Inferior outdoor-exposed performances of encapsulated a-Si:H photovoltaic modules deposited with a high speed

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Abstract

We investigate the stabilized performance of encapsulated hydrogenated amorphous silicon photovoltaic modules depending on the deposition speed. The module products are degraded differently depending on the light-soaking environment. The modules deposited at a high speed demonstrate significant degradation in an outdoor exposure test, despite moderate degradation during indoor light soaking. However, the modules deposited at a low speed show a relatively more stable performance against the outdoor exposure test. Notably, some modules show the trend that a higher initial performance stimulates a higher light-induced degradation, leading to a lower performance in the outdoor environment.

Introduction

It is well known that global warming caused by excess emissions of CO$_2$ has raised concerns about climate change, and nuclear power plants are no longer considered to provide a completely stable and cheap energy source following the Fukushima nuclear meltdowns. Sufficient supplies of clean energy are intimately linked with global stability, economic prosperity, and quality of life. Accordingly, clean renewable energy including solar, wind, and hydrogen energy has become a prime issue. A photovoltaic (PV) module using solar light is a promising candidate among the renewable energy sources because the sun is our primary source of clean, abundant energy. There has been an explosive, worldwide increase in the PV module market during the last two decades [1]. However, the current oversupply of bulk crystalline silicon (c-Si) PV modules for 80% of products and a decrease in government subsidies, due to the recent global economic crisis, threaten the PV market by causing a rapid drop in module prices. Thin-film silicon (Si) PV modules using hydrogenated amorphous Si (a-Si:H) and/or hydrogenated microcrystalline Si (µc-Si:H) absorbers are considered promising alternatives to the bulk c-Si PV modules due to advantages such as remarkably low consumption of the raw Si material (<1% of consumption of bulk c-Si PV modules); large-area deposition; low-temperature production; and a low-temperature coefficient. The thin-film Si PV technology also profits from the wide experience base of display industries [2]. However, the recent sharp drop in the module price has resulted in a need for cost-effective thin-film Si PV modules.

The best scenario for mass production of thin-film Si PV modules is to reach a competitive low production cost in the PV market by simultaneously obtaining the high conversion efficiency ($\eta$) and high throughput. However, the so-called “Staebler–Wronski effect (SWE)” in a-Si:H-based film remains as a major technical challenge for...
mass production. SWE is the light-induced degradation arising from the photocreation of dangling bonds accomplished by nonradiative recombination of photogenerated electron–hole pairs [3]. There have been extensive investigations during the past 30 years to reduce the SWE in a-Si:H absorbers that leads to the degradation of thin-film Si solar cells. The deposition of a-Si:H using H2 dilution of SiH4 is known as the best way to reduce SWE, but it is impossible to entirely eliminate SWE [4–9]. However, the thickness of the a-Si:H absorber is at least five times thicker than doping layers and the high H2 dilution of SiH4 decreases the deposition rate considerably. Hence, the deposition of the a-Si:H absorber is the bottleneck process for mass production of the a-Si:H single-junction PV modules. Furthermore, the fabrication processes should be designed based on the trade-off between the deposition rate and stabilized $\eta$ ($\eta_{st}$) because the nominal-rated power of the a-Si:H single-junction PV modules is determined from the stabilized performance. In this work, we investigate the light-induced degradation of encapsulated a-Si:H single-junction PV modules depending on the deposition rate of the i-a-Si:H absorber. This research aims to help to build guidelines for module design by comparing the indoor light-soaking test and the outdoor exposure test.

