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ScienceDirect

Solar Energy 124 (2016) 153–162

SOLAR ENERGY

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Analysis and reproduction of snail trails on silver grid lines in crystalline silicon photovoltaic modules

Namsu Kim [a,*], Kyung-Jun Hwang [b], Dajung Kim [c], Ju Ho Lee [d], Shinyoung Jeong [e], Dae Hong Jeong [e]

[a] *Mechanical Design and Production Engineering, Konkuk University, Republic of Korea*
[b] *Mechanical and Aerospace Engineering, University of California at San Diego, La Jolla, CA 92093, USA*
[c] *Components and Materials Physics Research Center, Korea Electronics Technology Institute, Republic of Korea*
[d] *Reliability Technology Research Center, Korea Electronics Technology Institute, Republic of Korea*
[e] *Department of Chemistry Education, Seoul National University, Republic of Korea*

Received 23 August 2015; received in revised form 22 November 2015; accepted 26 November 2015
Available online 19 December 2015

Communicated by: Associate Editor Frank A. Nüesch

Abstract

In recent years, discolored silver grid lines in crystalline silicon photovoltaic modules, known as snail trails, have been an enormous concern to the solar industry even they do not appear to compromise the electrical performance of the module. In this study, the chemical and structural origins of the snail trail, especially focusing on the silver grid lines, have been investigated by Raman spectroscopy and transmission electron microscopy. Confocal micro-Raman spectroscopy as a non-destructive analysis method was applied. It was proved that Raman spectroscopy is powerful tool for non-destructive failure analysis. It was found that brownish or dark discolored silver fingers are due to the formation of silver acetate as well as its reaction with encapsulant. Silver acetate was synthesized by silver carbonate originated from the reaction of Ag ions and carbon dioxide and acetic acid that originated from the degradation of the encapsulant. In order to verify analysis results, the reproduction of snail trails were performed under lab environment.
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Keywords: Crystalline PV module; Failure analysis; Failure reproduction; Snail trails; Discoloration

1. Introduction

Snail trails, also called snail tracks, have been found in many modules made by different module manufacturers and have recently become a widespread phenomenon (Richter et al., 2012; Rutschmann, 2012; Ines Rutschmann, 2012; Peng Peng et al., 2012; Alan Xu and Han, 2012). They have been considered a type of optical discoloration, as shown in Fig 1(a)–(c). In most cases of snail trails, crystalline silicon photovoltaic (c-Si PV) modules show discoloring of silver (Ag) grid lines after a certain time, ranging from several months to several years after initial installation (Rutschmann, 2012; Ines Rutschmann, 2012; Peng Peng et al., 2012; Sylke Meyer et al., 2013). Although it was reported that they have an insignificant impact on the performance of the PV module, the discoloring of the silver grid lines is enough to be detected by visual inspection (Rutschmann, 2012; Ines Rutschmann, 2012; Peng Peng et al., 2012). Hence, more customers of PV modules request replacement of the module from the module manufacturers. As a result, manufacturers have conducted

* Corresponding author.
E-mail address: nkim7@konkuk.ac.kr (N. Kim).

http://dx.doi.org/10.1016/j.solener.2015.11.040
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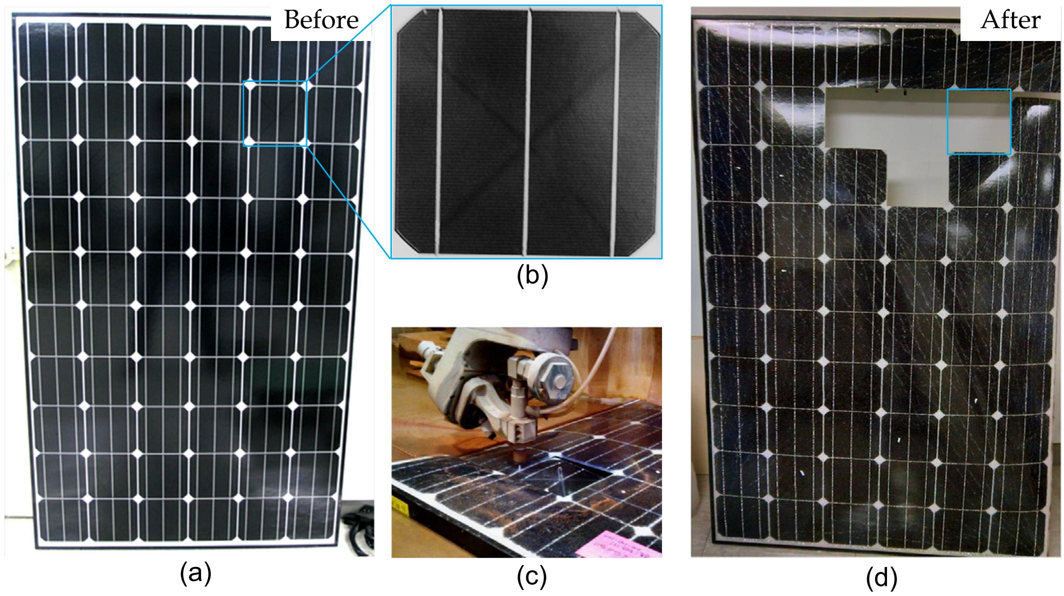

