ELECTROLUMINESCENCE ON THE TCO CORROSION OF THIN FILM MODULES

Thomas Weber, Elfriede Benfares, Stefan Krauter* and Paul Grunow
Photovoltaik Institut Berlin AG, Wrangelstr. 100, D-10977 Berlin, Germany
Phone: +49 (30) 814 52 64 111, Fax: +49 (30) 814 52 64 101, e-mail: weber@pi-berlin.com
*University of Paderborn, Institute for Sustainable Energy Concepts, Pohlweg 55, D-33098 Paderborn, Germany

ABSTRACT: The corrosion of thin film modules is a known reliability problem, which occurs when modules are biased electrically negative towards ground in warm and humid areas. Modules that are critical in respect to TCO corrosion are currently restricted to certain inverter topologies and to dry climates. Therefore TCO corrosion tests are under consideration as an additional stress test for the product qualification of thin film modules. At the moment there is only limited information on how certain modules will behave at high electrical potential against ground in humid areas.
The effect is explained by the drift of positive sodium ions and diffusion of water vapour to the glass/TCO interface. In the subsequent electrochemical reaction the TCO starts to dissolve from the glass at the module edges. In the final stage, the electrical circuit gets interrupted and the module fails completely. In this study the effect is monitored via electroluminescence for various semiconductor technologies, module encapsulation schemes and fixtures. Additionally, the power loss and the leakage currents of the biased modules are recorded. The feasibility of this testing sequence for thin film module product qualification is discussed to secure real field conditions. Finally, design rules for thin film modules are suggested.
Keywords: TCO corrosion, electroluminescence, reliability

1 INTRODUCTION

The electrochemical corrosion of photovoltaic thin film modules using transparent conductive oxides (TCO) as front contacts on the front cover glass were initially investigated by Mon et al. [1],[2]. They showed that the encapsulant is playing a dominant role, where ethylene vinyl acetate (EVA) performs better than polyvinyl butyral (PVB), because of a lower electrical conductivity of EVA by three orders after moisture ingress under damp heat conditions. The leakage current is determining the corrosion rate together with susceptibility of the encapsulated semiconductor. A laboratory method to evaluate the corrosion susceptibility of the TCO layer was proposed by Jansen et al. [3]. Later on, the team of BP Solar [4], [5] gave a comprehensive overview on the electro-migration of the sodium in the glass as root cause for decomposition of the TCO at the glass. They showed, that the corrosion can be blocked by reducing the moisture ingress, setting the modules on a positive electrical potential vs. the ground potential, by choosing a glass with low sodium content, and by using zinc oxide instead of tin oxide for the TCO. Although the investigation carried out has been quite complete in explaining and solving the problem, BP Solar dropped their entire thin film activities on a-Si and CdTe in late 2002 because of the possible TCO corrosion effect.

In the meantime, thin film modules on the basis of amorphous silicon have experienced a large market introduction, because the technology was made available by equipment supplier from the flat panel display industry as large-scale turn-key production lines. For the case of Cadmium Telluride, the company First Solar has managed to become the largest producer of photovoltaic modules world-wide. Commercial modules are now equipped with in-laminate butyl tapes as edge seals to block moisture ingress. As an alternative approach, the fixation points which are used for mounting the modules are moved away from the module edges. Extended distances of the active areas from the edges reduce critical moisture ingress and the leakage current as well. More recently, TCO corrosion has been investigated by [6][7][8]. They confirmed that especially in humid areas and for negative potentials against ground TCO corrosion poses a reliability risk for superstrate thin film modules.

In this work electroluminescence imaging after damp heat exposure with bias voltages is used to map the corrosion effect on commercial glass/glass modules.

