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Polymer foil additives trigger the formation of snail trails in photovoltaic modules

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ABSTRACT

After several months of operation, many photovoltaic (PV) modules develop a discolouration defect called *snail trails* which appear as irregular dark traces across the cells. These traces are caused by silver nanoparticles accumulating within the encapsulation foil directly above the grid finger. In this work we systematically investigate combinations of encapsulation and back-sheet foils with respect to their susceptibility for snail trails. We can show that certain additive compositions within the encapsulation and back sheet foils are critical for the formation of the discolouring silver nanoparticles. We suggest a reaction model explaining the formation of snail trails from a chemical point of view. This fundamental understanding allows the rapid testing of foils for their snail trail sensitivity as well as the special design of resistant foils.

1. Introduction

The investigation of defects and degradation in photovoltaic (PV) modules has become an important subject, since reliability and product lifetime are key to system performance and to warranty conditions. One of the degradation effects that have been observed increasingly during recent years is “snail trails” because of its visual appearance. Snail trails occur a certain period (several months to several years) after initial installation and appear as discolorations on the cell edges and as intersecting dark lines. It is a widespread phenomenon affecting modules from more than 13 manufacturers worldwide [1] which has been found on modules with mono-crystalline silicon cells as well as those with multi-crystalline silicon. Despite manifold concerns of customers, as yet there is no indication that they cause a significant decrease in module efficiency [2]. However, longer-term negative influences cannot be ruled out and require further study. It could be shown previously that moisture is a key factor in the formation of snail trails [3,4]. Under operating conditions, environmental moisture can enter the PV module through the back-sheet foil. However, the cell itself is an effective barrier to moisture entering the sunny side. The cell edges or cracks are the only sites where entered water may diffuse onto the cell surface. There, a small fraction of silver from the grid fingers may be dissolved and migrate into the encapsulation foil on top of the grid fingers. By a chemical reaction which has yet to be resolved in detail the dissolved silver ions are reduced and form metallic nanoparticles showing a typical brownish colour and a particle plasmon resonance [5].

To uncover the reaction conditions provoking the formation of those silver nanoparticles, we set up a series of experiments to study the chemical differences between the foil types as well as the relationship between the foil combination and the snail trail sensitivity. We used a test procedure based on mini modules for a systematic variation of encapsulation and back-sheet foils. In combination with chemical analysis of those foils, the results enable us (i) to present a reaction model for the formation of snail trails and (ii) to predict whether a certain foil combination is prone to snail trails or resistant.

2. Material and methods

The laboratory test to provoke snail trails had the following setup. Mini-PV modules were prepared by laminating a single multi-crystalline cell with encapsulation foil (various types) between float glass and back-sheet foil (various types). One cell type with silver paste from one batch was used during the experiments. The mini-modules were equipped with electrical contacts. Photographs and electroluminescence EL images were taken for initial documentation. The test modules were treated for 500 h or 1000 h under the following damp-heat conditions: temperature 85 °C, rel. humidity 85%, current 8 A.

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Laser ablation ICP-MS was performed using a LSX 213 instrument (Cetac, USA) coupled with a high-resolution inductively coupled plasma mass spectrometer (ICP-MS, Thermo Scientific). Intensities for phosphorus (P), sulphur (S) and silicon (Si) isotopes were recorded with sufficient mass resolution. The matrix signal of carbon (C13) was used to normalize the signals of the individual scans to an uniform ablation level for better comparability. The ablation was done as double line, i.e. in a first ablation the surface of the material was removed and the second run at the same site was used for analysis. Thus the analysed material represented a layer between 15 and 20 μm underneath the surface.

To provoke silver nanoparticle formation in the test-tube samples of different encapsulation and back-sheet foils about $3 \times 3\ \text{cm}^2$ in size were incubated for 24 h in 50 ml of 0.01 M, 0.1 M or 1 M aqueous $AgNO_3$ solution (AppliChem A0536.0025) at 40 °C. The discolouration of the foil samples was documented in photographs.

UV–vis spectroscopy measurements were carried out using a Varian Cary 300 (Mulgrave, Victoria, Australia) two-channel, double monochromator spectrometer. In the sample compartment, a 70 mm integrating sphere coated with Spectralon (PTFE) from Labsphere (North Sutton, NH, USA), type DRA-CA-30I, was used for all measurements. A baseline correction for 0% and 100% transmission was carried out using the sphere immediately before the measurement series with air in both the sample and the reference channel. For both the measurement and the baseline correction, a calibrated reflectance standard in 8° geometry was used.

