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## Snail trails: root cause analysis and test procedures

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### Abstract

The “snail trail” discoloration effect observed at many PV modules after some time in the field was investigated with regard to their microscopic and chemical properties and environmental conditions. We show here the combined results of studies on defect modules after outdoor exposure as well as on mini modules after laboratory DH tests and provide a mechanistic model for the snail trail formation. Finally, we can show that a detailed chemical and physical characterization of encapsulation polymers is a fundamental prerequisite for quality assurance and reliability in solar module production.

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*Keywords:* Snail trails; module defects; laboratory test method

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### 1. Introduction

Since several years a discoloration effect, the so-called snail trail effect, is occurring in crystalline silicon photovoltaic modules under outdoor exposure. The visual appearance of these modules is affected by a local discoloration of the Ag contact fingers. This leads to customer complaints from solar plant operators, investors and private owners [1]. It is known so far, that snail trails may occur on cell edges and at or close to micro cracks across the solar cells within the modules. The formation conditions of snail trails are related to material and process induced sources. Some critical material related factors identified so far are back sheet foils due to their water vapor permeability as well as EVA foils and silver pastes due to their different chemical components [2-4].

In our present contribution we investigated photovoltaic modules with snail trails from various producers, which have been under outdoor exposure for several months. In parallel, an accelerated test to provoke snail trails has been developed at mini module level. This approach allows a systematic study of various material combinations (metallization, EVA, back sheet material) aiming at an understanding of the underlying chemical degradation mechanism.

## 2. Experimental

### 2.1. Analysis of snail trail affected PV modules

Photovoltaic modules with snail trails from various producers, which have been under outdoor exposure for several months, were investigated. Initially, each module was inspected visually and an EL measurement was performed. Following, positions with significant snail trail effect were identified and regions of interest were prepared for detailed microstructural and chemical analysis by detaching smaller pieces from the module and disassembling the cell fragments from the glass as well as from the encapsulation and backsheet foil. After detailed microscopic imaging of discolored sites the following analyses were performed. To compare the discolored and a reference grid finger in detail, cross sections were prepared with the Focused Ion Beam (FIB) technique using a Pt protection bar. The delaminated discolored EVA foil was coated by a few nanometer thin Pt-layer and additional with a Pt bar at the target region in order to prepare a TEM lamella by the FIB technique. The TEM lamella was prepared perpendicular at the transition region between clear and discolored EVA [3]. The elemental and chemical analyses were performed by TEM. EDX spectra were acquired as line scans and as mapping using the STEM mode for an area of  $155 \times 200 \text{ nm}^2$ . At removed discolored and reference EVA of a further snail trail module ToF-SIMS measurements are carried out at regions previously connected with the Ag contact fingers.

### 2.2. Development of a laboratory test method

A laboratory test to provoke snail trails had the following setup. Mini PV modules were prepared by laminating one multi-crystalline cell with EVA foil (various batches) between float glass and backsheet foil (various batches). During preparation micro cracks were induced intentionally. The mini modules were equipped with electrical contacts. Photos and EL images were acquired for initial documentation. The test modules were treated for 500 or 1000 h under the following damp-heat conditions: temperature  $85^\circ\text{C}$ , rel. humidity 85%, current 8 A.

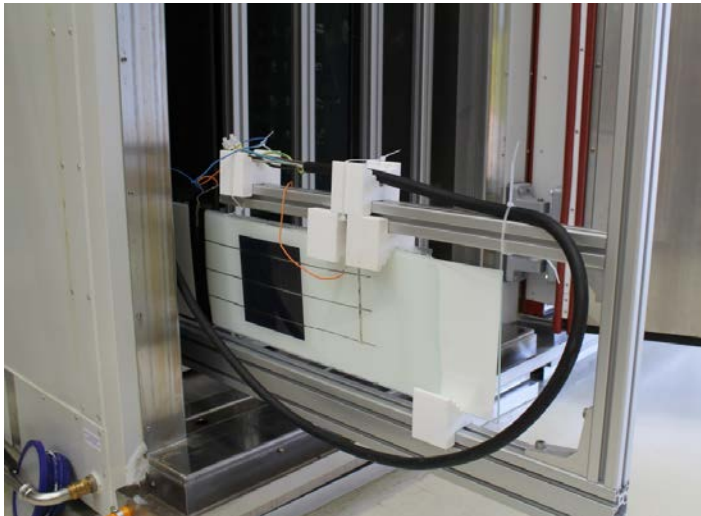


Fig. 1. Damp-heat treatment of mini modules

Optical inspection, EL measurements und microscopic imaging were performed after withdrawal of the modules from the damp-heat chamber.