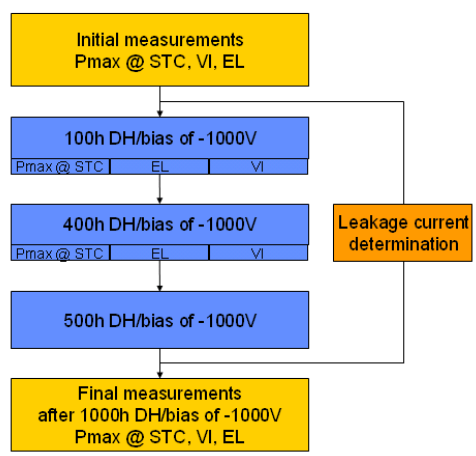

Figure 1: Testing scheme for our TCO corrosion test incl. leakage current determination. After 100, 400, and 500 hours (total: 1,000 hours) visual, electroluminescent and electrical results are determined

Electroluminescence imaging has become a very popular characterisation method at the module level in the last years [9], [10] and [11]. Electroluminescence on the TCO corrosion of thin film modules in the laboratory is subject of this work.

2 EXPERIMENTAL SETUP

The modules have been exposed to damp heat at 85°C and 85% relative humidity (DH) at a negative bias voltage of -1000V vs. the ground. Before and after the exposure the IV curves have been recorded using a Class

AAA flasher Pasan SSIIIb, electroluminescence imaging (EL) via CCD camera and visual inspection (VI). The maximum power (P_{max}), the shunt (R_{sh}) and series resistance (R_s) have been extracted from the IV curve under standard test conditions (STC). Additionally, the leakage currents have been logged during the damp heat exposure. All tests have been accomplished according to IEC 61646 [12]. Additional parameters for the evaluation of the TCO corrosion are the corroded area from VI, EL results and the leakage current during the complete exposure time.

Four different types of modules with different semiconductor materials and fixation points have been investigated in the biased damp heat test (BDH) according to the test scheme in Fig.1. The encapsulation material was PVB for all modules except for Cadmium Telluride (Type D) which has been equipped with EVA and an edge seal (see Table **I**).

Table I: Overview of the modules under investigation in the biased damp heat measurement (BDH)

Type	A	B	C	D
Technology	a-Si	a-Si/µ-Si	a-Si/µ-Si	CdTe
Module fixture	frame	clamps	innovative	clamps
Encapsulant	PVB	PVB	PVB	EVA
Sealing	no	no	no	yes

3 RESULTS AND DISCUSSION

3.1 Amorphous module

Module **Type A** is a commercial amorphous Si module which is framed. During the experiment the module was mounted using clamps. Fig. **2a** shows the initial EL picture of this module with clearly defined edges and a relatively homogeneous luminescence emission over the complete area. The signal level is relatively poor. Local shunts are visible as dark dots. After the BDH the sharpness of the edges and the total EL-intensity are reduced (Fig. **2b**).

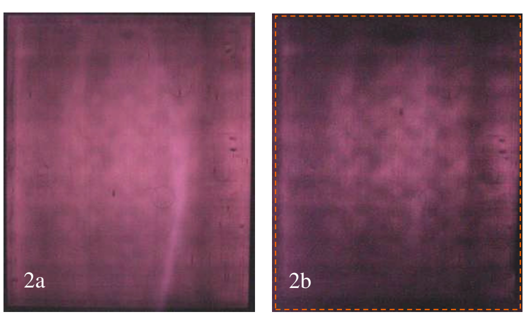

Figure 2: EL pictures of module Type A (a-Si, framed). 2a: initial EL-picture, 2b: EL-picture after 1,000 hours of BDH, which shows reduction of active area.

Visual inspection after the experiment reveals a corroded area of 9 cm² over some cells on the upper side of the module.

3.2 Micromorphous Silicon modules

The second commercial module under evaluation has been module **Type B**, a micromorph Silicon tandem module, consisting of an amorphous and a microcrystalline layer. This unframed module was fixed with four clamps. The distance between µ-Si semiconductor to module edge is 10 mm.

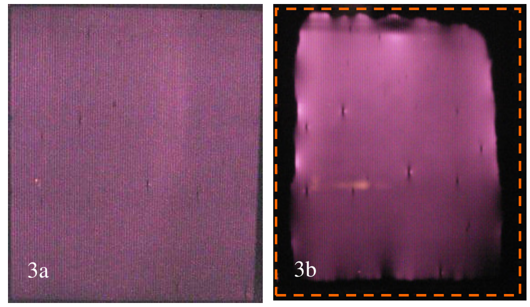

Figure 3: EL pictures of module Type B (µ-Si, laminate, fixed with clamps):
3a: initial EL-picture, 3b: EL-picture after 1,000 hours of BDH, showing reduction of active area. The module edge is marked as a red dashed line.