**Experimental Details**

A series of 1.43 m² p-i-n-type, a-Si:H single-junction, PV modules were produced using the fully automated in-line system built in Jeungpyeong, Korea. This mass production system with the annual capacity of 20 MWp is the first mass production line for thin-film PV modules in Korea. Figure 1 provides the schematic images for the fabricated PV modules. All the PV modules were fabricated using the same recipe except the deposition rate of the intrinsic absorber. 1.1 m × 1.3 m (so-called “Gen5”) NSG, NJFL 400 glasses (textured SnO₂:F coated by a floating line technique on the soda-lime glasses) were used as substrates. Each unit cell has the structure of glass/SnO₂:F/hydrogenated p-type amorphous silicon-carbide (p-a-SiC:H) window layer (15 nm)/p-type buffer layer (p-buffer) (5 nm)/intrinsic a-Si:H (i-a-Si:H) absorber (300 nm)/hydrogenated n-type a-Si:H (n-a-Si:H)/ZnO: B back reflector/metal back contact (300 nm). For the deposition of thin-film Si layers, two Gen5 cluster-type 13.56 MHz radio-frequency (RF) plasma-enhanced chemical vapor deposition (PECVD) systems were used. Each type of layers was deposited at the substrate temperature around 200°C in the respective separated chamber to minimize the dangling bonds [10] and residual impurity cross-contamination. The p-a-SiC:H window layer was deposited using a mixture of SiH₄, B₂H₆, H₂, and CH₄ reactant gases. To reduce the carrier recombination loss at the p/i interface, the layer of p-buffer is carefully selected and inserted between the p-a-SiC:H window layer and i-a-Si:H absorber [11–14]. For the deposition of the i-a-Si:H absorber, H₂ and SiH₄ were used as reactant gases. Depending on the process parameters of SiH₄ concentration (SC), that is, $\text{SC} = \text{[SiH}_4\text{]} / ([\text{SiH}_4] + [\text{H}_2])$, substrate temperature, process pressure, and plasma density, two kinds of the deposition rate for i-a-Si:H were obtained. One is the low deposition rate of 0.20 nm/sec, which is the conventional deposition rate for the i-a-Si:H absorber using RF PECVD. The other is the high deposition rate of 0.35 nm/sec. For the deposition of n-a-Si:H, a mixture of SiH₄, PH₃, and H₂ reactant gases was used. The n-type degenerate ZnO:B [15] back reflector was prepared at the substrate temperature of 170°C using a metal organic chemical vapor deposition (MOCVD) technique [16]. Bubbled diethylzinc (DEZ) and water (H₂O) vapor were introduced into the reaction chamber via the high-purity Ar (99.999%) carrier gas. The B₂H₆ gas was used as a doping source. The Al back contact was prepared at the substrate temperature of 100°C via RF magnetron sputtering with the high-purity Al (99.999%) target. To reduce the powder problems during the deposition, carriers were transferred vertically through the sputtering chambers. The monolithic series integration was materialized via the plurality of three parallel laser-scribed patterns (P1, P2, and P3 patterns). The Q-switched infrared (IR) laser with the wavelength of 1064 nm was used for P1 patterns, whereas the Q-switched green laser with the wavelength of 532 nm was used for P2 and P3 patterns. All the lasers were illuminated from the glass substrate side to prevent the damage on the stacked layers. The conditions for the pulse overlap and laser power were determined not to generate any burr and flake [17]. In our experiments, it is found that the cell width of

![Figure 1. Planar and cross-sectional structures of the fabricated a-Si:H single-junction photovoltaic module.](image-url)
7.0 mm is optimum to minimize the power loss of the fabricated modules using the NSG, NJFL 400 glass substrates with the sheet resistance of 13 Ω/m². Finally, the module encapsulation was performed by laminating the back sheet including an Al foil with an ethylene-vinyl acetate (EVA) film at 170°C. Based on the reinforced process and quality controls, the considerably high yield over 95% was achieved.

The photo current–voltage (I-V) characteristics for the fabricated modules were measured under the standard test conditions (STC; 25°C, AM 1.5 G, and 1000 W/m²) using a class A flasher (Spire, SPI-Sun Simulator 4600SLP). The indoor light-soaking test was performed at 50°C using a class C solar simulator based on the International Electrochemical Commission (IEC) 61646 light-soaking test for thin-film terrestrial PV modules. In addition, the IEC 61646 outdoor exposure test was executed with >60 kWh/m² local irradiance. Each module was installed on the open rack facing south with the tilt angle of 30° in the open-circuit state. Total plane-of-array irradiance was offered via the monitoring facility.

