RELIABILITY RESULTS FOR HIGH-EFFICIENCY FOIL-BASED BACK-CONTACT PV MODULES

V. Rosca*, M.J.A.A Goris, L.A.G. Okel, B.B. Van Aken, N. Guillevin, A.A. Mewe, I. Cesar, L.J. Geerligs
ECN Solar Energy, Westerduinweg 3, 1755 LE, Petten, The Netherlands.
*Corresponding author: tel. +31885154612; fax. +31885158214; e-mail: rosca@ecn.nl

ABSTRACT: In this paper we have presented an overview of the recent reliability results obtained at ECN for foil-based p-MWT, and novel high-efficiency n-MWT and IBC back-contact modules. As deduced from extensive TC and DH testing on p-MWT modules, two alternative low-cost conductive back sheet foils were shown to improve the module reliability. Exposure to DH of the foil-based modules can cause Cu discoloration. This is observed for EVA and a number of alternative encapsulants, with moisture ingress and some specific interactions between encapsulant and Cu substrate playing a role. The n-MWT modules showed improved resistance to DH exposure as compared to n-Pasha (front-to-back tabbing) modules. TC300 and DH2000 tests were passed for frameless IBC Mercury 2x2 modules built using standard foil-based module manufacture process and standard module materials.
Keywords: High-efficiency, c-Si, PV Modules, Reliability, PV Materials

1 INTRODUCTION

The foil-based back-contact c-Si PV module technology offers a significantly lower cell-to-module fill factor loss than standard tabbed front-to-back contact technology. It also offers improved design flexibility, and is compatible with any back-contact cell type [1-6]. This module technology is ready for large-scale implementation, with equipment manufacturers and material suppliers offering qualified and diverse commercial solutions [2]. In the past few years, a significant reduction of the costs per Wp for foil-based back-contact PV modules has been achieved by reducing the material and process costs [3], on the one hand, and by improving the cost-performance ratio of high-efficiency back-contact cells such as n-type metal wrap through (n-MWT) and interdigitated back contact (IBC) on the other hand [4,5]. However, validation and implementation of novel cell processing solutions and materials should include extensive reliability studies on module level.

At ECN the foil-based back-contact PV technology is currently being applied for interconnection of high-efficiency cells, such as n-MWT and IBC. These cells are manufactured using low-cost processes, including screen printing, but also low-Ag or Ag-free seed-and-plate metallization solutions are used. Good results in comprehensive reliability studies are crucial for successful large-scale implementation of these very promising high-efficiency cell and module technologies. In this paper we report the results of accelerated degradation studies on small-size modules manufactured with p-type as well as these novel high-performance n-type back-contact cells, with emphasis on the reliability aspects related to the conductive back sheet and encapsulant.

2 EXPERIMENTAL

2.1 Modules manufacture and materials.

Figure 1 shows a schematic drawing of the lay-out of a foil-based module and cross section of such a module after lamination. Conductive adhesive paste is stencil printed on the conductive back-sheet. The rear-side encapsulant sheet is then punched and placed on the back sheet with the openings in the encapsulant corresponding to the position of the conductive adhesive. The interconnection and encapsulation step are combined in a single lamination step, as the conductive adhesive and encapsulant are chosen to work under similar curing conditions.

All modules were manufactured using the semi-automatic EuroLab pilot back-contact module assembly line produced by Eurotron B.V. (The Netherlands). The line is equipped with a mechanical milling station that allows patterning of a conductive foil, a stencil printing station, cell placement tool, and the encapsulant pre-tacking station. Modules were laminated in an industrial three-chamber laminator (3S, Meyer Burger).