### 3. Results and discussion

#### 3.1. Snail trails are located at micro cracks or cell edges

As shown exemplarily in figure 2 the typical dark traces called “snail trails” are always located at the cell edge or along micro cracks which can be easily detected by EL. It has to be stated that not every micro crack develops snail trails. However, if a snail trail within the cell area is observed always a micro crack can be found at the same position.

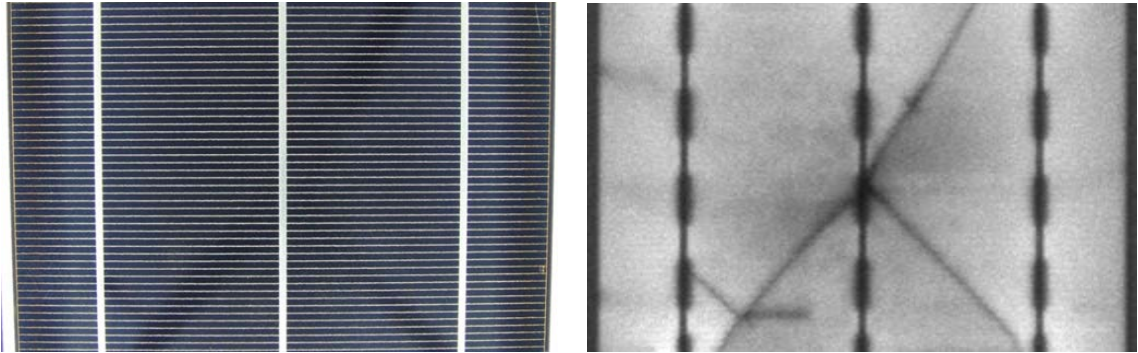


Fig. 2. Visual appearance of snail trails at cell edges and along micro cracks (left), EL image of the same cell piece to indicate the micro crack positions (right)

#### 3.2. A brownish discoloration of the grid finger appears as dark trace

In most cases the optical impression of a dark trace is caused by a brownish discoloration at the grid finger position. The cell surface itself is usually not discolored (fig. 3). The width of the dark traces varies between 5 and 9 mm.

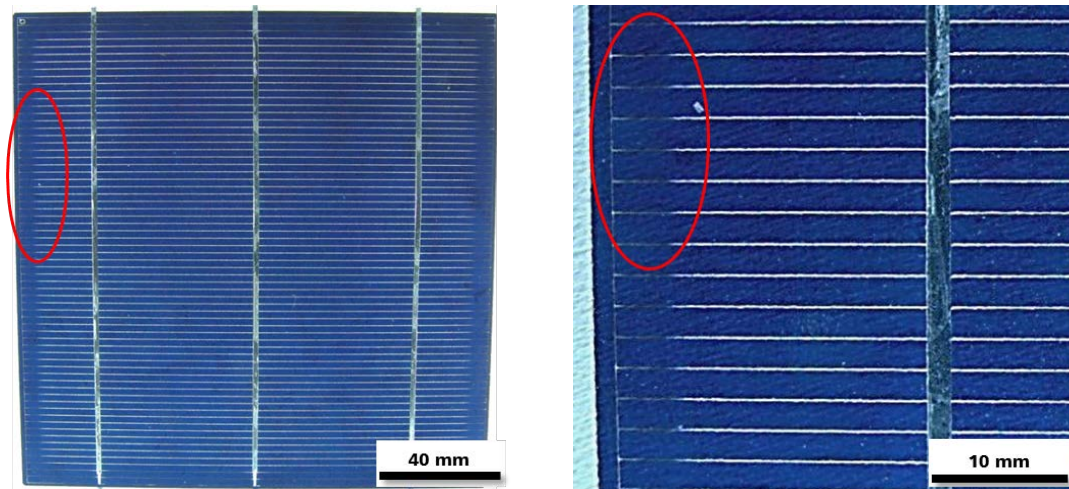


Fig. 3. A typical snail trail at the edge of a whole cell (left), image section: dark discoloration of the grid fingers at the same position (right)

### 3.3. The discoloration of the grid fingers is imprinted into the EVA foil

After disassembly of modules with snail traces it became obvious that the discoloration of the grid fingers has spread into the encapsulation foil. Figure 4 shows an example of a dismantled module piece. The cell surface displays partly discolored grid fingers as well as dark imprints at the respective sites of the delaminated EVA foil.