Results and Discussion

Regardless of the deposition rate of i-a-Si:H, the fabricated a-Si:H single-junction PV modules have the distribution of initial maximum power \(P_{\text{max}}\) from 112 to 122 W, which is corresponding to aperture-area initial \(\eta_{\text{ini}}\) \(= \frac{P_{\text{max}}}{P_{\text{oc}}} \) of 8.5–9.0%. Table 1 describes the initial and stabilized performances of the a-Si:H single-junction PV modules against the indoor light-soaking test. The H-series samples denote the modules fabricated with the high deposition rate, whereas the L-series samples denote their counterparts fabricated with the low deposition rate. For the modules deposited with the high deposition rate, higher initial \(P_{\text{max}}\) leads to a higher degradation ratio \(\Delta \eta / \eta_{\text{ini}}\) against indoor light soaking. The stabilized \(P_{\text{max}}\) values of the modules are distributed from 92.0 to 97.4 W, which are corresponding to aperture-area \(\eta_{\text{sta}}\) of 6.8–7.2%. The module with highest initial \(P_{\text{max}}\) of 121.5 W (sample HS) is stabilized to lowest \(P_{\text{max}}\) of 92.0 W, whereas the module with initial \(P_{\text{max}}\) of 115.8 W (sample H2) is stabilized to highest \(P_{\text{max}}\) of 97.4 W. As a result, the light-induced degradation ratio is distributed in the range 15.9–24.3%. On the contrary, the trend of the indoor light-induced degradation for the modules deposited with the low deposition rate is a bit different. These modules show higher stabilized \(P_{\text{max}}\) (96.1–102.0 W) than those fabricated with the high deposition rate. These stabilized \(P_{\text{max}}\) values are corresponding to aperture-area \(\eta_{\text{sta}}\) of 7.1–7.5%. The module with initial \(P_{\text{max}}\) of 116.5 W (sample L2) is stabilized to lowest \(P_{\text{max}}\) of 96.1 W, whereas the module with highest initial \(P_{\text{max}}\) of 122.4 W (sample L5) is stabilized to highest \(P_{\text{max}}\) of 102.0 W. The light-induced degradation ratio is distributed in the range 12.2–17.8%. From the comparison between the samples that have similar initial \(P_{\text{max}}\), it is found that the modules deposited with the high deposition rate have the 1–8% higher light-induced degradation ratio than those deposited with the low deposition rate against the indoor light-soaking test based on the IEC 61646 standard.

Table 1. Indoor light-soaking results of the a-Si:H single-junction PV modules fabricated with different deposition rates of i-a-Si:H.

| Deposition rate (nm/sec) | Sample number | Status | \(V_{\text{oc}}\) (V) | \(I_{\text{sc}}\) (A) | FF | \(P_{\text{max}}\) (W) | \(\eta_{\text{sta}}\) (%) | \(\Delta \eta / \eta_{\text{ini}}\) (%) |
|-------------------------|---------------|--------|----------------|----------------|-----|----------------|----------------|----------------|
| High (0.35)             | H1 Initial    | 134.3  | 1.17  | 0.71  | 111.6 | 8.2   | –              |
|                         | Stabilized   | 129.5  | 1.14  | 0.63  | 93.0  | 6.8   | 16.6          |
|                         | H2 Initial    | 133.6  | 1.22  | 0.71  | 115.8 | 8.5   | –              |
|                         | Stabilized   | 132.0  | 1.19  | 0.62  | 97.4  | 7.2   | 15.9          |
|                         | H3 Initial    | 133.2  | 1.23  | 0.71  | 116.3 | 8.6   | –              |
|                         | Stabilized   | 130.7  | 1.19  | 0.61  | 94.9  | 7.0   | 18.4          |
|                         | H4 Initial    | 137.6  | 1.24  | 0.70  | 119.4 | 8.8   | –              |
|                         | Stabilized   | 131.4  | 1.20  | 0.61  | 96.2  | 7.1   | 19.4          |
|                         | H5 Initial    | 135.8  | 1.26  | 0.71  | 121.5 | 8.9   | –              |
|                         | Stabilized   | 129.9  | 1.20  | 0.59  | 92.0  | 6.8   | 24.3          |
| Low (0.20)              | L1 Initial    | 135.1  | 1.16  | 0.72  | 112.8 | 8.3   | –              |
|                         | Stabilized   | 132.7  | 1.13  | 0.66  | 99.0  | 7.3   | 12.2          |
|                         | L2 Initial    | 137.1  | 1.18  | 0.72  | 116.5 | 8.6   | –              |
|                         | Stabilized   | 133.8  | 1.14  | 0.63  | 96.1  | 7.1   | 17.5          |
|                         | L3 Initial    | 137.3  | 1.18  | 0.73  | 118.3 | 8.7   | –              |
|                         | Stabilized   | 134.4  | 1.13  | 0.64  | 97.2  | 7.1   | 17.8          |
|                         | L4 Initial    | 139.8  | 1.20  | 0.72  | 120.8 | 8.9   | –              |
|                         | Stabilized   | 135.4  | 1.16  | 0.64  | 100.5 | 7.4   | 16.8          |
|                         | L5 Initial    | 137.4  | 1.22  | 0.73  | 122.4 | 9.0   | –              |
|                         | Stabilized   | 135.2  | 1.18  | 0.64  | 102.1 | 7.5   | 16.6          |
Figure 2 shows the normalized light-soaked behaviors of the a-Si:H single-junction PV modules fabricated with different deposition rates of i-a-Si:H. The module fabricated with the low deposition rate is corresponding to the sample L4 in Table 1, whereas that fabricated with the high deposition rate is corresponding to the sample H4.

