Thin Solid Films 661 (2018) 116–121

Contents lists available at ScienceDirect

Thin Solid Films

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

Performance degradation due to outdoor exposure and seasonal variation in amorphous silicon photovoltaic modules

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ARTICLE INFO

Keywords:
Thin-film silicon
Photovoltaic
Staebler–Wronski effect
Degradation
Performance ratio
Maximum power

ABSTRACT

Thin-film silicon (Si) related photovoltaic (PV) modules suffer performance deterioration owing to outdoor exposure. We investigate the performance degradation and seasonal variation of hydrogenated amorphous Si (a-Si:H) related PV modules. The normalized maximum power (P_{MAX}) of the single- and multi-junction modules tested herein decreased greatly and then stabilized after ~3 or 4 years of outdoor exposure. In summer (August 2016 and 2017), the P_{MAX} of all a-Si:H related PV modules increased by 2.0%–3.8% over the P_{MAX} in winter (December 2015 and 2016). In addition, the a-Si:H related PV modules show higher performance ratio (PR) in summer and lower in winter. These results are due to thermal annealing and light induced degradation effects in a-Si:H related PV modules. The a-Si:H related PV modules' PR two months after outdoor installation is lower than that before installation, which is explained by initial light exposure induced degradation.

1. Introduction

By the end of 2016, the total capacity of the photovoltaic (PV) power-generation systems installed worldwide reached at least 303 GW. Among these, the amount cumulatively introduced by the 25 countries that are members of the International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) is 265 GW, and most of this generation capacity is connected to power grids. By 2017, PV systems will contribute to ~2% of the world's electricity generation [1]. After the feed-in tariff (FIT) program was introduced in Japan in July 2012, commercial PV power plants have been constructed in quick succession. Almost all these PV systems were introduced under the FIT program. About 90% of PV modules that have been introduced so far are silicon (Si) based, and the availability and safety of Si suggest that it will continue to be a popular material in PV systems.

Solar cells made of a thin-film material such as hydrogenated amorphous Si (a-Si:H) and hydrogenated microcrystalline silicon (μc-Si:H) generally offer inferior power-generation efficiency (about 10%–13%). These materials can be fabricated not only on glass substrates but also on polymer or thin metal-foil substrates, leading to flexible and lightweight thin-film PV modules, and these features make them cost-effective and practically useful. Therefore, thin-film Si solar cells are expected to be integrated into building materials in addition to their applications in consumer electronics and large-scale generation facilities. a-Si:H modules have been on the PV market longer than other thin-film technologies. They exhibit a well-documented light-induced degradation effect, in which the efficiency degrades by ~10%–30% in the first several hundred hours of light exposure [2]. One of the main challenges with thin-film-Si-based PV modules is to overcome their performance degradation with outdoor exposure. When the a-Si:H layer is exposed to light or when an electric current is applied to the layer, performance degradation occurs [3]. However, the rate of the degradation decreases over time, and performance can be recovered with thermal annealing at high temperatures above 150 °C due to the well-known Staebler–Wronski effect (SWE) [4–6]. Staebler and Wronski first observed a reduction in the dark conductivity and photoconductivity of a-Si:H after light exposure and found that this degradation is reversible by annealing at high temperatures. The SWE occurs due to the recombination-induced breakdown of weak Si—Si bonds by optically excited carriers after thermalization, which produces defect centers that lower the carrier lifetime [7]. Annealing removes the defects to restore performance [8]. Several authors have reviewed the possible models for the structure of these defects and the reaction mechanism [9–11].

The solar spectrum varies considerably during the year, especially in the response range of a-Si:H alloys and other high-bandgap materials [12]. The performance of a-Si:H modules is significantly influenced by the solar spectrum even under the same solar irradiance conditions because a-Si:H's spectral response is biased toward shorter wavelengths

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https://doi.org/10.1016/j.tsf.2018.07.017
Received 2 May 2018; Received in revised form 27 June 2018; Accepted 13 July 2018
0040-6090/

Table 1
Types and configurations of installed thin-film PV systems.

Types	Total P_{MAX} (kW)	Array configuration	Year of installation
a-Si:H *a*	5.0	2S × 5P × 5A	Sep./2010
a-Si:H *b*	1.35	3S × 6P × 1A	Jul./2011
a-Si:H/μc-Si:H *a*	5.12	5S × 2P × 4A	Sep./2010
a-Si:H/μc-Si:H *b*	1.76	4S × 4P × 1A	Jul./2011
a-Si:H/a-SiGe:H	2.5	3S × 6P × 2A	Aug./2014

S: series, P: parallel, A: array.

from about 350 to 800 nm [13–15]. Therefore, the seasonal influence of solar spectrum must be quantitatively evaluated to accurately estimate the annual energy output of a PV system at a given location [16]. Thermal annealing and light exposure produce irregularities in the output power of a-Si:H PV modules. Consequently, accurately estimating the power generated by a-Si:H PV modules is difficult [6, 17].

In this study, we investigate the degradation in performance indicators of a-Si:H related PV modules and evaluate their energy output. In addition to observing the effects of environmental conditions on the outdoor performance of the installed PV technologies, we compared performance in the summer and winter months caused by thermal annealing and light exposure effect. The relationship between the indoor measurements and the module's energy yield is mentioned.

2. Experimental methods

At the end of 2016, ten types and twenty different models of PV modules were installed outdoors at the AIST Kyushu Center located in Saga Prefecture, Japan (33.2°N 130.3°E, climate classification: Cfa). Five models of a-Si:H related PV modules were installed for outdoor exposure tests, as shown in Table 1. Single-junction (a-Si:H *a* and *b*) and thin-film Si multi-junction (a-Si:H/μc-Si:H *a* and *b*, a-Si:H/a-SiGe:H) PV modules are commercially available from different manufactures. However, the detailed structures and materials of these PV modules were not made available to the authors.

