Reliability of Back-Contact MWT Modules under Hot and Humid Conditions

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Authors’ contributions

This work was undertaken in the context of the collaboration between CDER in Algeria and ECN in the Netherlands. Authors VR, MGG, WE and JAMVR from ECN solar energy carried out the protocol and the experimental results. Authors FB, AHA and MSB performed the analysis, the literature searches and the drafting of the manuscript. Author POL brought a critical view and improvements regarding the contents, clarity of the contribution and the layout of the paper. All authors have read and approved the final manuscript.

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ABSTRACT

Aims: Back-contact metallization-wrap-through (MWT) modules made with different materials were manufactured and tested at ECN in the Netherlands.

Study Design: Damp heat testing (DH, 85°C and 85% relative humidity) was performed to investigate the effect of the module materials and potential failure mechanisms on electrical performance degradation.

Place and Duration of Study: ECN Solar Energy, P.O.Box 1, 1755 ZG Petten, Netherlands and Centre de Développement des Énergies Renouvelables, Division Energie Solaire Photovoltaïque, Route de l’Observatoire, BP 62, Bouzaréah, 16340, Alger, Algeria, between June 2011 and March 2015.

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Methodology: Fourteen back-contact MWT modules with different combinations of four conductive backsheet foils (inner isolation layers, also referred to as inner layer dielectric, ILD), two electrically conductive adhesives (CA) and two encapsulants were tested.

Results: Results reveal that modules which combine conductive backsheet foil with two types of ILD and ethylene-vinyl-acetate (EVA) showed the highest degradation levels. It is suggested that effects of moisture in EVA cause a weakening of the adhesion strength at the ILD/Cu interface and then delamination between conductive adhesive and Ag-plated contacts applied to the copper interconnection foil. Removal of ILD significantly improves the stability of back-contact modules. Enhanced reliability is observed for modules which combine ILD-free foil Cu backsheet, conductive adhesive and polyolefin or EVA as encapsulant.

Conclusion: Removal of ILD is the most interesting approach and is currently adopted by foil manufacturers. Importantly, the modules built with ILD-free backsheet and either polyolefin encapsulant or EVA showed respectively only 0.3% and 1.6% maximum power loss after 2000 hours of damp heat which is well below the requirement of the IEC 61215 standard.

Keywords: Back-contact module; metallization wrap through cell; damp heat test; reliability.

1. INTRODUCTION

Commercial solar cell module manufacturers offer long-term product warranties in the range of 20-30 years. To ascertain long-term stability without actual field data, several accelerated tests are employed. An important tool in the qualification of solar cell modules is the Damp Heat (DH) test [1], where modules are placed in humidity and temperature controlled environment for extended exposure. According to the IEC 61215 standard [2], photovoltaic modules should not degrade by more than 5% in relative output power during 1000 hours at 85°C and 85% relative humidity (rh) to pass the DH test.

The metallization wrap through (MWT) technology developed by ECN Solar Energy (The Netherlands) is one of the most promising new technologies for achieving low-cost and high-efficiency solar cell modules [3-5]. Standard crystalline silicon solar cells are interconnected front to rear by (tinned) copper wires in straight lines. In the MWT technology the solar cells are perforated with typically sixteen holes, in which the front side metallization is wrapped through to the back of the cell to form back contacts. 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 the use of a patterned conductive backsheet foil and a conductive adhesive to make the electrical connection between the cells (see Fig. 1b). This back-contact module technology offers the advantage of up to 10% higher power conversion efficiency and lower yield loss by the low stress handling and interconnection technology; modules with cells down to 120 µm thickness have been manufactured without cell breakage [3,8,9,12]. MWT modules have proved to be reliable in climatic chamber testing and IEC certification has been achieved by several parties [12-15].
3. EXPERIMENTAL

Fourteen modules were manufactured and tested at ECN with different constituting materials. They were introduced in a climatic chamber to test the compatibility between the various module components. The effect of damp heat has been investigated for the fourteen MWT modules made with different combinations of four conductive backsheet foils (inner layer dielectric ILD-1 and ILD-2, ILD-1 with an aluminium (Al) layer in the backsheet and no ILD), two encapsulants (ethylene-vinyl-acetate (EVA), polyolefin) and two electrical conductive adhesives (CA-1, CA-2). The polyolefin used releases no acetic acid upon degradation contrary to EVA. CA-1 was used in combination with foils with ILD-1. These foils have Ag-plated contacts applied to copper (Cu). CA-2 was used in combination with foils without ILD and was applied directly on copper [15].

