Current Applied Physics 15 (2015) 285–291

Contents lists available at ScienceDirect

Current Applied Physics

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

Damp heat and thermal cycling-induced degradation mechanism of AZO and CIGS films in Cu(In,Ga)Se_2 photovoltaic modules

Dong-won Lee [a, b], Won-ju Cho [a], Chan-ik Jang [b], Jun-kwang Song [b], Chi-hong Park [c], Kyung-eun Park [c], Ji-seung Ryu [d], Heesoo Lee [d], Yong-nam Kim [b, *]

[a] Department of Electronic Materials Engineering, Kwangwoon University, 447-1, Wolgye-dong, Nowon-gu, Seoul 139-701, Republic of Korea
[b] Material Technology Center, Korea Testing Laboratory, 222-13, Guro3-dong, Guro-gu, Republic of Korea
[c] Solar Cell Laboratory, LG Innotek Co., Ltd., Osan 447-705, Republic of Korea
[d] School of Materials Science and Engineering, Pusan National University, Busan 609-309, Republic of Korea

ARTICLE INFO

Article history:
Received 2 September 2014
Received in revised form
1 December 2014
Accepted 16 December 2014
Available online 20 December 2014

Keywords:
CIGS
Al-doped ZnO
Thermal cycle
Damp heat
Degradation

ABSTRACT

This paper characterizes and compares the degradation mechanisms of Cu(In,Ga)Se_2 (CIGS)-based thin film photovoltaic (PV) modules during exposure to damp heat (85 °C/85% RH) for 1000 h and thermal cycling (−40 °C/85 °C) for 1000 cycles. After damp heat (DH) exposure, the efficiency of the PV modules was reduced from the initial value of ~12.5 ± 0.1% to 10.5 ± 0.2% due to increase of the resistivity in the AZO and CIGS layers. The optical band gap was also decreased from the initial value of 3.60 eV–3.54 eV after 1000-h DH exposure. This behavior was associated with oxygen adsorption and the generation of hydroxides in the AZO layer. The efficiency of the PV modules after subjection to thermal cycling (TC) was decreased to 11.4 ± 0.2% due to increase of the resistivity of the AZO and CIGS layers. The increase in the resistivity was interpreted as being due to oxygen adsorption, as well as the formation of micro-cracks in the AZO films.

1. Introduction

Cu(In,Ga)Se_2 (CIGS) thin film solar cells have widely been used as a material for the absorber layer because of their band gap and high absorption coefficient for solar radiation [1–3]. The best efficiencies achieved for CIGS thin film solar cells and for large CIGS modules are 20% [4,5] and above 14% [6], respectively, but long-term product warranties in the range of 20–30 yrs still need improvement. To ascertain the long-term stability without actual filed data, several types of accelerated degradation tests have been performed.

One way to investigate long-term stability when outside of the lab is to apply repeated or prolonged accelerated degradation tests on the modules [7,8]. According to the IEC 61646 standard [9], thin-film modules should pass the damp heat (DH) test (1000 h at 85 °C and 85% RH), thermal cycling (TC) test (200 cycles at −40 °C to 85 °C), and a preconditioning procedure based on light soaking (LS), among other requirements. Many studies on the degradation of CIGS solar cells during the application of various stresses have been performed, mainly focusing on the degradation behaviors of CIGS solar cells [10–12] and TCO layers after damp heat [13–16]. However, to clearly explain the degradation behaviors of CIGS modules, failure analysis of the TCO and CIGS absorber layer in the modules is needed under the DH and TC tests.

In the present study, damp-heat-induced and thermal-cycling-induced degradation behaviors of CIGS modules were presented through failure analysis of non-encapsulated modules to clarify the degradation behaviors of CIGS cells. Consequently, degradation mechanisms were suggested by examination of the relationship between conversion efficiency, fill factor (*FF*), open circuit voltage (V_{oc}), short circuit current (I_{sc}) and electrical properties of the AZO and CIGS layers. To explain the degradation behaviors of the AZO and CIGS layers, we report on the structure and chemical bonding state of the layers as determined by XRD and X-ray photoelectron spectroscopy (XPS), as well as their electrical properties.

2. Experimental

Non-encapsulated CIGS modules 475 mm × 375 mm in size were fabricated by evaporation systems. Soda-lime flat glass was

* Corresponding author. Material Technology Center, Korea Testing Laboratory, 7 Gurodigital 8(pal)-gil, Guro-gu, Seoul 152-718, Republic of Korea.
E-mail address: ynkim@ktl.re.kr (Y.-n. Kim).

http://dx.doi.org/10.1016/j.cap.2014.12.023
1567-1739/

used as the substrate, and a molybdenum back-contact with a thickness of ~0.5 μm was deposited with DC magnetron sputtering. The deposition of a CIGS layer with a thickness of ~2 μm was carried out with linear sources using co-evaporation of the elements Cu, In, Ga, and Se. A CdS buffer layer with a thickness of ~0.05 μm was deposited by chemical bath deposition, and the approximately 0.5-μm-thick intrinsic ZnO layer was deposited by RF magnetron sputtering. AZO was deposited by DC magnetron sputtering to approximately 1-μm thickness.

