Solar Energy Materials & Solar Cells 164 (2017) 80–86

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Study on snail trail formation in PV module through modeling and accelerated aging tests

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ARTICLE INFO

Keywords:
Snail trails
Cell cracks
Simulation
Backsheet
Oxygen transmission rate

ABSTRACT

In recent years, a defect on the surface of photovoltaic (PV) modules called ‘snail trails’ has become a widespread reliability issue, affecting many modules installed in the field. In this work, silver acetate is identified as one component of snail trails through non-destructive Raman analysis. The chemical reaction between the silver grid line, oxygen and acetic acid on top of the micro-crack is proposed as the mechanism. The generation and/or diffusion of acetic acid released from ethylene vinyl acetate (EVA) encapsulant, oxygen and moisture are modeled using finite element method to predict the formation of silver acetate. The simulation results indicate that the existence of micro-crack plus cell gap are necessary for snail trail formation and act as the pathway for transport. As the source of acetic acid, encapsulant plays an important role in snail trail formation. Oxygen transmission rate of backsheet also has significant influence on snail trail formation. Water vapor transmission rate is shown to have no effect on snail trials over a wide rate of transmission rates. An accelerated aging snail trail test has been developed that can simulate snail trails within days, and is compared to modeling and field results.

1. Introduction

Snail trails are a widespread degradation phenomenon of photovoltaic modules affecting many module manufacturers in the past few years [1,2]. It is a discoloration effect of silver grid lines on crystalline silicon cell surface, occurring at micro cracks and/or along cell edges. Currently no evidence indicates that snail trails directly decrease electrical output, but cell cracks, which are precondition for snail trail, can have a negative impact on module performance.

The mechanism of snail trail formation has been proposed to be silver nanoparticles formed in the presence of phosphite reducing agent in the encapsulant EVA [3,4], or silver containing nanoparticles resulting from chemical reaction between the silver grid line and EVA to produce products such as silver oxide [2], silver chloride [2], silver carbonate [5–7] and silver acetate [6,7]. Besides encapsulant, backsheet is also suspected to play a role in the formation of snail trails, since it allows certain amount of moisture to diffuse to the cell surface through the encapsulant at micro-cracks or cell gaps [4].

In this work, the chemical reaction responsible for the formation of silver acetate is proposed. Finite element method (FEM) was employed to model and simulate the generation/transport of related species within the module to predict the formation of silver acetate. Key factors to snail trail formation such as crack, encapsulant and backsheet properties were also studied. Two accelerated aging methods were developed to quickly stimulate snail trail formation. Lab test results are in good agreement with our simulations and to the formation of snail trials in the field. These findings provide insights for the PV industry to mitigate the snail trail issue.

2. Experiment

2.1. WVTR and OTR measurement

Water vapor transmission rates (WVTR) of various backsheets and encapsulants were measured using MOCON PERMATRAN-W® 700 according to ASTM F1249, under 100% RH and nitrogen gas flow rate of 10cc (100 cc for EVA due to its large WVTR value). Oxygen transmission rates (OTR) were measured using MOCON OX-TRAN®

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http://dx.doi.org/10.1016/j.solmat.2017.02.013
Received 4 November 2016; Received in revised form 8 February 2017; Accepted 9 February 2017

2/21 according to ASTM F1927-07, under 60% RH. Both WVTR and OTR measurement were carried out at temperatures ranging from 23 to 60 °C. Afterwards, the Arrhenius-model was fitted to the results of each sample to extrapolate WVTR and OTR at 70 °C, which is the same temperature in our accelerated aging test.

$$WVTR=WVTR_0 e^{\frac{-E_{WVTR}}{RT}} \tag{1}$$

and

$$OTR=OTR_0 e^{\frac{-E_{OTR}}{RT}} \tag{2}$$

2.2. Outdoor and accelerating aging tests

2×2 cells mini modules were prepared for outdoor exposure and one-cell mini modules with electrical load (0.15 Ω, 5 V) were prepared for accelerated aging tests. Single crystalline silicon cells of 5 in. or multicrystalline silicon cells of 6 in. were laminated with encapsulant EVA, Ionomer, and polyolefin based encapsulant (POE) at a standard condition (145 °C for 15 min including 3 min vacuum and 12 min pressure). Tempered glass was used as front cover. Backsheets with different transport properties were selected with different core materials including PET, and polyamide. Cracks were generated intentionally using dropping ball method (Steal ball diameter 25 mm, plastic tube 1.2 m) and electroluminescence (EL) measurements were conducted afterwards to ensure appropriate crack formation. For the outdoor aging experiments, the modules were exposed to natural sunlight and environmental stress of Shanghai China. An accelerated aging test for snail trials was developed using both high temperature and ultraviolet (UV) radiation with resistive load. As shown on Fig. 1, mini modules were put into Q-lab QUV under the condition (70 °C, 0.55 W/m^2 @ 340 nm) or Atlas Weather-Ometer® (CI4000) under similar condition (70 °C, 0.55 W/m^2 @340 nm, 50% RH). The relative humidity ~20% RH during winter and ~70% RH during summer in QUV chamber is expected according to lab monitor data, Shanghai. Snail trail formation rate is counted as the time needed to visually observe snail trails along the micro-crack. Each module design is repeated at least three times to obtain the average snail trail formation rate.