All the samples had the same type of multicrystalline silicon photovoltaic cells and glass. Table 1 describes the samples exposed to the DH test. Chamber tests at 85°C and 85% relative humidity for 2000 hours were performed. Visual inspections were realized at initial time, after 1000 hours and 2000 hours. Electrical performances of the short-circuit current $I_{sc}$, of the open-circuit voltage $V_{oc}$, of the maximum power $P_{max}$ and of the fill factor FF were initially taken before and after exposure to 2000 hour DH test for the different samples of Table 1. Here damp heat tests were performed for a duration of 2000 hours which is twice the one required by IEC 61215 [2]. To check the performance of the modules during the test, these measurements were also performed after 1000 hours. The electrical performance of the modules was measured using a Class A solar simulator (Pasan SS3b) under Standard Test Conditions (STC) (AM=1.5, G=1000 W/m$^2$, $T_c$=25°C) in accordance with the IEC 60904-3 standard. The I-V curves are measured by applying an impulse voltage with a linear ramp to the terminals of the module within one flash of the solar simulator lamp. The measuring system error referring to the maximum power is relatively inferior to 3%. The relative error for measuring $V_{oc}$ and $I_{sc}$ were 1.3% and 2.2% respectively.

Table 1. Modules manufactured and tested

| Module | Foil/ILD type | Conductive adhesive | Encapsulant |
|--------|--------------|---------------------|-------------|
| M01, M02 | ILD-1 | CA-1 | EVA |
| M03, M04 | ILD-2 | CA-1 | EVA |
| M05, M06 | ILD-1 with Al | CA-1 | EVA |
| M07 | ILD-1 | CA-1 | Polyolefin |
| M08 | ILD-2 | CA-1 | Polyolefin |
| M09, M10 | ILD-1 with Al | CA-1 | Polyolefin |
| M11, M12 | no ILD | CA-2 | EVA |
| M13, M14 | no ILD | CA-2 | Polyolefin |

4. MODEL FOR I-V CHARACTERISTICS

To appreciate the impact of damp heat on electrical performances, the degradation of the I-V characteristics of these photovoltaic modules has to be determined and analyzed [16]. To plot the I-V characteristics, an explicit model known as Rauschenbach’s model is used [17]. The electrical equivalent circuit which comprises one diode is represented in Fig. 2. Current $I$ produced by the photovoltaic module is computed as a function of voltage $V$ [18]. The model to plot the I-V curve was developed under Matlab environment. The relation between $I$ and $V$ is given by:

$$I = I_{sc} \left(1 - C_r \left(\exp \left(\frac{V}{C_2 V_{oc}}\right) - 1\right)\right)$$

(1)
where the coefficients $C_1$ and $C_2$ are given by the following expressions:

\[
C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) \exp\left(-\frac{V_m}{C_2 V_{oc}}\right)
\]

\[
C_2 = \frac{V_{sc} - 1}{\ln(1 - \frac{I_m}{I_{sc}})}
\]

\[\text{(2)}\]

In order to quantify the degradation of the short-circuit current ($I_{sc}$), the open-circuit voltage ($V_{oc}$), the maximum power output ($P_{max}$) and the fill factor (FF) of the PV module, measured standardized values are compared to the ones of the reference given by the datasheet of PV module. The relative difference $\Delta X$ in percentage quantifies the degradation of one considered parameter. It can be expressed in the following form [19]:

\[
\Delta X(\%) = \left(1 - \frac{X}{X_0}\right) \times 100
\]

where in our case $X = [I_{sc}, V_{oc}, P_{max}, FF]$ after degradation and $X_0 = [I_{sc0}, V_{oc0}, P_{max0}, FF_0]$ represents the reference values of the parameters given by the manufacturer in standard test conditions (STC).

5. RESULTS AND DISCUSSION

The following section discusses the results of I-V characteristic evolutions for all the modules M01-M14 (Fig. 3) in Standard Test Conditions (STC) and the accelerated aging effect on the maximum power (Fig. 4). Initial measured values are given in Table 2. Degradations of electrical parameters are shown in Table 3. Comparison of damp heat effects is effectuated for the different photovoltaic modules and testing failure is analyzed.