Before measurements, the modules were removed from their supporting structures and cleaned. Their performance indicators were measured indoors using a pulsed solar simulator, PVS 1222i (Nisshinbo Mechatronics), with a pulse width of 100 ms under standard testing conditions (STC; irradiance = 1000 W/m^2, AM 1.5 G standard spectrum, and module temperature = 25 °C) [17]. Twice yearly, in winter (December 2014, December 2015, and December 2016) and summer (August 2016 and August 2017), the exposed modules were brought indoors and their outputs were measured under STC using the solar simulator. These outputs were normalized to the nominal values. Nominal values were obtained from the manufacturer also on the basis of indoor measurements under STC. During outdoor exposure, the modules were installed in one to five arrays. Current–voltage (*I*–*V*) curves of the PV arrays during outdoor installation were measured using *I*−*V* curve tracers (Nippon Kernel System PVA01950). The PV arrays were connected to the grid using a multistring-type power conditioning system (PCS) with isolation transformers. In all a-Si:H based PV arrays, the PCS was connected continuously with maximum power point tracking and maximum power (P_{MAX}) was measured every 10 min. The sweep time for each *I*−*V* curve was 500 ms. In addition, module temperature was measured at 1 min intervals using a Type T (copper-constantan) thermocouple mounted at the center of the rear surface [18]. Performance ratios (PRs) were calculated from P_{MAX} and the direct solar radiation intensity at that time. The solar spectrum at the optimum tilt angle for south-facing solar panels has been measured by the Japan Weather Association (JWA) in AIST Kyushu Center since 2008, and the optimum tilt angle was determined to be 26° [17]. Meteorological parameters, such as direct solar irradiance, in-plane solar irradiance, solar spectrum, air temperature, wind velocity, wind direction, and relative humidity were monitored using a CLIMATEC

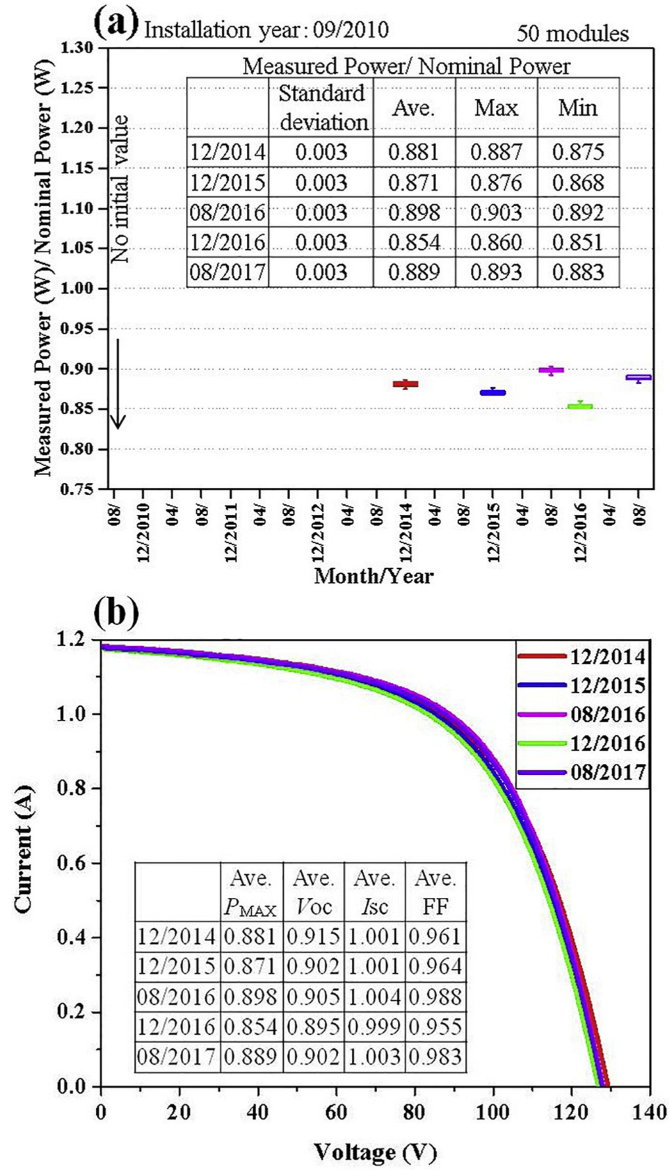

Fig. 1. (a) Time-dependent variation in the normalized P_{MAX} of the a-Si:H *a* PV module and (b) *I*−*V* curves based on indoor measurements under STC. The band inside the box plot in (a) indicates the median power. The upper and lower parts of the box indicate one standard deviation. The error bars indicate the maximum and minimum powers. The average *I*−*V* parameter values in the table inserted in (b) indicate the average normalized value.

measurement system [19]. PR, defined in IEC 61724 [20], is used as an indicator of outdoor module performance and is given by

$$\mathrm{PR} = \frac{P_{MAX}}{P_{MAX(STC)}} \times \frac{G_{STC}}{G} \quad (1)$$

where $P_{MAX(STC)}$ is the nominal P_{MAX} under STC, G is the measured solar irradiance, and G_{STC} is the solar irradiance under STC (1000 W/m^2) [21].

3. Results and discussion

3.1. Indoor measurements of a-Si:H related PV modules

Figs. 1 and 2 plot P_{MAX} for the single-junction (a-Si:H *a* and *b*) modules normalized to nominal values and *I*−*V* curves based on indoor measurements under STC. The outdoor exposure test for the first single-