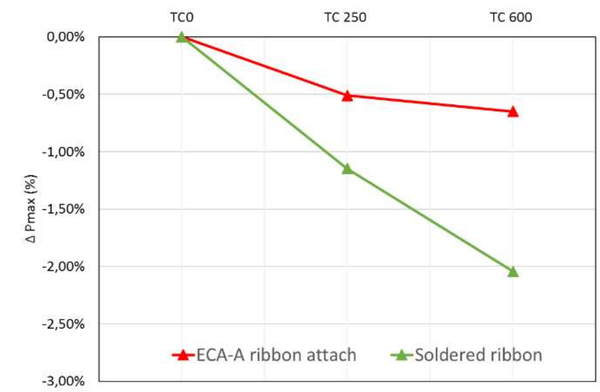


FIGURE 4. Thermal cycle performance of single cell modules assembled with ECA-A as shingle attach and ribbon attach compared to single cell modules assembled with ECA-A as shingle attach and soldered ribbon.

To further evaluate the performance of the acrylate ECAs, full modules with 1-meter long strings were assembled and cycled from -40°C to 85°C, see Fig. 5. For ECA-A, an average of three strings and for ECA-B, an average of two strings are plotted. Both materials show only a decrease in power out-put of below 1% after 200 thermocycles. But, one can see that a lower difference in Pmax after 200 thermocycles compared to the initial Pmax output for ECA-A versus ECA-B. This can most probably be explained by the lower contact resistance and bulk resistivity of ECA-A as compared to ECA-B and the fact that the same volume and contact area was used in the module assembly.

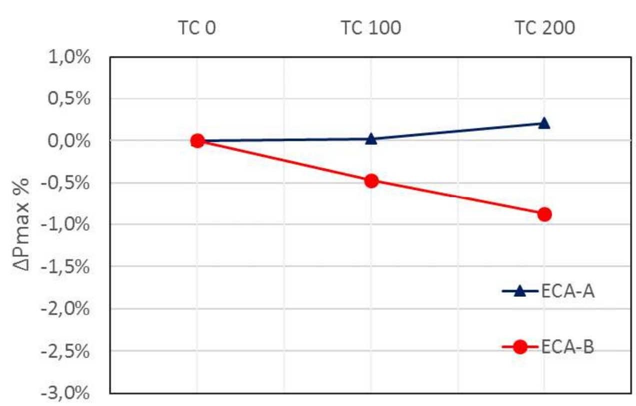


FIGURE 5. Thermal cycle performance of modules assembled with ECA-A and ECA-B.

CONCLUSION

The use of electrically conductive materials to assemble shingled modules in a reliable way was proven both for single-cell modules as well as full, 1-meter string modules. In addition, it was shown that the use of electrically conductive materials as bussing material for the ribbon is more favorable than soldering of the ribbon. Moreover, application performance in high-volume processes of these ECAs was demonstrated. It was proven that extremely low deposits without a big performance degradation is possible. Together, these results demonstrate the potential for high reliability, cost-competitive shingled module technology through the use of ECAs.

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