EL emission of the micromorph Silicon module in Fig. 3a is higher and more homogenous compared to the amorphous Silicon module. Again, the edges are undamaged initially, but the shunt currents are more pronounced: A typically bright halo is visible around lengthy black dots. The halo derives from the thermal radiation around the local shunt currents. The temperatures in the semiconductor layers are high enough, that their thermal radiation can be sensed by the silicon CCD camera sensor at 1050 nm The cell stripes are very clearly visible. After the BDH exposure the EL picture in Figure **3b** reveals:

1) The active area is reduced by 22 % after counting and comparing the active EL area in the initial and final picture. The reduction depth over the whole edge varies from 27 to 204 mm ± 7 mm.
2) Additionally to the deactivation at the edges, a de-activated area at the junction box can be identified as a dark spot at the upper edge of the module (not as good as module C below). The j-box is tightening the opening in the back glass only to a certain degree by its glue-fixation, which leads to extra moisture ingress at the j-box.
3) Regions of higher emission are detectable at the edges to the remaining active area. This indicates the thermal radiation of new local shunts built by the on-going corrosion (Fig **3b)**

Visual inspection of the same module gave a corroded area of 888 cm² at the edges after 1000 hours biased damp heat. The evolution of the corroded area is presented in Table **II**. The corrosion starts from the clamps and expands over the whole module edge with a discontinuous depth and ends with 6.5 % share of the total area after 1000 h.

Table II: Increase of the corroded area from visual inspection for the biased damp heat treatment at -1000V for module Type B

Biased damp heat duration of exposure	vis. corroded area in cm²	relative share
100 h	26	0.2%
500 h	624	4.5%
1000 h	888	6.5%

In Fig. 4 one can see the corrosion of the module edges in the visual picture "VIS". The "EL" picture taken in the near infrared spectrum (NIR-EL). The non-active areas in the EL-image have been overlayed by the corresponding VIS image. This kind of presentation reveals the different results for the damaged area. In the NIR-EL picture an area of 22% could be identified as non-active, while visually it appears to be only 6.5%. The zoomed left corner images (as indicated with a red outline in Fig. 4) show the details of the TCO corrosion leading to a de-lamination of the TCO layer from front glass. The visible de-lamination is already the second level of the module's destruction, after the module has been de-activated already - as can be shown via EL imaging.

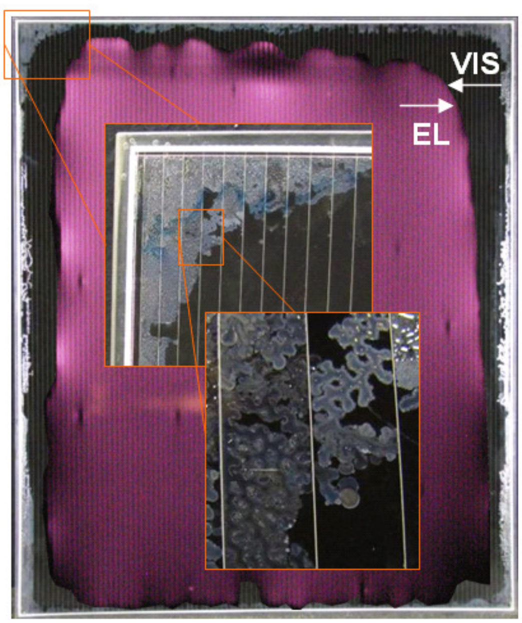

Figure 4: Electroluminescence picture as an overlay of the visual picture of module Type B. "EL" is marking the boundary of the active electroluminescent area to the de-activated area (22%). The "VIS" picture is showing the corroded area at the edges of the module (6.5%) with more details in the in-set images outlined in red.

Module **Type C** is another commercial micromorph Silicon module. In the experiment the module was fixed with a special mounting scheme to the backside and not to the open edges. Again, the leakage current was recorded as for the other amorphous silicon modules above. The distance from the edge of the active area to module edge was 15 mm.

