Systematic reliability studies of back-contact photovoltaic modules

This paper has been presented at the SPIE Optics and Photonics Conference,
12-16 August 2012, San Diego, USA

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October 2012
ECN-M--12-041

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ABSTRACT

Back-contact module technology offers the advantage of lower yield loss, higher power conversion efficiency, and significantly faster manufacturing as compared to conventional H-pattern modules. In this paper we present results of a systematic accelerated ageing study of ECN back-contact metallization wrap through (MWT) modules. A series of full-size (6×10 cells) MWT modules based on combinations of four different conductive back-sheet foils, two encapsulants, and two electrically conductive adhesives were manufactured and subjected to the damp heat conditions as defined in the IEC61215 edition 2 standard. Modules that combine conductive back-sheet foil with certain types of isolation lacquer (also referred to as inner layer dielectric, ILD) and EVA showed a high failure rate. It appears that a combined effect of moisture and EVA causes a weakening of adhesion strength at Cu/ILD interface and decisively contributes to delamination at Cu/ILD interface. This delamination puts stress on the interconnection and ultimately results in interconnection failure. Removal of ILD significantly improves the stability of MWT modules in damp heat, as up to 2000 hrs of testing only up to 2.4% relative power loss was observed, and also lowers the foil cost.

Keywords: back-contact PV modules, metallization wrap through technology, damp heat test, conductive back-sheet foil

1. INTRODUCTION

Power output of a PV module is determined by the cell efficiency as well as the optical and resistance losses in the module. The yield of the module manufacturing process is determined by the degree of cell breakage occurring, particularly during the interconnection process. In order to reach significant cost reduction for solar modules, the efficiency of the module must be increased, the material cost reduced and the process yield increased.

ECN Solar has developed a metallization wrap through (MWT) cell and back-contact module technology [1-4]. The back-contact module technology allows a single-step encapsulation and interconnection process of the back-contact cells. The main distinctive feature of this technology is use of a patterned conductive back-sheet foil and a conductive adhesive to make the electrical connection between the cells. This back-contact module technology offers the advantage of lower yield loss, higher power conversion efficiency, and significantly faster manufacturing as compared to conventional H-pattern modules. ECN has obtained IEC61215 and IEC61730 certificates for this technology.

The main advantages of MWT cells and back-contact modules include reduced shadowing due to the absence of bus-bars and tabs at the front of the cells. The cells can be placed closer together in the modules as no tabs pass between the front and rear of the cell. The current carrying component of the module can be wider than conventional tabbing as there are no shadowing losses. Therefore higher cell efficiencies and module output can be achieved in MWT modules as compared to H-pattern modules.

Figure 1 shows a schematic drawing of the build-up of an MWT 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. Cells are placed on the stack by a pick-and-place robot. This is the only cell-handling step; therefore, thinner and larger cells can easily be used with very low cell breakage rate. Finally, the front side encapsulant sheet and glass are placed. The complete stack is then inverted and laminated. The interconnection and encapsulation step are combined in a single lamination step as the conductive adhesive and encapsulant are chosen to have the same curing conditions. This module manufacturing process has been developed together with the Dutch equipment manufacturer Eurotron [1], and fully automated production lines for manufacturing of back-contact modules are now commercially available.

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Reliability of Photovoltaic Cells, Modules, Components, and Systems V, edited by Neelkanth G. Dhere, John H. Wohlgemuth, Proc. of SPIE Vol. 8472, 84720D · © 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.930441

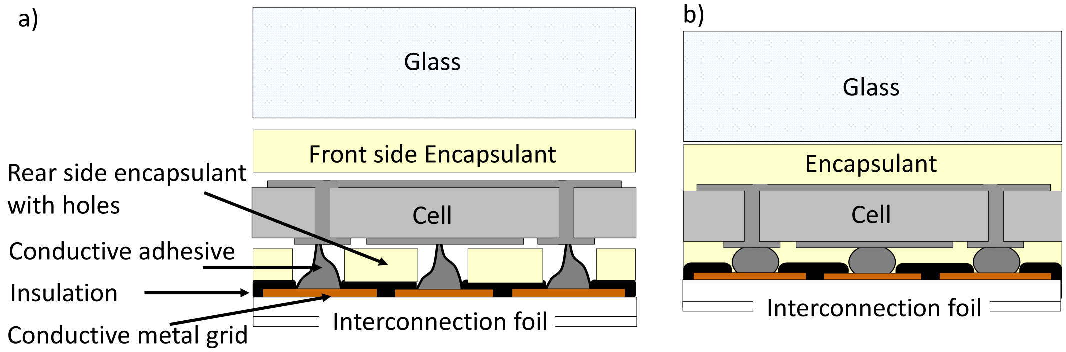

Figure 1. Schematic drawing of a) the build-up of an MWT back contact module with conductive back sheet foil and adhesive as interconnection and b) a cross section of such a module after lamination.