To study the long-term stability of non-encapsulated modules, damp heat (85 °C/85% RH) and thermal cycling (−40 °C/85 °C) tests were performed [17], along with a series of light soaking (LS) procedures [18]. After light soaking, the modules were measured indoors as soon as possible. Environmental tests for the non-encapsulated modules were carried out in an environmental test chamber (Challenge 250, ACS) with the stresses of high temperature and damp heat. The modules were exposed to 100, 200, 400, 600, 800, and 1000 h of heat, and then removed from the environmental test chamber. Thermal cycling tests of the modules were performed in a thermal cycling chamber (TSA-41L, TABAI ESPEC). The temperature profile in the thermal shock test was measured from −40 °C to 85 °C, with 30 min dwell times at both temperature extremes. Thermal cycling tests were carried out for up to 1000 cycles, and the modules were removed from the chamber after 100, 200, 400, 600, 800, and 1000 cycles. The conversion efficiency, Fill Factor (*FF*), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc}) of as-prepared non-encapsulated modules and of modules degraded under high temperature, damp heat, or thermal shock were measured using a solar simulator (WPSS-1.5 × 1.2HD-50 × 4, Wacom Electric Co., Ltd.).

To assess the causes of degradation in the AZO layers and CIGS layers after damp heat (DH) and thermal cycling (TC) tests, failure analysis was performed on the non-encapsulated modules. For the convenience of performing various analytical measurements, the CIGS modules before and after DH and TC tests were cut into ~5 cm × 5 cm specimens. Moreover, the back side of the CIGS layers were revealed for analysis by separating the Mo layer and CIGS/CdS/i-ZnO/AZO layers. The resistivity of the AZO layers and CIGS layers was measured at regions from the edge to the center using a 4-point probe system (Mitsubishi Chemical Corporation, Loresta-GP MCP-T600). For examination of the optical properties, AZO thin films were prepared by RF magnetron sputtering from an oxide ceramic target consisting of 98 wt% ZnO and 2 wt% Al_2O_3. The optical transmission of the AZO films was measured using a UV-VIS spectrophotometer (Agilent Technologies, Cary 300) in the 200–800 nm range. Cross-sectional images of the CIGS solar cells and surface images of the AZO layers were analyzed by FE-SEM (S-4700, Hitachi), and the change of crystal structure was analyzed by an X-ray diffractometer (X'pert PRO, Panalytical). XPS measurements were performed using an Ulvac-PHI system. High-resolution XPS conditions were fixed to a constant analysis energy mode, with 58.7 eV of pass energy and a monochromatic Al source.

3. Results and discussion

3.1. Results of the damp heat and thermal cycling tests

Fig. 1 shows changes in the (a) conversion efficiency, (b) Fill Factor (*FF*), (c) short-circuit current (I_{sc}), and (d) open-circuit voltage (V_{oc}) of non-encapsulated modules as a function of the degradation time. Before accelerated degradation tests, the modules showed conversion efficiencies (*eff*) of 12.4–12.6 % and Fill Factors (*FF*) of 65.4–65.9 %. As shown in the figure, the conversion efficiency, *FF*, I_{sc}, and V_{oc} of the non-encapsulated modules decreased as a function of the degradation time after damp heat (DH) and thermal cycling (TC) tests. After exposure to TC for 1000

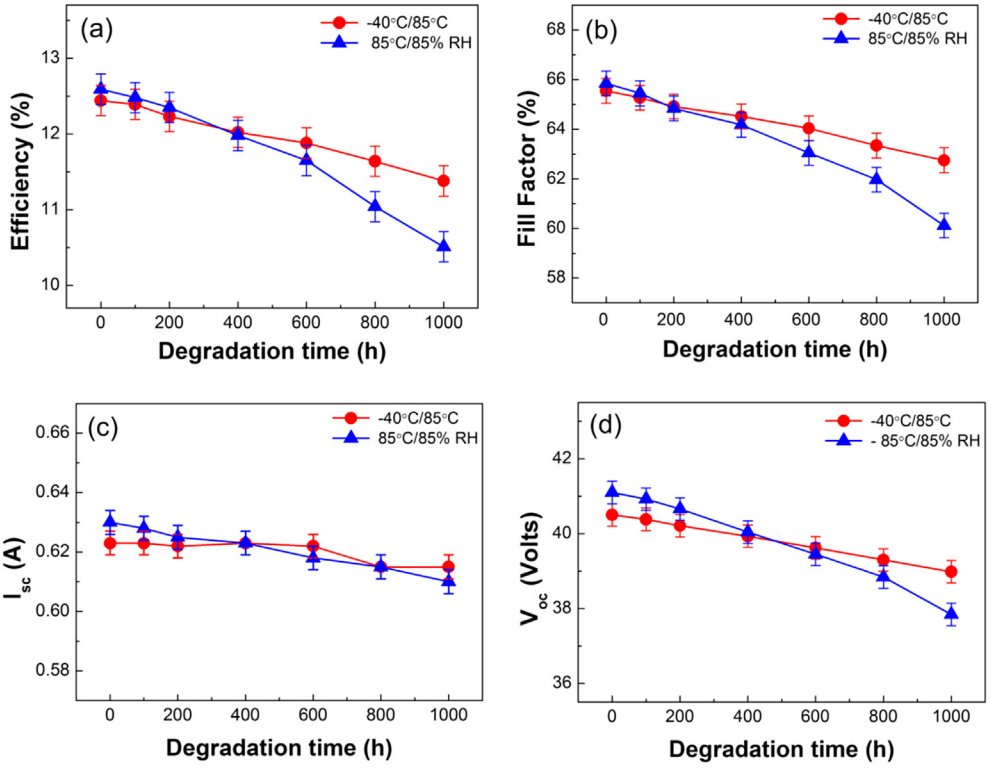

Fig. 1. Changes in (a) efficiency, (b) Fill Factor (*FF*), (c) short-circuit current (I_{sc}), and (d) open-circuit voltage (V_{oc}) of non-encapsulated modules as a function of degradation time under thermal cycling (−40 °C/85 °C) and damp heat (85 °C/85% RH) tests.