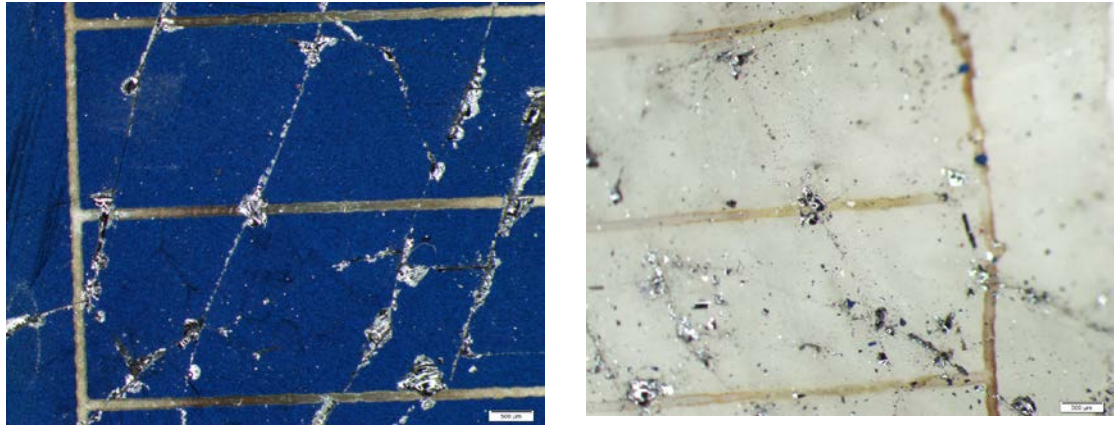


Fig. 4. Microscopic images of the uncovered cell surface (left) and the separated EVA foil (right) with discolorations

### 3.4. A chemical reaction takes place at the silver-foil interface

To further investigate the discolored surfaces the two materials were studied separately using SEM and TEM imaging. First, cross sections of the grid fingers were prepared and analyzed. As shown in figure 5 the main difference between a normal and a discolored site of a grid finger is a film at the silver surface containing organic material and particles [3].

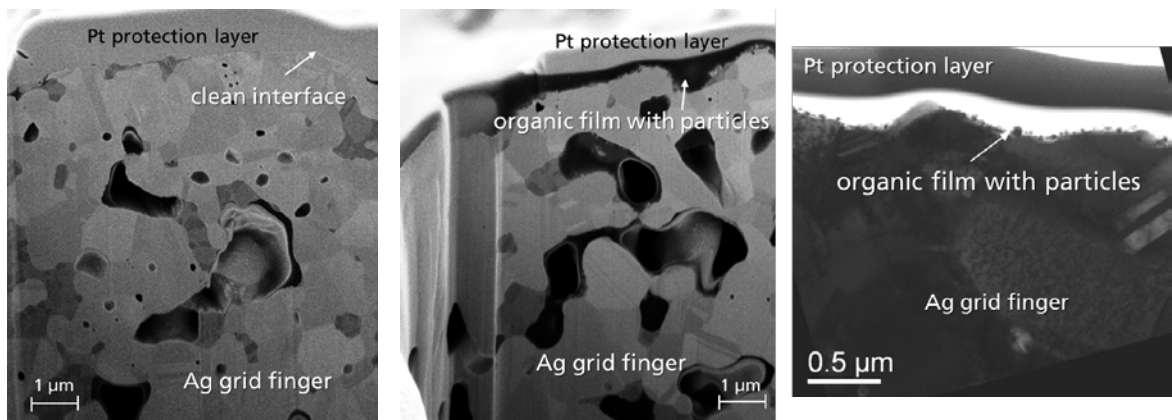


Fig. 5. SEM images of cross sectioned grid finger at a normal site (left) and at a discolored site (middle). An image section of (middle) with more details was obtained by TEM (right).

On the other hand, the dismantled EVA foil was analyzed. A TEM lamella perpendicular to the discolored interface was prepared in that way that a discolored and a clear area was covered (fig. 6a). The respective TEM image (fig 6b) shows a high concentration (2-4 per  $\mu\text{m}^2$ ) of particle clusters in the discolored area compared to almost no particle in the clear area.