All modules were built with commercially available EVA encapsulant, Ag-containing electrically-conductive adhesive (ECA), and a flat solar glass. Three types of conductive back-sheet foils were used: (1) reference (for ECN) Tedlar-PET-Cu foil (TP-Cu), (2) a TP-Al foil with a thin Cu layer applied locally by Cu cold spray [7] in order to ensure proper electrical contact between ECA and foil (TP-Al(Cu)), and (3) a prototype conductive Cu foil applied onto a polyolefin backing (PO-Cu). The TP-Cu and TP-Al(Cu) foils were patterned using mechanical milling just before module manufacture. The PO-Cu foil has been received with Cu layer already patterned by the supplier using a proprietary technique. Cells were either commercially available p-type MWT cells or n-type ECN cells (n-MWT and IBC Mercury), manufactured using in-house pilot cell-processing equipment.
Results presented in this paper were acquired by testing either single-cell or four-cell modules, which were not framed prior to characterization and testing. In this way a higher acceleration factor could be achieved for the selected climate chamber test (e.g., damp heat).

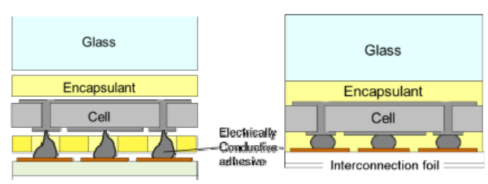

Figure 1. Cross section of a foil-based back-contact module before and after lamination.

2.2 Modules testing and characterization

The reliability of the modules was assessed using thermal cycling and damp heat tests as defined in IEC61215 standard. Modules were characterized by I-V measurements, electroluminescence (EL) imaging, and dark lock-in thermography (DLIT) before and after climate chamber tests. The I-V data was acquired using class AAA solar simulator (Pasan SS3b) under Standard Test Conditions (STC; in accordance with IEC60904-3 standard).

Figure 2 shows photographs of some of the modules manufactured and tested at ECN.

3 RESULTS AND DISCUSSIONS

Table I gives an overview of the recent reliability tests carried out at ECN on various types of foil-based back-contact modules. At least twice the IEC requirements are routinely passed in this laboratory for small-size frameless p-MWT, n-MWT, and more recently IBC modules, made with commercially-available or experimental materials. This is a strong indication of the overall robustness of the module concept as well as cell technology and module materials.

Table I. An overview of recent module reliability results obtained at ECN for foil-based back-contact modules. See text for details.

Mod. size	Materials[1]	Cell type	Stress tests passed[2]
4-cell	TP-Cu-EVA-ECA	p-MWT	TC400, DH2000
4-cell	PO-Cu-EVA-ECA	p-MWT	TC600, DH3000
4-cell	TP/Al(Cu)-EVA-ECA	p-MWT	TC700, DH3500
1-cell	TP-Cu-EVA-ECA	n-MWT	TC400, DH2000
4-cell	TP-Cu-EVA-ECA	IBC Mercury	TC300, DH2000

[1]TP- Tedlar-PET; PO- polyolefin; EVA- ethylene-vinyl acetate; ECA- electrically conductive adhesive (in all cases a Ag-based); TC- thermal cycling; DH- damp heat.
[2]IEC qualification criteria (power loss less than 5% and no obvious visual changes) were used.

3.1 Reliability results for p-MWT modules.

The reliability of the foil-based p-MWT modules has been extensively addressed and reported by ECN (see for example [8,9]). The conductive back-sheet foil was often the central module component in these studies, because it remains one of the expensive components and, just as for standard H-pattern modules, is the key component in ensuring the reliability and safety of PV modules. Note that in principle foil-based back-contact modules have somewhat different module lay-out and therefore might potentially present specific reliability issues.

In this section we report the reliability results for p-MWT modules built using different conductive back sheets. More specifically, modules built with a reference TP-Cu foil are compared to (i) a PO-Cu foil (different backing material) and (ii) TP-Al(Cu) foil, that is back sheet with the same polymer backing, but the Al conductive layer instead of Cu layer. Importantly, in TP-Al(Cu) back sheet a thin Cu interlayer is applied on Al in order to ensure a low contact resistance when contacted to ECA. In such foil-centered studies, fill factor is often the most informative parameter, for it often reflects changes in interconnection on cell or module level.