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

| Module code | $P_{max}$[W] | $I_{sc}$[A] | $I_{m}$[A] | $V_{sc}$[V] | $V_{m}$[V] | $V_{oc}$[V] | $V_{ml}$[V] | FF$_0$[%] |
|-------------|--------------|-------------|------------|-------------|-------------|-------------|-------------|----------|
| M01         | 240.78       | 8.51        | 7.92       | 37.52       | 30.40       | 75.39       |             |          |
| M02         | 242.19       | 8.53        | 7.99       | 37.65       | 30.31       | 75.40       |             |          |
| M03         | 243.34       | 8.52        | 7.95       | 37.67       | 30.60       | 75.82       |             |          |
| M04         | 243.20       | 8.52        | 8.03       | 37.68       | 30.30       | 75.77       |             |          |
| M05         | 242.04       | 8.53        | 7.96       | 37.73       | 30.40       | 75.18       |             |          |
| M06         | 244.63       | 8.53        | 8.03       | 37.81       | 30.47       | 75.83       |             |          |
| M07         | 242.85       | 8.54        | 7.95       | 37.40       | 30.54       | 76.07       |             |          |
| M08         | 244.71       | 8.56        | 8.04       | 37.52       | 30.45       | 76.21       |             |          |
| M09         | 244.97       | 8.57        | 8.03       | 37.65       | 30.51       | 75.94       |             |          |
| M10         | 244.24       | 8.55        | 8.03       | 37.56       | 30.40       | 76.02       |             |          |
| M11         | 243.36       | 8.55        | 8.00       | 37.70       | 30.40       | 75.49       |             |          |
| M12         | 245.38       | 8.56        | 8.08       | 37.78       | 30.38       | 75.86       |             |          |
| M13         | 247.53       | 8.57        | 8.12       | 37.72       | 30.50       | 76.52       |             |          |
| M14         | 247.68       | 8.60        | 8.04       | 37.74       | 30.79       | 76.33       |             |          |
Fig. 3. I-V characteristics for modules M01-M14 after 0, 1000 and 2000 hours under DH exposure 85°C/85% rh.

(a) M01 and M02 with ILD-1
(b) M03 and M04 with ILD-2
(c) M05 and M06 with EVA
(d) M09 and M10 with polyolefin
(e) M07 with ILD-1
(f) M08 with ILD-2
(g) M11 and M12 with EVA
(h) M13 and M14 with polyolefin

*Stated text*
Fig. 4. Degradation for the maximum power ($P_{\text{max}}$) for the fourteen MWT photovoltaic modules under damp heat exposure.
5.1 Modules with Same EVA but with Different Backsheet Foils (ILD-1, ILD-2)

The I-V characteristics and the degradation of $I_{sc}$, $V_{oc}$, FF and $P_{max}$ of both modules M01 and M02 with the same ILD-1 are illustrated respectively in Figs. 3a, 4 and Table 3. There is a strong decrease of the I-V characteristics with degradation for $V_{oc}$ of 64.3% and 42.3%. A large drop in FF and $P_{max}$ of respectively 39.8% and 27.2%, and, 78.6% and 59.5% is observed and slight degradation in $I_{sc}$ of 0.6% and 3.5% after 1000 hours of DH test. After 2000 hours of damp heat testing, both modules M01 and M02 were deteriorated due to delamination at the ILD-1/Cu interface (Fig. 5). Delamination, which is the most important cause of module failure, occurs when there is moisture ingress in the EVA encapsulant. Delamination is caused by adhesive fracture at ILD/Cu interface (green ILD remains attached to EVA). This puts stress on interconnection and could cause failure. Module M04 is slightly more degraded with reduced $I_{sc}$, $V_{oc}$, FF and $P_{max}$ of respectively 65.4%, 87.0%, 70.9% and 98.7% (Figs. 3b, 4 and Table 3). It appears that the combined effect of moisture and EVA causes a weakening of the adhesion strength at the interface between copper foil and ILD which favors delamination. This observation is in agreement with the previous study of Guichoux et al. [20] where it is pointed out that delamination between encapsulant and ILD is caused by the presence of moisture and ultimately results in module failure. Eerenstein et al. reported that these MWT modules successfully passed the DH test of 2000 hours and also the wet leakage test [12]. However, a few modules failed after 1000 hours of DH test. A failure analysis based on dark lock-in thermography (DLIT) data and the opening of the modules pointed out an interconnection failure possibly related to delamination.

5.2 Modules with Same EVA and with ILD-1 with Al

The I-V characteristics and the degradation rates of $I_{sc}$, $V_{oc}$, $P_{max}$ and FF for modules M05 and M06 having the same encapsulant (EVA) and ILD-1 with Al are illustrated in Figs. 3c, 4 and Table 3. The initial I-V characteristic remains stable after 1000 hours of DH test. After 2000 hours of damp heat testing, the module M05 is still very stable due to the presence of a moisture blocking Al layer integrated in the backsheet [6]. However, module M06 presents a drop in $V_{oc}$ of 11.43% which induces decrease of FF and $P_{max}$ by respectively 14.7% and 24.6%. No change was observed for $I_{sc}$. Visual inspection shows that high humidity in the test chamber provokes the apparition of delamination patches visible on the back side of the module. Cracks can be seen in
Fig. 5. Delamination area in module M01 after 2000 hours of damp heat exposure (85°C/85% rh)

Al at overlap with Ag. Module M06 has one cracked photovoltaic cell.