The conductive back-sheet foil consists of a polymer laminate (PVF-PET or alternative) with a Cu layer attached to it. The Cu layer is patterned to provide a series electrical connection between the cells. Patterning is currently done by wet-chemical etching. An isolation layer (an UV- or temperature-cured lacquer referred to as inner layer dielectric, ILD) is applied to the patterned conductive back-sheet to prevent unwanted electrical contact between cell and the foil. The introduction of a new module technology based on a back-sheet foil with an integrated conductive grid in combination with conductive adhesive raises issues in terms of the reliability of the concept. Recent studies carried out on small-size (single and four cells) and full-size (6×10 cells) modules pointed at a prominent impact of dimensional and functional stability of the conductive back-sheet foil on the module reliability [5,6]. Guichoux et al. [5] pointed at an interaction between encapsulant and ILD in the presence of moisture causing delamination and ultimately module failure. Eerenstein et al. [6] have reported on MWT modules successfully passing TC300, DH2000, and the wet leakage test. However, a few modules failed after 1000 hrs in DH. A failure analysis based on dark lock-in thermography (DLIT) data and opening the modules pointed at an interconnection failure possibly related to delamination.

The damp heat test is perhaps the most critical test for MWT modules. Our recent studies on small-size modules based on foils with ILD pointed at a significant performance loss after 1000 hrs in DH. Interestingly enough, better DH results were observed for small-size modules manufactured with foils without ILD. Figure 2 compares the effect of accelerated ageing in DH on the fill factor losses for 3 series of small-size modules and is meant to underpin the above observations. For modules based on foils without ILD an effect of the cell can also be inferred. However, these modules clearly perform much better in damp heat as compared to the modules based on foils with an ILD, irrespective of cell used.

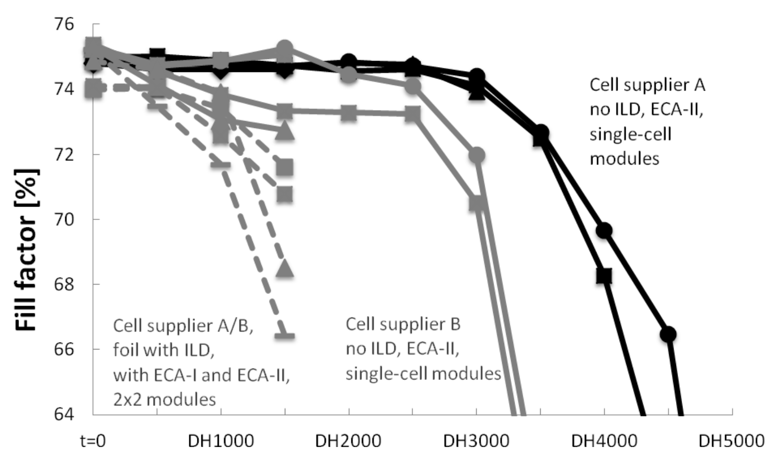

Figure 2. Effect of accelerated ageing in damp heat of a series of 2x2 modules based of foil with ILD01 and a series of single-cell modules based on foils without an ILD on the module fill factor. Cells of two different suppliers (A and B) were used in order to assess the effect of cell.

In this paper we present results of an accelerated ageing study of ECN back-contact MWT modules. A series of full-size (6×10 cells) MWT modules based on combinations of four different conductive back-sheet foils, two encapsulants, and two electrically conductive adhesives (ECA) were manufactured and subjected to damp heat (DH) conditions (85°C and 85% relative humidity) as defined in the IEC61215 edition 2 standard. We present and discuss the results of this study with an emphasis on the impact of the conductive back sheet foil on reliability of the modules.

2. EXPERIMENTAL

Full-size modules were manufactured on a pilot back-contact module assembly line at ECN. For details on the module manufacture process see refs [1, 2]. To test the compatibility between various module components under damp-heat conditions, modules with four different conductive back-sheets, two encapsulants, and two ECAs were built. See Table 1 for the list of modules and their composition. The MWT cells were part of a large batch purchased from a cell manufacturer. Cells were characterized by I-V testing and sorted according to their efficiency range.