In Fig. **5a** the initial EL-picture is shown. The module exposes a very homogenous EL-signal with sharp edges and a few shunts. After treating the module in BDH we observed only little changes to the initial EL-picture. Moisture ingress through the junction box and via the module's edges are visible, but less pronounced as above. The active area (EL) is reduced by 4 % (module edge marked with orange rectangle, see Fig. **5b**). Some new shunts developed in the area of the mounting fixtures, which are marked with green rectangles. Visually, we could not find any corroded area. The module is the most resistant against TCO corrosion. Even after an inspection after 2000 h in BDH type C shows neither corroded nor deactivated areas in EL (not shown here).

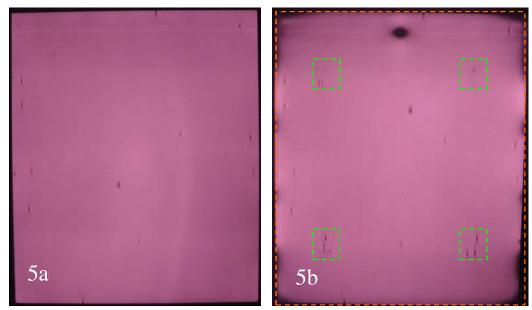

Figure 5: EL pictures of module Type C (μ-Si, laminate, fixed with special mounting fixtures at the backside). 5a: initial EL-picture, 5b: EL-picture after biased damp heat shows reduction of active area and new shunts, marked with green rectangles, developed in the area of the mounting fixtures.

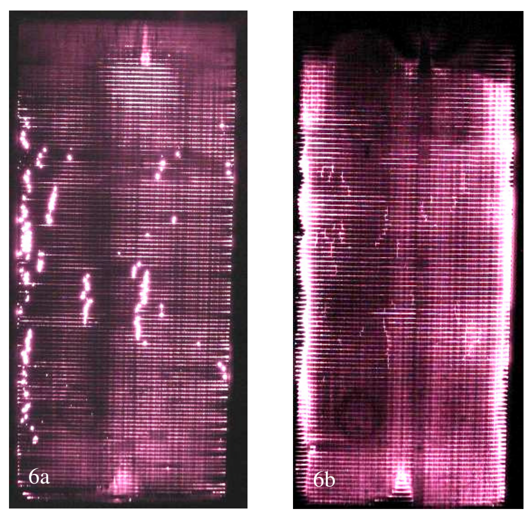

Figure 6: EL pictures of module Type D (CdTe laminate, fixed with clamps). 6a: initial EL-picture, 6b: EL-picture after experiment showing new shunts developed at the module edges on the left and right side.

3.3 Cadmium Telluride modules

Module **Type D** is a commercial CdTe module, which is fixed with clamps during the exposure and has an extra sealing at the edges. Initially, the module shows an inhomogeneous EL picture with a lot of shunt regions at the edges and all over the module (see Fig. **6a** showing bright dots and lines). After the BDH exposure the EL picture reveals non-active regions at the module top and shunted cell edges at the right and left module side. Shunts in the center part vanished in the EL image after treatment (Fig. **6b**). TCO corrosion was not visually visible as for the Silicon modules.

Table III: Experimental results after 1,000 h of damp heat treatment and -1,000 V applied to the modules.

Param.	Type Technology Module fixture	A a-Si frame	B a-Si/µ-Si clamps	C a-Si/µ-Si innovative	D CdTe clamps
ΔP_{max}		-13%	-57%	-3%	-26%
ΔR_s		30%	57%	15%	-5%
ΔR_{sh}		-49%	-90%	-22%	-78%
Corroded area in cm²		9	888	0	-
Share on total area		<0.01	6.5	0	-
Non-active EL		-	22%	4%	-
Charge Q per perimeter in C/cm after 1000 h		0.035	9.263	0.029	-
Charge Q per perimeter in C/cm at ΔP_{max}= -10%		0.031	1.931	0.050	-

3.4 Comparison

In electroluminescence all modules show inactive areas near the edges. But these areas are not necessarily visible as corrosion, i.e. as a de-lamination of the TCO layer from the front glass. Corrosion of the thin film Silicon modules appears on a later stage after preceding deactivation of the thin film cell.