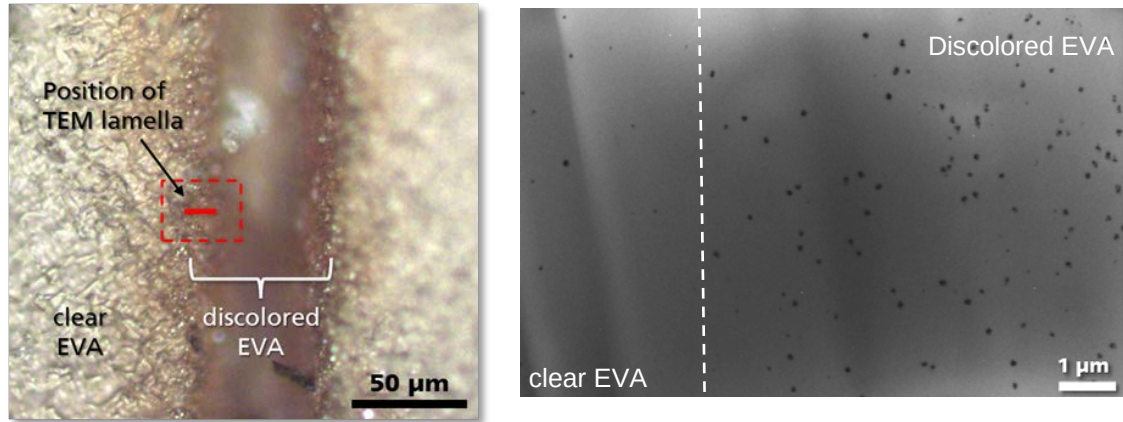


Fig. 6. Position of the TEM lamella (top view) covering a clear and discolored section (left). TEM image of the TEM lamella perpendicular to the top view (right)

### 3.5. Chemical composition of particles causing the brownish discoloration

The chemical composition of the discolored region and the particles, respectively, were analyzed by collecting EDX and ToF-SIMS spectra. As shown in Fig. 7, we found that the particles are enriched of Ag, S and P. Moreover, ToF-SIMS data revealed also Cl as typical component of the discolored material (data not shown) [3].

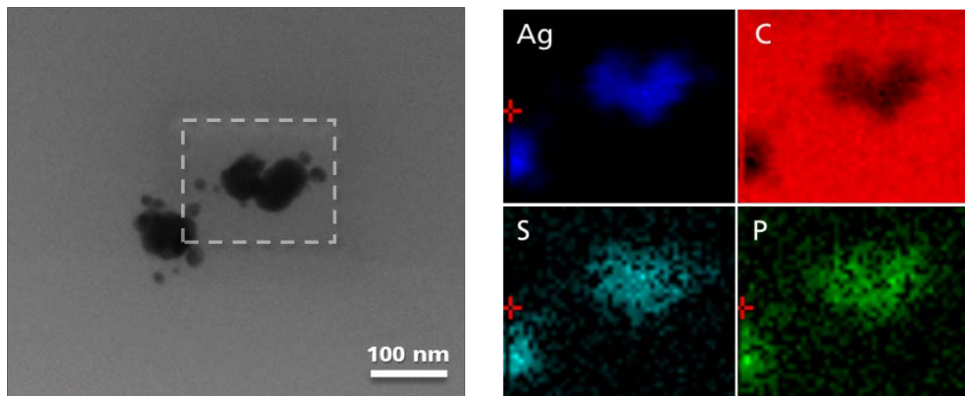


Fig. 7. TEM bright field image of a particle chosen for EDX analysis (left), EDX mappings for Ag, C, S and P of the marked area (right).

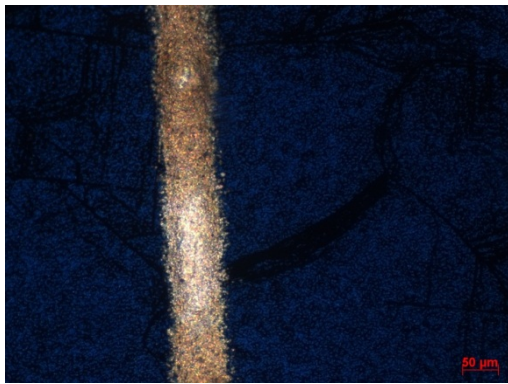
### *3.6. Model of snail trail formation*

Based on the results presented above we propose the following model of snail trail formation: moisture diffuses through the backsheet foil and reaches the cell surface at the edges or through micro cracks. In the presence of an electrical field, operation temperature and possibly UV irradiation corrosion processes at the interface between silver contact and encapsulation foil are triggered leading to a migration of silver into the EVA foil and the formation of Ag containing particles. A second precondition is the presence of S, P and/or Cl containing components, probably within the polymers, allowing a chemical reaction between silver and those components [4].

