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Energy Procedia 67 (2015) 175 – 184

Energy Procedia

5th Workshop on Metallization for Crystalline Silicon Solar Cells

Cross testing electrically conductive adhesives and conductive back-sheets for the ECN back-contact cell and module technology

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Abstract

ECN set up a cross testing project in which suppliers of electrically conductive adhesives (ECA) and conductive back-sheet (CBS) foils participated. In the component part of the project, combinations of adhesive and foil were characterised for peel strength and contact resistance. The separate components were tested on dot geometry (ECA) and surface structure (CBS). In the module manufacture and testing part, 12 combinations of ECA and CBS were used in 4-cell MWT modules. The modules were tested up to 2000 hours in damp heat and 400 thermal cycles (both tests, 2 times the requirement of IEC61215).

Most combinations passed the 5% power loss criterion. One of the conductive adhesives performed well on three different types of back-sheet which is supportive of a robust technology. Other results show that it is important to thoroughly test interesting combinations of ECA and CBS at module level before adding them to the recommended bill of materials.

Peer-review under the responsibility of Gunnar Schubert, Guy Beaucarne and Jaap Hoornstra

Keywords: Electrically conductive adhesives; ECA; conductive back-sheet foil; CBS; back-contact; MWT; durability testing

1. Introduction

ECN has developed an integrated cell- and module technology for back-contact cells, using a conductive back-sheet (CBS) foil. The interconnection between cells and CBS is based on an electrically conductive adhesive (ECA) which is cured during the lamination cycle of the laminate [1]. The technology has proven to be reliable in climate chamber testing of MWT modules [2-5] and IEC certification has been achieved by the module manufacturers Tianwei New Energy Holdings [6] and Nanjing Sunport Power [7]. A high power 60-cell module with over 300 Wp made with n-MWT cells was manufactured in September 2014 [8].

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Peer-review under the responsibility of Gunnar Schubert, Guy Beaucarne and Jaap Hoornstra
doi:10.1016/j.egypro.2015.03.301

The conductive back-sheet in the current design consists of a sheet of copper laminated to a PET-PVF laminate as used in conventional modules. The copper is patterned to match the contact pattern on the rear side of the back-contact cells. During the module manufacturing process, the conductive back-sheet foil is fixed to a vacuum carrier after which conductive adhesive dots are stencil printed at positions corresponding to where the contact pads of the cells will be positioned. Next, a sheet of perforated EVA is placed on the back-sheet with the openings in the EVA corresponding to the position of the conductive adhesive dots. The conductive adhesive dots have a height greater than the EVA thickness. The cells are then placed on the stack, so making contact with the conductive adhesive. The stack is finished with a second sheet of EVA and a glass sheet. The stack is then inverted and laminated to cure the adhesive and EVA in one step.

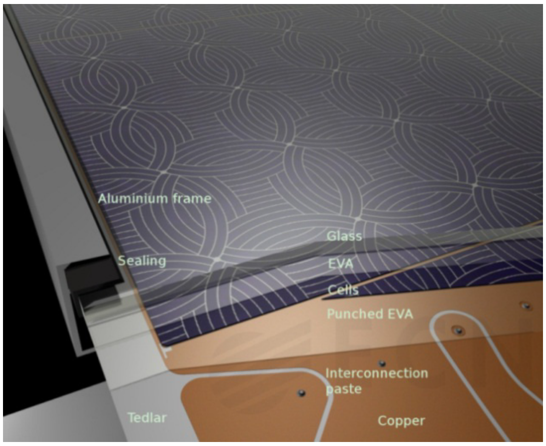

Fig. 1: Cross-section through a back-contact module showing the patterned copper layer in the conductive back-sheet, the interconnection paste (i.e. ECA), the EVA perforated at the position of the interconnection and the MWT cells.