Table 1 lists the modules manufactured and main components used in each 6x10 module. Four different back-sheet foils were chosen: two foils with different ILD type (ILD01 and ILD02); one foil with no ILD; and one foil with ILD (ILD01) and an Al layer integrated into the conductive back-sheet serving as a moisture barrier. These four foils were combined with two encapsulants; a standard cure EVA and a thermoplastic encapsulant (TP). Use of different ECAs was dictated by the type of the contact surface on the conductive back-sheet. All foils with ILD had silver-plated contact points and were used in combination with ECA-I. The ILD-free foil had no silver-plated contact points. Therefore, a different ECA (ECA-II) was used to ensure good electrical connection with bare Cu.

The modules were characterized at ECN (I-V measurements, electroluminescence (EL), dark lock-in thermography (DLIT)) before and after exposure to DH for 2000 hrs. Climatic chamber testing and characterization (I-V, EL) was performed at Photovoltaik Insitut Berlin (PI Berlin, Germany), where measurements were also performed after 1000 hrs.

Table 1. Experimental matrix and list of modules manufactured and tested in this work.

Code module	Conductive back sheet foil	Encapsulant	Electrically conductive adhesive
A800, A801	PVF-PET-Cu-ILD01	EVA	ECA-I[3]
A802, A803	PVF-PET-Cu-ILD02	EVA	ECA-I
A804, A805	PVF-PET(Al)-Cu-ILD01[1]	EVA	ECA-I
A806, A807	PVF-PET-Cu-ILD01	TP[2]	ECA-I
A808, A809	PVF-PET-Cu-ILD02	TP	ECA-I
A810, A811	PVF-PET(Al)-Cu-ILD01[1]	TP	ECA-I
A812, A813	PVF-PET-Cu (no ILD)	EVA	ECA-II[4]
A814, A815	PVF-PET-Cu (no ILD)	TP	ECA-II

[1] *This foil contains an Al layer in the PVF-PET back sheet and serves as a moisture barrier.*
[2] TP – *thermoplast*
[3] ECA-I was *used in combination with foils with ILD. These foils had Ag-plated contacts applied to copper.*
[4] ECA-II *was used in combination with foils without ILD and was applied directly on Cu.*

3. RESULTS AND DISCUSSIONS

Table 2 shows the I-V data acquired under standard test conditions after the module manufacture. The module output and the calculated encapsulated cell efficiency were in good agreement with the efficiency range of cells used. Accordingly, the cell-to-module losses were comparable for all modules (0.3±0.1% on average). This is an indication that the choice of components and/or their combinations did not significantly affect the cell-to-module losses at zero hours.

Figure 3 summarizes the results of the accelerated ageing of MWT modules in damp heat. Three modules failed in the first 1000 hours in DH (A800, A801, A802) and one failed after 1000 hours in DH (A803). These four modules contained foils with ILD (either ILD01 or ILD02) and EVA as encapsulant (see Table 1). For the modules based on other materials combinations, all but one (A812) showed a relative loss in power output under 2% after 2000 hours in DH. Module A812 showed a relative loss of ca. 2.4% after 2000 hours DH.

Table 2. Results of the I-V measurements under standard test conditions at t=0.

Module code	Pm[W]	Isc[A]	Voc[V]	FF[%]	Encapsulated cell eff. [%]	Avrg. cell eff. before encapsulation[%]
A800	243.95	8.631	37.503	75.36	16.71	16.9
A801	244.83	8.642	37.562	75.42	16.77	17.0
A802	245.69	8.633	37.576	75.74	16.83	17.1
A803	245.63	8.633	37.544	75.78	16.82	17.1
A804	243.85	8.643	37.615	75	16.7	17.1
A805	247.15	8.655	37.671	75.8	16.93	17.2
A806	246.35	8.652	37.354	76.23	16.87	17.2
A808	246.88	8.678	37.436	76	16.91	17.3
A810	247.12	8.686	37.493	75.88	16.92	17.3
A811	247.36	8.682	37.488	76	16.94	17.3
A812	246.86	8.668	37.635	75.67	16.91	17.3
A813	248.5	8.681	37.679	75.97	17.02	17.4
A814	249.9	8.693	37.595	76.47	17.11	17.4
A815	250.76	8.715	37.67	76.38	17.17	17.6

Failed modules A800, A802, and A803 were subjected to post-mortem inspection. No visual changes on the module front side could be found. Inspection of the back side of the failed modules revealed some signs of delamination of the conductive back-sheet. Delamination had a local character and covered 3 to 5% of the back side at most. Opening of the modules at the suspected areas pointed at adhesive fracture at ILD/Cu interface as the main failure mode of the foil.