2.3. Raman analysis

To analyze the chemical composition of the discolored silver grid lines, a confocal Raman microscopy Horiba XploRa was used for non-destructive Raman analysis of the PV module. The test chamber is sufficiently large to accommodate a single cell or 2×2 cell mini module to allow data acquisition using the complete module without module disassembly. The Raman scattering was collected in a back-scattering geometry through 50X LWD (long working distance) objective lens. Incident laser light wavelength 532 nm was emitted from a diode-pumped solid state laser (CL532-100-S, Crystal) with approximately 5 mW laser power at the module. All Raman spectra were recorded with a signal acquisition time of 5–10 s according to the signal intensity and a diffraction grating of 600 grooves per mm. (Filter: 50%, Slit: 100 µm, Hole: 500 µm). Since the incident laser will pass through the glass front cover and EVA to the silver grid line, the detected Raman shift is a mixture of EVA and silver grid line. The EVA Raman shifts are thus removed by Raman spectrum subtraction to leave pure silver grid signal.

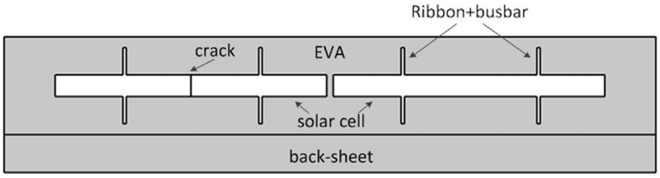

Fig. 2. Geometry of the PV module segment used for the FEM-simulation. From the bottom to top: backsheet, bottom EVA, solar cell and front EVA. A crack is on the left cell.

3. Simulation of silver acetate formation

'Transport of Diluted Species' module in COMSOL Multiphysics® was employed as the FEM tool [8]. Fig. 2 shows the geometry of PV module segment used for the simulation. Since the front cover glass is impermeable to gases, it is not shown on the picture. The module is 300 mm wide, containing two 5 in. cells with cell gap of 3 mm. The dimensions of the module are set similar to the module in our accelerated aging test: 3.2 mm front glass cover, 200 µm thick silicon cell, two 450 µm thick encapsulants and 350 µm thick backsheet. Two ribbons of 250 µm thickness are also included to mimic the real situation. To compare the influence of micro crack, a penetrating crack of 10 µm width is created on the left cell.

The ingress and outgas of atmospheric moisture and oxygen in a PV module can be considered approximately as pure diffusion phenomenon, since only a small amount of water and oxygen participate in the reactions related to snail trail versus large concentration in the atmosphere and module. The diffusion coefficient D is originally defined as the proportionality constant between the concentration gradient and the flux of gas:

$$J=-D\nabla C \tag{3}$$

where J and C are the flux and the concentration of permeant, respectively. The change in concentration of water vapor C_W and concentration of oxygen C_O with time is thus represented by:

$$\frac{\partial C_W}{\partial t}=-\nabla J_W=\nabla\bullet(D_W\nabla C_W) \tag{4}$$

$$\frac{\partial C_O}{\partial t}=-\nabla J_O=\nabla\bullet(D_O\nabla C_O) \tag{5}$$

D_W and D_O are diffusion coefficient of water vapor and oxygen.

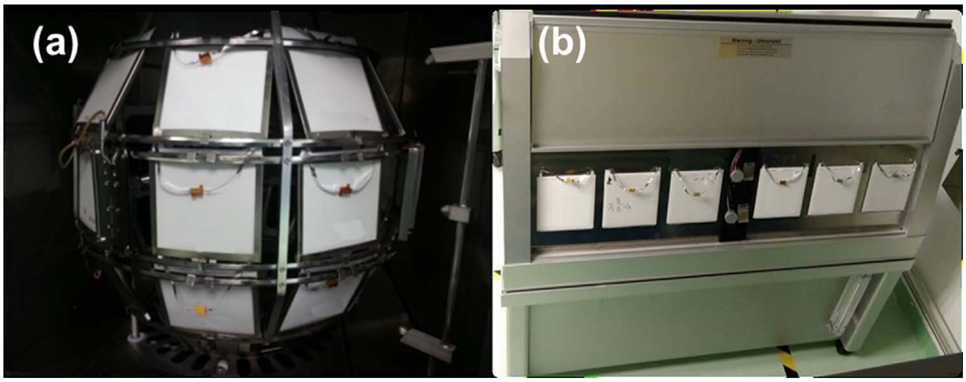

Fig. 1. Experimental set-up for (a) Weather-Ometer and (b) QUV accelerated aging test. One-cell mini modules with resistive load are employed for testing.