The conductive back-sheet was adapted a few years ago under pressure from the market that demanded a lower cost price for the technology. The old CBS had silver plated contact spots and a mask print to facilitate the plating process, while the current CSB foils are mask-free and they are directly contacted by the conductive adhesive. Another development was that the structuring of the CBS could not only be done by etching the conductive layer, but also by milling [9]. A protective layer is usually applied to protect the surface of the copper against oxidation during storage. If the copper layer is structured by etching, an organic solderability preservative (OSP) can be applied. This is often a very thin layer of a benzimidazole based organic material that melts and dissolves during soldering. If the CBS is structured by milling, the copper is usually protected by a $ZnCrO_4$ finish applied by the manufacturer of the copper foil. Both types of preservatives were not developed for use with conductive adhesives with a different chemistry and a lower processing temperature than solder and the compatibility with existing ECAs was not trivial.

Developments in the conductive adhesives were that the chemistry was adapted to improve the contact resistance and peel strength on a range of OSP layers and $ZnCrO_4$, and the silver content was decreased to get a lower price level reducing the cost of the adhesive by over 50%. The silver content was reduced from over 80 wt-% to less than 20 wt-% in a few years' time by replacing the silver particles by silver coated metal particles. ECAs with even lower silver content are under development [10] and will be tested in back-contact modules.

In this article the cross testing results of four selected ECAs and three CBS foils will be presented. Experiments on component level show the peel strength, the contact resistance, the geometry of stencil printed ECA dots and the surface characterisation of the CBS foils. Experiments on 4-cell module level show the cell-to-module (CtM) losses of the 12 combinations and the influence of climate chamber testing. The objective of the research is to investigate the contribution of different materials to the robustness of the back-contact technology.

2. Cross test set-up

ECN set up a cross testing project in which three suppliers of electrically conductive adhesives (ECA) and three suppliers of conductive back-sheet (CBS) foils participated.The suppliers were invited to send their components for screening on peel strength and contact resistance. A total of 31 ECA-CBS combination were screened and each supplier selected its best performing component for further testing. For clarity, the results of component testing show only the results of the selected components and a reference adhesive (ECA 4). The suppliers and product numbers cannot be revealed as agreed in the research contract. The ECAs in this paper are numbered 1 to 4 and the CBS foils A to C, see Table 1.

Table 1: Presentation of the selected materials

#	ECA description	#	CBS description of conductive layer
1	Low silver content	A	Copper with $ZnCrO_4$ finish
2	Low silver content	B	Copper with OSP finish
3	Low silver content	C	Aluminium with copper finish
4	High silver content		

The components were at first tested on peel strength and contact resistance in most of the ECA-CBS combinations. After this the printability of the adhesives was tested by characterisation of the printed dots, the roughness of the CBS foils was determined and the surface of two foils was analysed by XPS. In the module manufacture and durability testing part, 12 combinations of ECA and CBS were used in 4-cell MWT modules. The modules were tested up to 2000 hours in damp heat and 400 thermal cycles (both tests equivalent to 2 times the requirement of IEC61215).

3. Component testing

3.1. Peel strength

The adhesion of the adhesive to the foil has a strong influence on the module lifetime and this aspect was therefore tested in a peel test. The test was performed on 6 mm wide CBS-ECA-CBS strips, connected in a T-peel sample, and a peel orientation of 180° (See Fig. 3). The ECA had been stencil printed on the CBS with a layer thickness of 200 microns that simulated the thickness of the EVA layer in the modules. The strips were laminated as in a standard lamination cycle. Four samples per ECA-CBS combination were used and the maximum peel force was measured. The median results per combination were converted to a peel strength, see Fig.4. The peel test results show some variation, but no significant trend for a particular ECA or CBS was found.

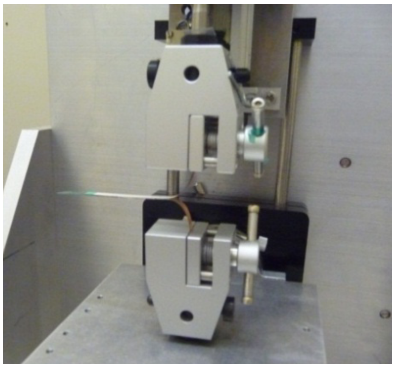

Fig.3. T-peel sample during testing.