We did not observe corrosion after damp heat treatment only, as requested in IEC 61646. Although visible corrosion starts at the module edges, thin film Silicon modules show darkening in the area of the junction box, due to damp penetration at the opening in the back glass through the interface of the junction box and the backside glass. Module fixtures at the backside led to more shunts in the region of their fixation. Nevertheless, the innovative mounting fixtures reduce field intensities compared to mounting clamps at the "open edges". Leakage current pathways are longer and the corrosion of the TCO is avoided. At the same time, the distance from semiconductor to module edge is important. The module Type C with 15 mm distance shows no corrosion effects compared to the module Type B with 10 mm distance. It seems that for Silicon modules an additional sealing can be omitted if these design conclusions will be taken into account.

Beside the visual and EL inspection we investigated the modules in power determination under standard test conditions (STC) and recorded the leakage currents for Type A, B and C. Table **III** summarizes the data obtained directly after 1000 h in the BDH. Power losses on this stage are only assignable to modules mounted with frame or clamps by increasing series resistances and decreasing shunt resistances. Type C is very resistant against TCO corrosion. The power determined under standard test conditions (STC) shows a decline of -9 % after 2000 h of BDH compared to -3 % after 1000 h.

The leakage currents determined corresponds to the results from Gossla et al. [7]. The higher the charge flow is the higher is the degradation. An increasing of the series resistance and decreasing of the shunt resistance are monitored.

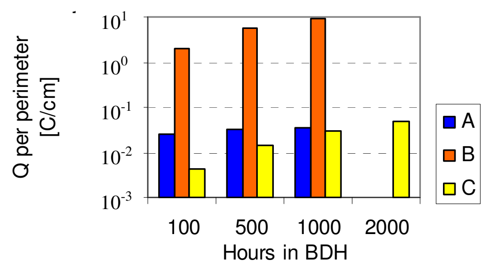

Figure 7: Charge Q per perimeter for biased damp heat for the silicon thin film modules.

The results of the leakage current determination are presented in Fig. **7**. For Type A, B and C we show the transferred charge per perimeter after 100, 500 and 1000 hours and for Type C after 2000 hours. Modules with poor damp tightness show a high charge flow (Type B). From the charge which has flown, when the power loss reaches -10%, one can conclude that the µ-Si semiconductor of Type B is very inert and on the other hand the a-Si film of Type A is very sensitive to corrosion (Table **III**). This comparison at a fixed total charge is independent from the exposure time, mounting structure, applied voltage and module damp tightness and reveals the stability of the thin film cell in the module.

4 CONCLUSION

All modules investigated show corrosion after electrically biased damp heat treatment. Silicon thin film modules show TCO corrosion and degradation depending strongly on the module design. CdTe modules degrade as well, but show different effects regarding TCO corrosion, dissolving and shunting. Results for CIGS modules are not presented here but corrode as well, but maybe independent from the sodium diffusion.

The corrosion affects the maximum power of the modules under STC conditions by an increase of series resistance and reduction of shunt resistance.

Electroluminescence reveals different failure modes than visual inspection and enables to detect the corrosion on an earlier stage.

From the total charge flow after 1000 h, one can conclude on the damp tightness of the encapsulant. The corrosion is further influenced by the mounting scheme, dimensions of the modules edges, and the applied system voltage with its polarity. These are the key parameters for the corrosion on the module and system side.

The value of the total charge flow at the point of 10% power drop, allows benchmarking of the thin film cells towards their inertness against corrosion inside the module.

Both aspects are important development targets for stable modules, which do not need any restrictions to a certain inverter topology or even only dry locations.

We propose to allow a power drop of less than 20% as an acceptance criterion after 1000 hours of electrically biased damp heat treatment for both polarities. Because the power drop from the corrosion is nearly linear with the exposure time, a pass criteria not greater than 5% for P_{max} after 250 hours appears also to be reasonable, thus allowing a reduction of testing time and related costs.

This corresponds to lifetime of 45 years for modules passing that criterion on the basis of the total charge flow per perimeter as estimated by Gossla [7].

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