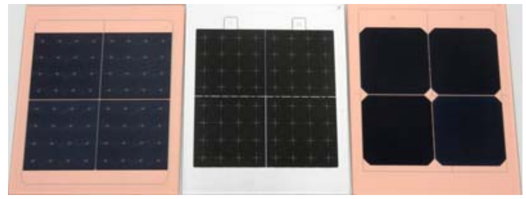

Figure 2. Photographs of some back-contact modules manufactured and tested at ECN for this study. Left: p-MWT module with TP-Cu foil. Middle: p-MWT module with TP-Al(Cu) foil. Right: IBC Mercury module.

As can be deduced from graphs presented in Figure 3, the modules built with all three foils showed very good results in both DH and TC tests. In TC, modules built with TP-Al(Cu) and PO-Cu foil showed improved performance (TC600 passed, meaning x3 times IEC requirement) as compared to the reference modules. Visual inspection shows hardly any visual changes for all modules tested in TC, and EL and DLIT images normally showing no indication of dramatic local failures, but rather point at gradual changes over the whole module and cell areas (data not shown). This makes it difficult to pinpoint the failure mechanism, at least for the modules considered here.

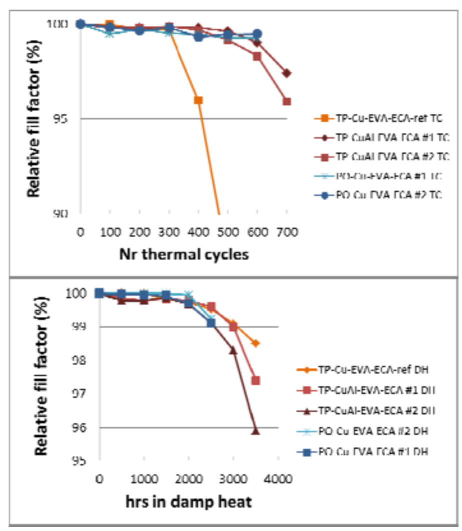

Figure 3. Effect of TC and DH exposure on the relative FF of p-MWT modules. main module components are indicated in the legend.

It is worth mentioning that no crack formation in cells was observed for any modules during module manufacture and during TC tests (nor in DH). This generally applies to all foil- and ECA-based back-contact modules, provided the ECA has been reasonably optimized (in terms of processing and thermomechanical characteristics). Furthermore, if the foil shrinkage is kept low (<0.2% after 30 min. at 150°C as an indicative value), then it is unlikely to cause issues in TC. Accordingly, all three foils showed very good results in TC. Note, that the state of the Cu foil surface (roughness, presence and nature capping layer) can have an effect on the contact resistance between ECA and Cu and therefore cell-to-module FF losses. Nevertheless, these losses were comparable for all three foils, although the surface finish and capping differed to our knowledge.

Turning now to the results of the DH tests, these are very positive as well: DH3000 (3000 hours at 85°C, 85% RH) test was passed for modules without any edge protection, and the difference between the modules built with different foils was smaller than in TC tests. In fact, the reference module (also subjected to DH) showed the lowest relative FF change in this test. In contrast to modules in TC, modules tested in DH showed some visual changes. These are signs of Cu staining or tarnishing, mainly along the module edge. This staining is related to moisture ingress and depends on Cu finish and encapsulant material used. Modules built with TP-Al(Cu) showed hardly any visual change though: Al seems to be adequately protected by the native Al oxide, and Cu, which was applied locally (around the interconnection points), could not be inspected.

Figure 4. Visual appearance of glass-encapsulant-TP-Cu laminates after DH1500 test. Left: EVA; center: thermoplastic POE; right: thermosetting POE.