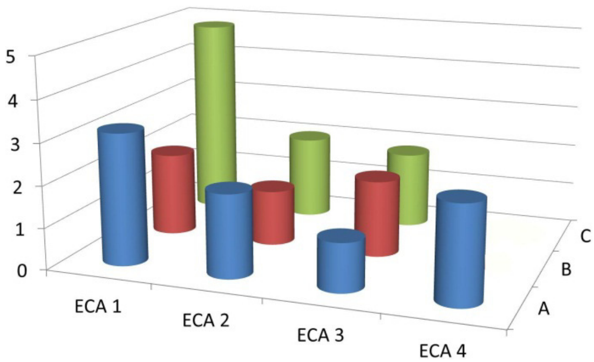

Fig. 4. Median peel strength in N/cm. The combinations 4-B/C were not available at the time of testing.

3.2. Contact resistance

The electrical resistance between the adhesive and the cell and between the adhesive and the conductive back-sheet determines the electrical losses in the module. The contact resistance was therefore measured in a dedicated CBS-ECA-CBS test structure (See Fig. 5) consisting of two structured back-sheet foil layers. Structuring was done by mechanical milling at Eurotron. This method of patterning prevents any damage or chemical finish alteration on the foil surface. Contact resistance is defined in this project as the resistance of the whole contact, thus the sum of twice the resistance of the interface ECA-CBS plus the bulk resistance of the ECA dot. Each contact was measured by a 4-point method and the final value was taken as the median resistance of all contacts, see Fig. 6.

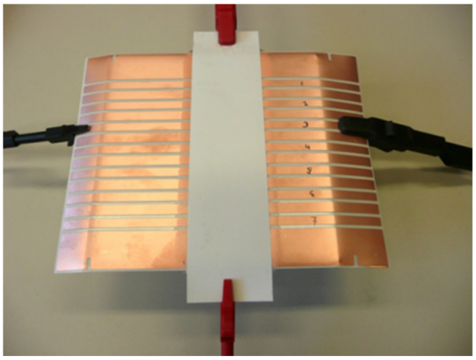

Fig.5. Sample for contact resistance measurements on 7 CBS-ECA-CBS contacts.

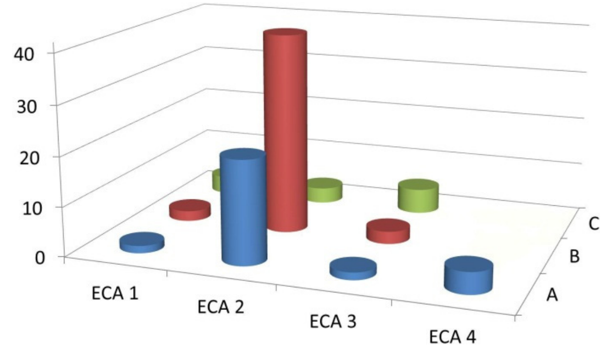

Fig. 6. Median resistance of the CBS-ECA-CBS contacts in mΩ. The combinations 4-B/C were not available at the time of testing.

The preferred contact resistance for an interconnection is below 3 mΩ. The test sample contains 2 times the resistance of the interface ECA-CBS, but as the interface ECA-cell metallisation is considered to be lower than ECA-CBS, the value of 3 mΩ is still a safe criterion.

Only four combinations met the criterion. The ECA 2 combinations on foil A and B were absolutely out of specification. Also CBS-type C was on the high side (3.2-5.1 mΩ), as well as combination 4-A (4.4 mΩ).

3.3. Dot geometry

The printability of the ECAs was tested by stencil printing dots on type A of the selected CBS foils. The stencil hole dimensions were identical as in the module build, namely ∅1.7 x 0.4 mm. The foils with printed dots were cured on a hot plate and five dots per ECA were characterised by confocal microscopy. The results of this measurement are shown in Figures 7 and 8.