Fig. 1. (a) and (b) Analyzed PV module displaying snail trail, (c) specimen preparation using water-jet cutter, (d) PV module after cutting.

extensive research to determine the origin of snail trails and their impact on PV modules during long-term operating time. However, there has been neither an exact identification of the culprit of the formation of snail trails nor widely accepted analysis procedures. This is due to the difficulty in isolating the defects in laminated PV modules and their sources, but it significantly impacts the analysis results (Gambogi et al., 2009; Kazmerski, 1998; Kim and Graham, 2013; Kim et al., 2014).

In this work, a non-destructive method is employed to investigate the origin of snail trails on Ag grid lines using confocal micro-Raman spectroscopy. In defect analysis, one of the critical principles is to first investigate the detect in as non-destructive a way as possible because it can be investigated in its original state without disruptive influence (Gambogi et al., 2009; Li et al., 2012; Peike et al., 2011). Then, the results from the non-destructive specimen were compared with those from the destructive specimen. It was shown in previous work that the discoloration is due to nano particles or silver carbonate (Ag_2CO_3). Our results indicate that the discoloration of snail trails is due to the formation of silver acetate ($AgC_2H_3O_2$) as well as its reaction with encapsulant. To confirm these results, experiments for the synthesis of $AgC_2H_3O_2$ from Ag_2CO_3 and acetic acid (CH_3COOH) were conducted. In addition, experiments for discoloration of both Ag_2CO_3 and $AgC_2H_3O_2$ with encapsulant were conducted to investigate the origin of the discoloration phenomenon. Based on these results, snail trails in mini modules were successfully reproduced. Analysis of the reproduced snail trails was performed to compare the chemical characteristics and composition of the discolored surface between intentionally reproduced and naturally occurring snail trails.

2. Experiments and details

2.1. Microscopy study of snail trails in PV modules

The analyzed module was a c-Si PV module that displayed snail trails on Ag grid lines, as shown in Fig. 1(a)–(c). The module consists of tempered glass, EVA encapsulant, c-Si cells, and backsheet. The backsheet is a laminated structure of polyvinyl fluoride (PVF) film, polyethylene terephthalate (PET), and PVF film. The PV module was cut using an abrasive water-jet to obtain a size suitable for measurement by Raman spectroscopy, as shown in Fig. 1(d). Eight specimens of small size ($\sim$25 mm^2) were prepared for non-destructive and destructive analysis. In the case of the destructive specimens, Ethylene–vinyl acetate (EVA) encapsulant was cut through the in-plane direction to remove the glass using a microtome, which is generally used for transmission electron microscopy (TEM) sample preparation. The remaining EVA encapsulant was removed mechanically, as shown in Fig. 2(a) and (b). Non-destructive specimens were prepared without removing the glass and EVA encapsulant, as shown in Fig. 2(c) and (d). In addition, among eight specimens, four specimens were taken from the normal region (non-discolored Ag grid line) and others from the abnormal (discolored) region for comparison.

The surface microstructure and topography for both discolored and non-discolored Ag gird lines were investigated by stereoscopic microscopy and field emission scanning electron microscopy (FE-SEM, FEI Quanta 3D DualBeam). To compare and analyze the chemical characteristics and compositions of the discolored and non-discolored silver grid lines, a confocal Raman microscopy system (LabRam 300, JY-Horiba) equipped with an optical

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