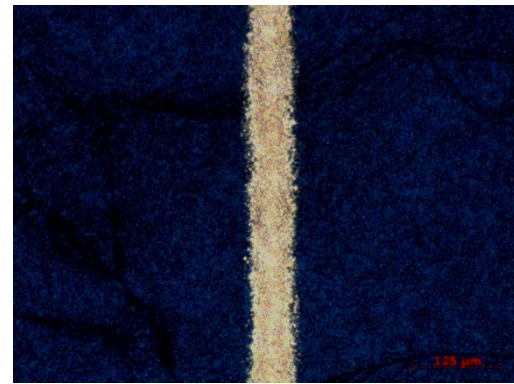
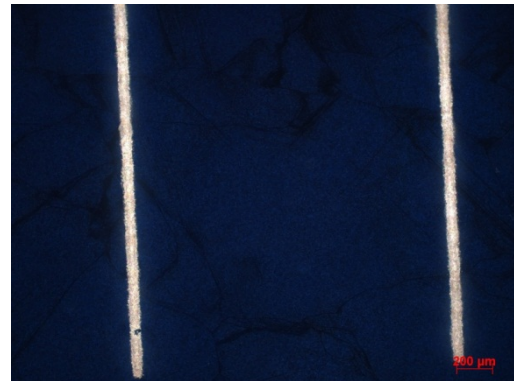
### *3.7. A laboratory test set up can provoke snail trails*

Using the laboratory test set up described in the experimental section, we were able to provoke snail trails in dependence of the used polymers. Shown in figure 8 are the results from two mini modules which were assembled using two different foil combinations. Whereas one of the modules showed typical snail trail discolorations at the cell edge and also at the micro crack (data not shown) the parallel sample did not show any discoloration. In order to identify the critical parameters of the polymer foils favoring the formation of snail trails chemical analyses of the foils were started. Preliminary results on the phosphorus content of the foils are in good correlation to the formation of snail trails (fig. 8 bottom). The mini module with snail trails was made from foils which contain significant more phosphorus than the foils which were used for the parallel mini modules without snail trails. Thus, the phosphorus content of the polymers, which may origin from antioxidants and stabilizers like TNPP (Tris-(mono-nonylphenyl)-phosphite) may represent one of the chemical factors to be optimized in order to avoid snail trails.

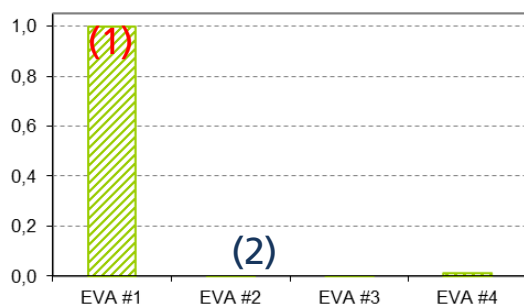
### Foil combination (1)



### Foil combination (2)



### Relative P content of various EVA foils



### Relative P content of various backsheet foils

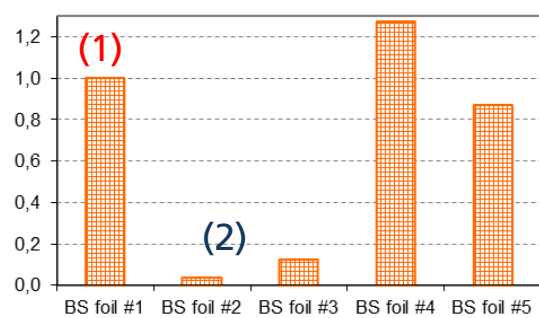


Fig. 8. Microscopic images of grid fingers at the cell edge after 500 h (top) and 1000 h (middle) under damp-heat conditions showing typical discolorations (left), or without discolorations (right). Comparison of phosphorus content within various EVA (bottom, left) or backsheet foils (bottom, right) as measured with laser ablation ICP-MS.

#### **4. Summary**

The discoloration effect called „snail trails“ was analyzed with respect to its microstructural and chemical properties. The typical dark traces are discolorations at the position of the grid fingers which are imprinted in the surface of the encapsulation foil. Triggered by moisture, temperature and electrical field a reaction at the silver-polymer interface takes place which leads to the formation of particles containing Ag, P and S migrate within the encapsulation foil.

A laboratory test procedure provoking snail trails was developed on the base of mini modules. It could be shown that certain properties of the encapsulating and the backsheets foil are a prerequisite for the formation of snail trails. The test set up may be useful for checking rapidly new polymer materials or material combinations.

#### **Acknowledgements**

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