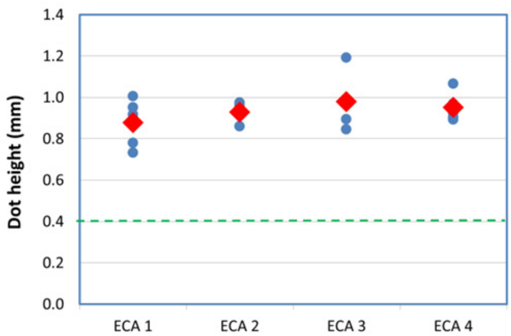

Fig.7. Individual heights of the stenciled dots (circles) and average value (diamond) per ECA. The stencil thickness was 400 micron.

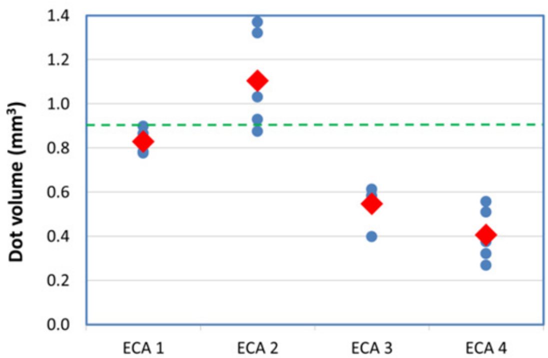

Fig.8. Individual volumes of the stenciled dots (circles) and average value (diamond) per ECA. The hole volume was 0.91 mm^3.

The height of all dots was in the same range, namely twice the stencil thickness. The height of a dot increases during lifting of the stencil due to friction to the walls of the stencil hole. This result implies that all ECAs were printed high enough to make contact with the cells as the EVA thickness was 200 microns. A significant difference is found in the dot volumes. The volume of ECA 1 equals nearly the hole volume, whereas the volume of ECA 2 is higher than the hole volume even after curing. An explanation of this observation was found in the relatively low viscosity of ECA 2, and a possible explanation is that in the double print strike a part of the ECA had flowed under the stencil. The volumes of both ECA 3 and 4 were significantly lower than expected, due to insufficient releasing of the ECAs from the stencil holes.

Figures 9 and 10 show pictures made by confocal microscopy that are examples of a good dot geometry with a constant cross section area over the height of the dot (ECA 1), and a poor geometry with a varying cross section area (ECA 2).

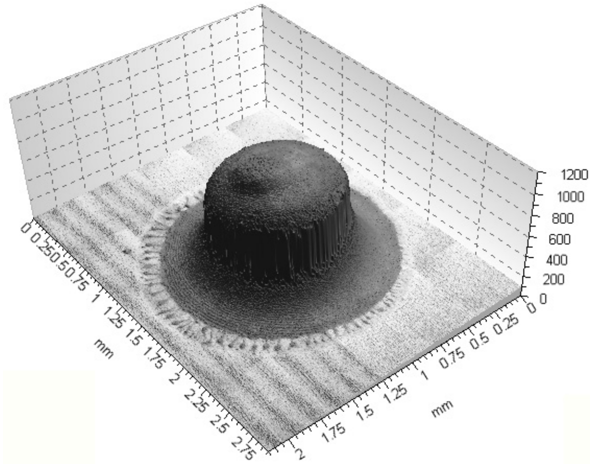

Fig.9. A printed and cured dot of ECA 1 as an example of a good geometry.

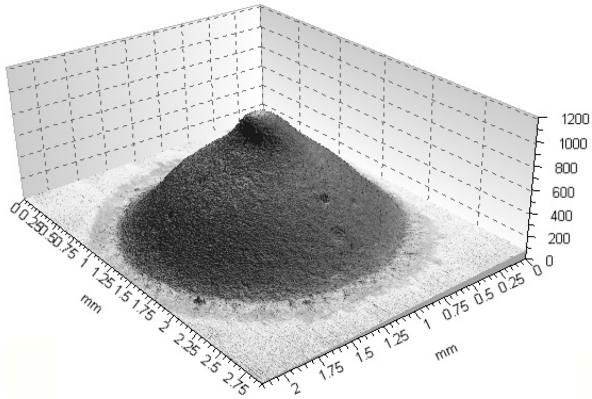

Fig.10. A printed and cured dot of ECA 2 as an example of a poor geometry.