5.3 Modules with Same Polyolefin and with ILD-1 with Al

The I-V characteristics and the degradation rates of $I_{sc}$, $V_{oc}$, FF and $P_{max}$ for modules M09 and M10 having the same encapsulant (polyolefin) and with ILD-1 with Al are displayed in Figs. 3d, 4 and Table 3.

The I-V characteristics are stable during the entire damp heat exposure of 1000 hours. After 2000 hours of damp heat testing, both M09 and M10 modules have a fall in $V_{oc}$ of 21.2% and 14.5%, which induces a decrease of FF and $P_{max}$ of respectively 5.4% and 12.3%, and, 25.8% and 25.0%, which implies a raise of the series resistance. For $I_{sc}$, no degradation was observed. Hence, the alteration is reduced with EVA for long times in this case. Visual inspection shows bubbles accumulated at the backsheet.

5.4 Modules with Same Polyolefin but with Different Backsheet Foils (ILD-1, ILD-2)

Results for modules M07 and M08, which have the same polyolefin encapsulant but two foils with different interlayer dielectric (ILD-1 and ILD-2) are compared. The I-V characteristics and the degradation of $I_{sc}$, $V_{oc}$, FF and $P_{max}$ for both modules M07 and M08 with the same encapsulant (polyolefin) are displayed in Fig. 3(e), Figs. 3f, 4 and Table 3.

The I-V characteristics remain unmodified after 1000 hours of DH test. Both modules M07 and M08 are also very stable after 2000 hours of damp heat testing. These results show that polyolefin encapsulant in combination with moisture does not induce delamination of the backsheet. Similar results were observed for thermoplastic encapsulants elsewhere [6].

5.5 Modules with Different Encapsulants (EVA, Polyolefin) without ILD

Comparison is performed here between both modules M11 and M12 which have the same EVA and both modules M13 and M14 with the same polyolefin but without interlayer dielectric (ILD). The I-V characteristics and the degradation rates of $I_{sc}$, $V_{oc}$, FF and $P_{max}$ of modules M11, M12, M13 and M14 are depicted in Figs. 3g, 3h, 4 and Table 3.

I-V characteristics remain unchanged after 1000 hours of DH test. After 2000 hours of damp heat testing, FF and $P_{max}$ are slightly degraded by 1.2% and 0.8%, and, 1.5% and 1.9% for modules M11 and M12 respectively.

I-V characteristics for both modules M13 and M14 stay very stable up to 2000 hours. Maximum power is slightly degraded by respectively 1.6% and 0.3% which is under 2%. This degradation is much less severe than for the other cases. There is no failure and the stability is the best. So, the elimination of both ILD and the silver contact dots related to delamination at the ILD/Cu interface permits an optimal stability of the MWT module. Hence, this packaging should be selected.

5.6 Maximum Power Degradation Comparison

The found maximum power degradations under damp heat are represented in Fig. 4 according to encapsulant (a), conductive adhesive (b) and ILD (c). The I-V characteristics remain quasi unmodified after 1000 hours for modules M04 to M14 since no major diminishes were observed for electrical quantities as shown in Figs. 3b to 3h
and 4. Degradation of $P_{\text{max}}$ remains under 5% after 1000 hours of DH test (see Table 3), as requested by the IEC 61215 standard. The photovoltaic modules have a better stability with the polyolefin encapsulant. Its maximum power decrease starts when approaching 2000 hours of test. Modules having the conductive adhesive CA-2 remain very stable. ILD-1 gives altered electrical characteristics after 1000 hours and total failure after 2000 hours. The adhesion of Al to ILD provides a better stability, even though maximum power gets affected after 2000 hours. The best results are obtained when there is no ILD. Thus, the optimal configuration as afore-mentioned is polyolefin encapsulant, conductive adhesive (CA-2) and no ILD.

6. CONCLUSION

Back-contact MWT modules with different packaging were tested under damp heat conditions. Results reveal that modules which combine conductive backsheet foil with two types of ILD and EVA showed higher degradation rates. Moisture ingress into the module and its interaction with EVA causes a weakening of adhesion strength at the ILD/Cu interface and could cause delamination between Ag-plated contacts applied to copper and conductive adhesive. Replacing EVA with an alternative encapsulant (e.g. a polyolefin) and/or use of a moisture barrier in the backsheet improves the module stability under damp heat. However, removal of ILD is the most interesting approach and is currently adopted by foil manufacturers. Importantly, the modules built with ILD-free backsheet and either polyolefin encapsulant or EVA showed respectively only 0.3% and 1.6% maximum power loss after 2000 hours of damp heat which is well below the requirement of the IEC 61215 standard.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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