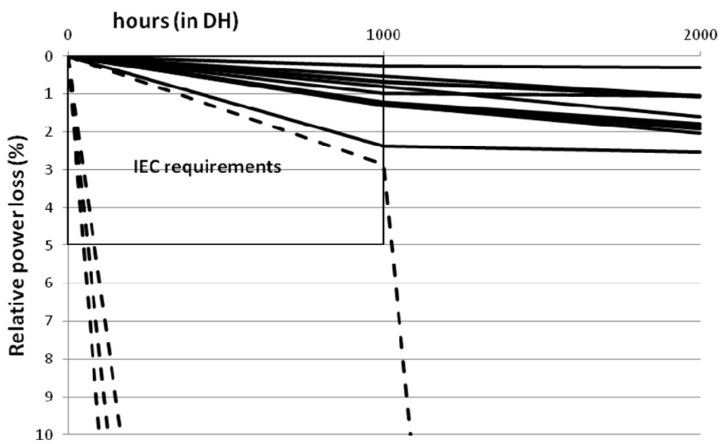

Figure 3. Effect of the accelerated ageing in damp heat on the relative power loss for a series of 6×10 MWT modules (see Table 1 for module composition). Data for four modules that failed before or after 1000 hrs in DH is given by dash lines. These were modules A800, A801, A802, and A803.

The above results point at delamination at the ILD/Cu interface as the most likely cause of the module failure. As such a delamination was observed neither for modules that contained an alternative encapsulant (thermoplast) nor for modules that had a moisture barrier in the back sheet (Al layer), this delamination occurs due to a combined effect of EVA and moisture. The exact rate and extent of delamination probably depends on the moisture ingress and accumulation rate, EVA acidity, and perhaps initial stress/strain in the isolation lacquer and or polymeric backing (can depend on processing/batch differences). In any case, delamination at Cu/ILD interface put mechanical stress on the interconnection, which might cause loss of mechanical and electrical contact between the foil and the cell contacts.

The adhesion between Cu and ILD could be time dependent. As learned from systematic peel tests carried out on small laminates that simulate the module (data not shown), adhesion between ILD (01 or 02) can be very low if measured right after DH test, but the adhesion improves as the sample dried out. Moreover, the fracture mode could change from adhesive right after DH test to cohesive (in ILD) after a few weeks time. This effect should be taken into account when investigating and improving the foil reliability. Furthermore, ECAs generally show good adhesion to both foil and cells. Different ECAs could show different adhesion strength and/or mechanical properties (elasticity), and therefore different resistance to the stress/strain.

Delamination at Cu/ILD interface and module failure can be prevented in a number of ways. These include prevention of moisture ingress in to the module by use of moisture-blocking Al back sheet. The second method is to use an alternative to EVA as the encapsulant. Thermoplastic encapsulants in combination with moisture do not show delamination of the back-sheet. The final option is to remove the ILD from the back sheet. Indeed, the rear side encapsulant sheet seems to be able to provide sufficient electrical isolation between cell and the back sheet. Omission of ILD would obviously eliminate the issues related to delamination at Cu/ILD interface. Note that foils with ILD normally contain silver-plated contact dots. These are meant to minimize the contact resistance between foil and (Ag-based) ECA. There are ECAs suitable for contacting directly on Cu; so, application of additional contact dots is not required. Elimination of both ILD and the silver contact dots would simplify the foil manufacturing process and would allow a significant materials cost reduction.

4. CONCLUSIONS

In this paper we presented results of an accelerated ageing study of ECN back-contact MWT modules. A series of full-size (6×10) MWT modules based on combinations of four different conductive back-sheet foils, two encapsulants, and two electrically conductive adhesives were manufactured and subjected to the damp heat conditions as defined in the IEC61215 edition 2 standard. Modules that combine conductive back-sheet foil with ILD and EVA showed a high failure rate. It appears that the combined effect of moisture and EVA causes a weakening of adhesion strength at Cu/ILD interface. The resulted delamination at Cu/ILD interface puts stress on interconnection and ultimately results in interconnection and module failure. Replacing EVA with an alternative encapsulant (e.g., a thermoplast) and/or use of a moisture barrier in the back sheet improves the module stability in damp heat. However, removal of ILD is the most interesting approach, as this not only significantly improves the stability of MWT modules in damp heat, but also lowers the foil cost.

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