3.4. Surface characterisation

The conductive back-sheets were characterised on roughness by confocal microscopy. A SEM picture (Fig. 11) and a confocal picture (Fig. 12) of CBS A are included as an example.

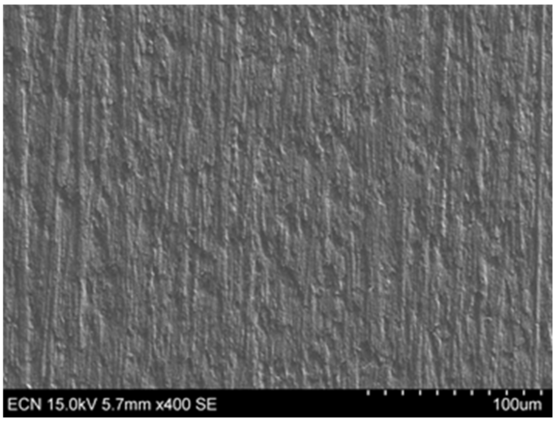

Fig.11. SEM picture at 400x of conductive back-sheet A

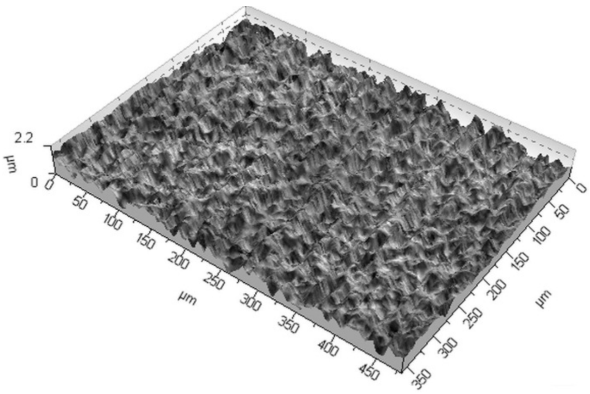

Fig.12. Confocal microscopy picture of the same.

Table 2 shows the roughness as the arithmetic mean height R_a in one direction or S_a in two directions. The roughness values of all three back-sheets are in the same range and no influence on the adhesion of the ECA due to surface enlargement is expected. Table 2 also contains the results of XPS-analysis of two out of three back-sheets.

Table 2: Roughness values and composition of top-layer

CBS	Ra (µm)	Sa (µm)	XPS-analysis
A	0.13	0.30	Zinc chromate
B	0.10	0.19	Benzimidazole on zinc chromate layer or remains
C	0.05	0.16	N.a. (Top-layer is copper according to supplier)

The composition of CBS B was a surprise. The zinc chromate layer is usually stripped-off during etching in the structuring process. It is not clear if a uniform chromate layer was present or that only the remains of the layer were detected. An influence on the peel strength and contact resistance was expected, but this was not significant, see Figures 4 and 6.

3.5. Discussion on the component test results

The electrical resistance between the adhesive and the cell and between the adhesive and the foil determines the electrical losses in the module. The adhesion of the adhesive to the foil has a strong influence on the module lifetime. Both aspects are dependent on the adhesive-foil interaction, particularly on the surface treatment of the foil and on the chemistry of the adhesive. In spite of the fact that all foil interfaces were different, no clear influence of foil nor ECA was found. In the case of contact resistance the differences were higher. In general, ECA 2 had a much too high resistance in 2 out of 3 combinations and CBS C showed resistances that were on the high side. Oddly enough the combination 2-C had one the lowest values whereas the highest was expected. This shows that materials selection must be done on combinations of both foil and adhesive and that the results of one combination are not necessarily transferrable to another combination.

The surface condition of CBS B did not look optimal with remains of a zinc chromate layer under the OSP finish. However, this did not result in a significantly bad peel strength and in the case of contact resistance 2 out of 3 ECAs gave a good result on this foil.