Figure 4 shows examples of Cu tarnishing for a number of small (200x200mm) cell-free laminated made with glass, TP-Cu foil and different encapsulants. Although the extent of tarnishing is excessive due to absence of edge sealing, this is a clear indication of Cu discoloration being related to a combined effect of moisture and encapsulant in contact with Cu. Accordingly, laminates made with the assumedly more inert non-EVA encapsulants also shows Cu tarnishing along the sample edge, although the Cu discoloration is confined to the very edge of the glass. The difference in color of the tarnish layer points at some specific interaction between encapsulants and Cu surface (or components of capping layer) in the presence of moisture, which might be an important marker for testing and qualification of alternative encapsulants for use in foil-based modules. On the other hand, specific interaction could also result in migration of the products of a surface reaction to the bulk of encapsulant, as for example is the case for PVB interaction with metals (Ag and Cu) in DH [10]. Furthermore, we could not find a clear-cut link between Cu staining and the module performance losses, at least for EVA and some non-EVA materials we have been testing recently. For instance, systematic peel tests carried out on cell-free laminates do not point at major differences between loss of encapsulant adhesion for stained and bright Cu areas in DH.

3.2 Results for n-MWT modules.

We have previously reported results of reliability studies of front-to-back tabbed modules made with n-type cells ("n-Pasha" cells). [11,12] As main conclusion of DH tests carried out on single-cell modules, the performance degradation is related to corrosion of the front metallization that occurs in the presence of acetic acid (from EVA encapsulant) and/or remains of the solder flux [11]. Accordingly, improved resistance to DH conditions was observed for modules made with thermoplastic encapsulants.

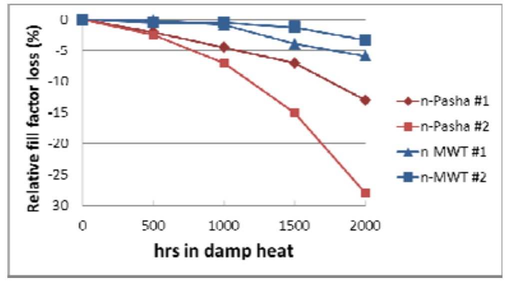

Figure 5. Effect of DH exposure on FF loss for frameless single-cell n-Pasha (tabbed cell) and n-MWT modules. Both types of modules were made with EVA.

Figure 5 shows the effect of DH exposure on FF of single-cell n-pasha modules and single-cell ECN n-MWT modules. Both types of modules were made with very similar EVA, and had no edge sealing in order to achieve higher degree of acceleration of degradation. The n-MWT module shows improved resistance to DH conditions. This result points at combination foil and ECA as a more robust interconnection scheme, at least for this standard bill of materials.

Table II. Summary of the reliability data for 2x2 IBC (Mercury) modules. Average data for 3 modules is given, with standard deviation never exceeding 0.5 for any parameter.

Rel. change [%]	DH500	DH1000	DH1500	DH2000
Isc	-0.37	-0.53	-0.96	-1.15
FF	-1.16	-1.63	-2.28	-2.88
Pm	-1.55	-2.24	-3.79	-4.03
	TC100	**TC200**	**TC300**	**TC400**
Isc	-0.28	-0.40	-0.74	-0.65
FF	-0.02	-0.16	-1.80	-7.58
Pm	-0.23	-0.51	-2.58	-7.99

3.3 Results for IBC (Mercury) modules.

ECN has proposed and has been developing together with industrial partners the "Mercury" IBC cell (an IBC cell with conductive front floating emitter), combined with so-called "Sirius" interconnection design aimed at back sheet interconnection with optimized cost and performance [5]. This cell has screen printed metallization grids, similar to ECN's n-Pasha and n-MWT cells. From the reliability point of view, this cell presents an interesting case, for all metallization is situated on the rear side of the cell. Note however that the process flow does not differ much from that for n-MWT or n-Pasha cell, with same n-type cell industrial equipment applicable for manufacture of the "Mercury" IBC cell. Finally, the "Sirius" interconnection design (62 interconnection points and no multi-level metallization) has been developed to minimize losses on the cell level and enable an efficient and robust interconnection on the module level.