X-ray photoelectron spectroscopy measurements were carried out by an XPS spectrometer Sage 100 (Specs Surface nano Analysis GmbH). Al-Kα irradiation was used at a pressure of 10^{-7} mbar in Constant Analyser Energy mode, which results in a depth resolution of 5–7 nm.

3. Results and discussion

3.1. *Certain polymer foil combinations promote the formation of snail trails.*

Based on the observation that not all PV modules exhibit snail trails, even not all from one manufacturer, we supposed that specific properties of the polymer foils used for the assembly of a PV module may be critical for snail trails. Thus, we used the snail trail lab procedure [6] to test different foil combinations systematically. Besides typical encapsulation foils made from poly(ethylenevinylacetate) (EVA) we also tested polyolefine-based encapsulants. In addition, different back-sheet foils were used with a core consisting of polyethylene terephthalate (PET) or polyamide (PA) and varying front and back layers. Table 1 lists the polymer composition of all tested foils. All samples were typical polymer foils used for the PV module production as purchased from different manufacturers. No information was available on the composition of the additive.

Mini modules were assembled with various combinations of the different types of encapsulation and back-sheet foil. A constant

Table 1
Polymer composition of the encapsulation and back sheet foils used for the snail trail test matrix. (PA, PA6, PA12:various polyamide types, PVDCN: Polyvinyldicyanide, PE: Polyethylene, PVF: Polyvinyl fluoride, PET: polyethylene terephthalate).

Back sheet	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7
front	PA12	PVDCN	PA12	PA6	PA	PA12	PVF
core	PA	PET	PET	PET	PET	PA	PET
back	PA12	PE	PA12	PA6	Fluoropolymer	PA12	PVF
Encapsulant	Type 1	Type 2	Type 3	Type 4	Type 5		
Polymer type	EVA	EVA	EVA	Polyolefine	Polyolefine		

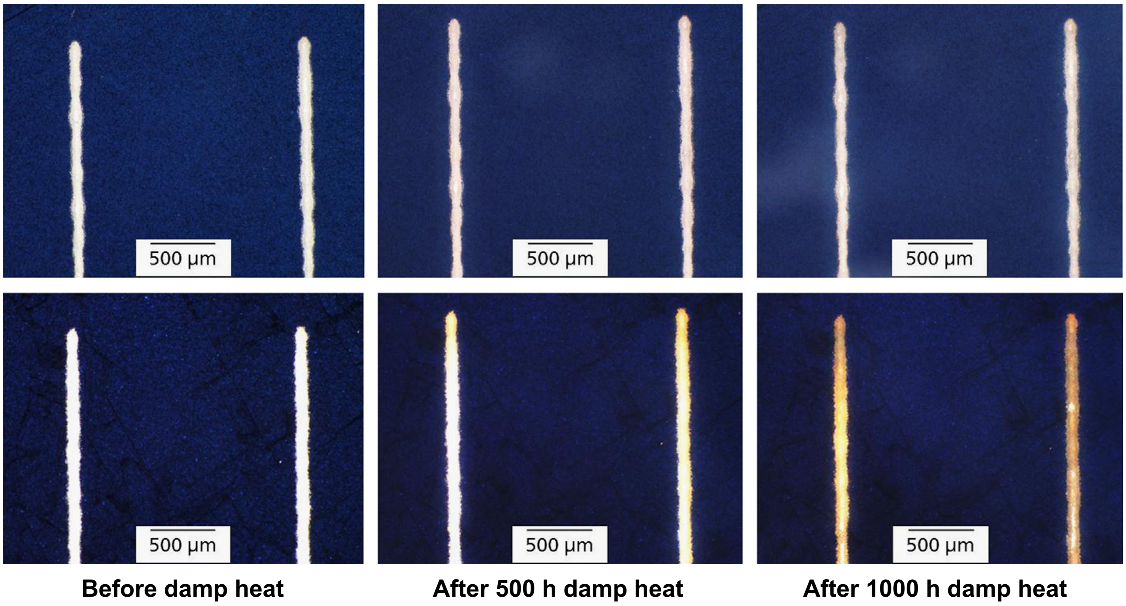

Fig. 1. Microscopic detail (cell edge) of mini modules before and after damp heat treatment. No discolouration appeared with module #1 (top), significant brownish discolouration of the grid fingers (at the cell edges) was found for module #2 (bottom). See online version for a better impression of colour. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)