The rheology of an ECA plays an important part in the geometry of the stencil printed dot and in the printed volume. Also the adhesion of the ECA to the walls of the hole in the stencil is expected to attribute to the geometry and the volume. The results show that ECA 1 printed dots with a good shape, whereas the ECA 2 had a too low viscosity that probably resulted in dots with a non-optimal shape and a too large volume. The prints of ECA 3 and 4 showed a relatively low volume.

4. Module manufacturing and durability testing

4.1. Module manufacturing

The 12 selected ECA-CBS combinations were presented in Table 1. Five 4-cell modules were manufactured per combination; two for damp heat (DH) testing, two for thermal cycle (TC) testing and one spare. The mechanical structuring of a CBS is shown in Fig. 13. Only the back-sheets A and C were patterned in this way as the supplier of type B preferred to use its own patterning process. A completed module is shown in Fig. 14.

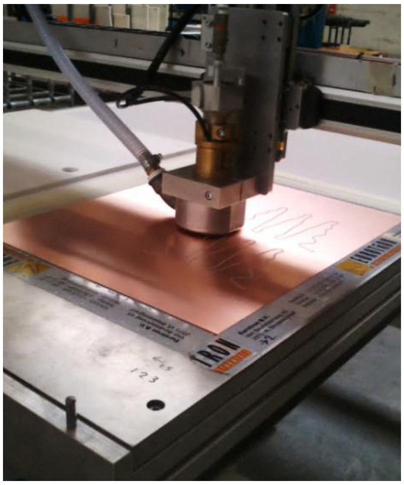

Fig.13. Mechanical structuring of a conductive back-sheet performed at Eurotron. Not all foils were mechanically structured depending on the preference of the supplier.

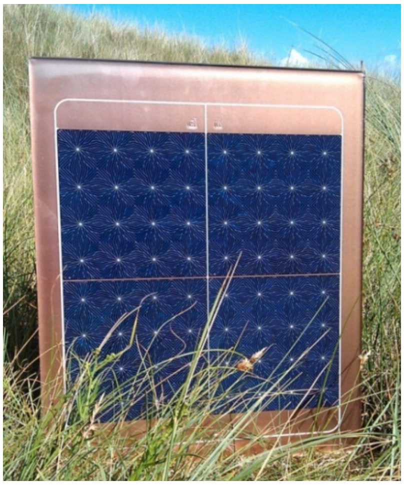

Fig.14. An example of one of the 4-cell modules used for climate chamber testing.

The average cell and module parameters are given in Table 3, including the average cell-to-module (CtM) changes. The average results were a little below the expectations of a well performing 4-cell module with a target value for CtM in the fill factor of -2.5%; the average value of all modules was -3.3%.

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Table 3: Average cell and module parameters

Parameter	Cells	Modules	CtM change
I_{sc}	8.433 A	8.489 A	+0.7%
V_{oc} (4-cells)	2.438 V	2.445 V	+0.3%
Fill factor	77.19%	74.63%	-3.3%
P_{mpp} (4-cells)	15.87 W	15.50 W	-2.3%

A closer look to the CtM changes is done for the fill factor results per combination of 5 modules in Figure 15. In this figure a CtM loss of at maximum 2.5% is taken as the limit for a good performing module, while a loss higher than 3.5% refers to an out of spec module.

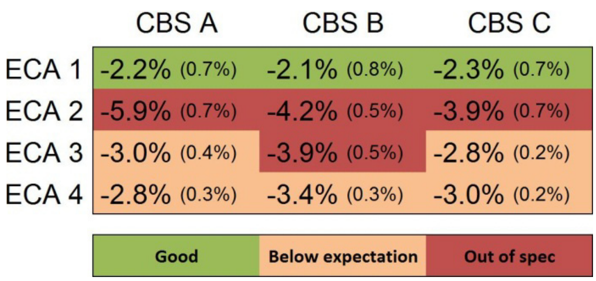

Fig.15. Average CtM FF results per ECA-CBS combination of 5 modules (standard deviation between brackets).