In order to assess the reliability of modules based on this newly-developed IBC cell, we have manufactured and tested a number of 2x2 IBC modules and subjected them to TC and DH test. Table II summarizes the results of that study. Modules passed DH2000 test (2x IEC requirement) and TC300 (1.5x IEC requirement) with the standard bill of materials without any additional process optimization. TC test was extended to TC400, but module power (Pm) losses exceeded 5% loss allowed by IEC standard. As a main concluson, compatibility of ECN's Mercury IBC cell with the Sirius back foil interconnection design, with standard back foil-based module manufacturing process and materials has been demonstrated.

4 CONCLUSIONS

In this paper we have presented an overview of the recent reliability results obtained at ECN for foil-based p-MWT, and novel high-efficiency n-MWT and IBC back-contact modules. Effect of the conductive back sheet and encapsulant on the module reliability was illustrated and discussed in some detail.

As deduced from TC and DH testing on p-MWT modules, the conductive back sheet foils recently proposed as potentially more cost-effective alternatives to standard TP-Cu foil, improved the module reliability. Characteristics of both the polymer backing sheet and the conductive layer (Cu vs. Al) are shown to have an effect on the module reliability.

The n-MWT modules showed improved resistance to DH exposure as compared n-Pasha (front-to-back tabbing) modules, which can be assigned to a more robust interconnection for foil-based n-MWT modules.

Exposure to DH can cause Cu discoloration, which can affect the module visual appearance. Discoloration of Cu foil can be observed for EVA and alternative encapsulants, with both moisture ingress and some specific interactions between encapsulant and Cu substrate playing a role.

We also reported the reliability results for IBC Mercury modules with Sirius interconnection design. TC300 and DH2000 tests were passed for frameless 2x2 modules built with standard bill of materials for the back-contact module (TP-Cu foil, EVA, Ag-containing ECA). This is a clear indication of compatibility of ECN's IBC Mercury cell with standard backfoil-based module manufacture process and module materials.

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REFERENCES

[1] P.C. de Jong, Photovoltaic International (2010) 138.
[2] J. Govaerts, K. Baert and J. Poortmans, Photovoltaic International (2012) 116.
[3] I. Bennett, W. Eerenstein, V. Rosca, Energy Procedia 38 (2013) 329.
[4] I. Cesar, N. Guillevin, A.R. Burgers, A.A. Mewe, M. Koppes, J. Anker, L.J. Geerligs, A.W. Weeber, Energy Procedia 55 (2014) 633.
[5] I. Cesar, N. Guillevin, A.R. Burgers, A.A. Mewe, E.E. Bende, V. Rosca, B. van Aken, M. Koppes, J. Anker, L.J. Geerligs, A.W. Weeber, Proceedings 29th European Photovoltaic Solar Energy Conference, Amsterdam, 2014.
[6] Y. Wu, B.B. van Aken, G. Janssen, J. Loffler, F. Li, Y. Shen, W. Yang, J. Shi, G. Li, Z. Hu, J. Xiong, G. Coletti, Proceedings 29th European Photovoltaic Solar Energy Conference, Amsterdam, 2014.
[7] M.J.A.A. Goris, , I.J. Bennett, W. Eerenstein, Energy Procedia 55 (2014) 342.
[8] M. Guichoux, C. Tjengdrawira, D. Veldman, P.C. De Jong, Proceedings 35th IEEE Photovoltaic Specialist Conference, Honolulu, Hawaii, USA, 2010.
[9] V. Rosca, I. Bennett, W. Eerenstein, Proc. of SPIE Vol. 8472 84720D-1, 2012.
[10] C.L. Reed, Presented at Polymers in Photovoltaics Conference, Cologne, 2011.
[11] I.J. Bennett and B.B. Van Aken, Proceedings of 2nd n-PV workshop, Amsterdam, the Netherlands, 2012.
[12] B.B. Van Aken, M.J. Jansen, N.J.J. Dekker, Proceedings of 39th IEEE Photovoltaic Specialists Conference, Tampa, USA, 2013.