The colours in Figure 15 show that 3 modules are considered to perform well, 5 perform below expectation and 4 are out of spec. The influence of the CBS on the results does not seem to be significant. The best modules were all manufactured with ECA 1. All modules made with ECA 2 are out of spec. The modules containing ECA 3 and 4 are generally below expectation with one out of spec specimen for ECA 3. These two ECAs showed a too low printed dot volume, see Fig. 8.

An unexpected phenomenon is that the standard deviation of the best performing ECA is higher than the two intermediate performing adhesives ECA 3 and 4.

4.2. Durability testing

The durability of the modules was determined in a damp heat and thermal cycle test. Two modules per combination were tested in damp heat and two in thermal cycle. The modules had been tested up to 2000 hours in damp heat (DH2000), and 400 cycles in thermal cycle (TC400). Both tests had 2 times the requirement for IEC 61215. In this standard a module is considered to pass the DH1000 or TC200 test if a 5% power loss criterion is not exceeded.

4.2.1 Damp heat testing

The modules for damp heat (85°C / 85%RH) were characterised by IV power measurements after 500, 1000, 1500 and 2000 hours. The final results per combination (average of 2 modules) are shown in Fig. 16 for both the relative power and fill factor.

All modules had passed the ΔP<5% criterion at DH1000. Most modules also passed this criterion at DH2000; two modules with ECA 2 did not pass and the average power loss of modules with this ECA was 4 per cent. ECA 2 also showed the highest contact resistance of all tested adhesives.

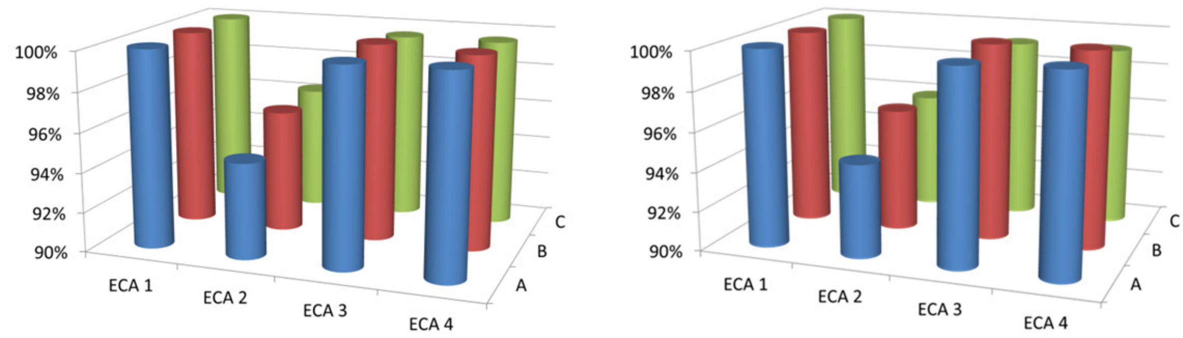

Fig.16. Relative power (left) and fill factor (right) after 2000 hours damp heat, average of 2 modules per combination.

4.2.2. Thermal cycle testing

The modules for thermal cycling (-40/85°C) were characterised by IV power measurements after 100, 200 and 400 cycles. The MWT-cells used in the modules have a known LID/CID-sensitivity [11] and a power drop of 1 to 2% due to CID that had been expected in the first run up to 100 cycles. These effects can be identified, as the observed power drop is larger than the FF drop. The results per combination (average of 2 modules) are shown in Fig. 17 for the relative power and fill factor.

Most modules had passed the ΔP<5% criterion at TC200, except for the 4-B combination that electrically and visually failed in the range of 100-200 cycles. Most modules also passed the criterion at TC400, but three more modules did not, viz. one module with combination 2-C and two with 4-A.

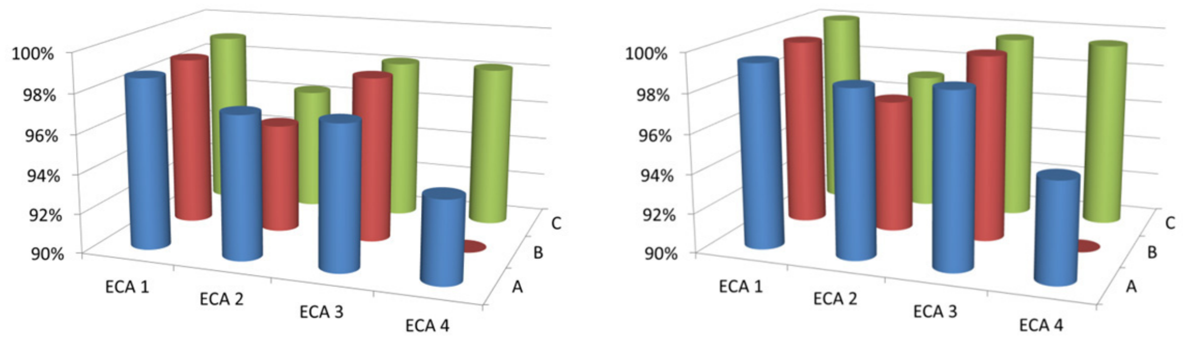

Fig.17. Relative power (left) and fill factor (right) after 400 thermal cycles, average of 2 modules per combination.

4.3. Discussion on the module results

The most obvious observations of the initial and durability results are that 1) no significant influence was found for the CBS-type, and 2) a significant influence was found for ECA 2 that showed poor results in all cases. In the case of conductive back-sheets it was expected that the module results of CBS B would be negatively influenced by the remains of a zinc chromate layer under the OSP finish, although it cannot be excluded that the layer was fully striped-off in the module build batch. Also, the higher contact resistances of CBS C had no significant effect on the CtM loss of the modules.

In contrast to the poor results of ECA 2, ECA 1 showed good results for all modules. The results for both ECA 3 and 4 varied. They showed a mediocre result in the initial performance, a good result in damp heat and a varying and poor result in thermal cycle testing in the case of ECA 4. ECA 3 performed well in thermal cycle testing.

The sample design to represent a realistic interconnection for measuring the contact resistance did not give a high correlation with CtM changes as was expected. Also, no correlation was found between peel strength and deterioration in thermal cycling. The only component test that correlates strongly with the module results is the characterisation of the dot geometry. ECA 1 had a regular dot geometry and the module performance was initially good and also in durability testing. ECA 2 had a too low viscosity and showed severe slumping of the dot; the module results were overall poor. However, it must be emphasised that enough adhesive was printed to achieve a sound interconnection and the poor module results may be due to the intrinsic properties of the adhesive. The ECAs 3 and 4 showed a high variation in dot geometry and printed volume (25-60%); the initial module results were mediocre that could be explained by this variation.

5. Conclusion

MWT modules made using four different conductive adhesives and three different foil types have been tested up to 2000 hours in damp-heat and for 400 thermal cycles. Most combinations passed the 5% power loss criterion. One of the conductive adhesives (ECA 1) performed well on three different types of back-sheet which is supportive of a robust technology. Two others (ECA 3, 4) showed a marginally too high CtM fill factor loss that might be caused by a too low volume of the printed ECA dots. But the damp-heat testing were good for all combinations, and the thermal cycle testing for 4 out of 6 modules performed well. This shows that it is important to test potential combinations of ECA and CBS thoroughly on module level before adding them to the bill of materials.

Both the measurement of the contact resistance and peel strength only showed a weak relationship with CtM loss (contact resistance) and damp heat testing (peel strength). The correlation between the geometrical quality of the stencil printed dot and the CtM loss was higher.

6. Recommendation

To improve the robustness of the back-contact technology it is recommended that the suppliers of ECA and CBS foils collaborate closely in order to find ECA-CBS combinations with optimal performance. Better specification of product parameters such as rheology of the ECA and surface finish of the CBS foil is also needed.

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