Figure 2 shows the normalized light-soaked behaviors for the fabricated a-Si:H single-junction PV modules under consideration (samples H4 and L4 in Table 1). After 144-h indoor light soaking, the modules are stabilized based on the IEC 61646 standard. For all the modules, the fill factor (FF) displays the dominant light-induced degradation compared with the open-circuit voltage ($V_{oc}$) and short-circuit current ($I_{sc}$). Moreover, the higher degradation of FF for the module deposited with the high deposition rate is the main contribution for the higher light-induced degradation ratio. Also, the module deposited with the high deposition rate shows the slightly higher degradation of $V_{oc}$ compared with its counterpart deposited with the low deposition rate. However, the degradation of $I_{sc}$ is almost identical. In addition, the module deposited with the high deposition rate (sample H4) depicts the stable behavior with the light-induced degradation ratio of 20.7% as a result of prolonged light soaking for 481 h.

Figure 3 exhibits the results of the damp heat test for the a-Si:H single-junction PV modules fabricated with different deposition rates of i-a-Si:H as a result of the damp heat test.

Figure 3 shows the normalized $\eta$ of the a-Si:H single-junction PV modules fabricated with different deposition rates of i-a-Si:H as a result of the damp heat test.

Figure 4. Monthly mean module temperatures and monthly mean ambient temperature during the outdoor exposure test. Monthly accumulated plane-of-array irradiance was also plotted.

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gle-junction PV modules are not sensitive to moisture ingress. Figure 4 displays the outdoor exposure test conditions. Various a-Si:H single-junction PV modules fabricated with the high and low deposition rates were simultaneously subjected to the outdoor exposure test from March. The outdoor exposure test for the half of the PV modules was finished in mid-May, whereas the test for other PV modules was finished at the end of May (see Table 2). Only sample L6 was subject to the outdoor exposure until mid-July (just before the rainy season in Korea). With the enhancement of the monthly mean value for ambient temperatures from March to May, both the monthly mean values for the daily maximum module temperatures and the daily minimum module temperatures elevated. During the period, monthly accumulated solar irradiance also considerably increases month after month. However, the monthly mean value of daily maximum module temperatures in June (51.4°C) is almost similar to that in May (50.3°C) despite the small increases in the monthly mean values of ambient temperatures and daily minimum module temperatures. The saturated module temperature can be attributed to the open rock mounting during the outdoor exposure test. It was reported that the PV module temperature can be influenced on the ambient temperature, wind speed, plane-of-array irradiance, and module mounting [18]. Table 2 provides the results of the outdoor exposure test. The modules fabricated with the high deposition rate have the light-induced degradation ratio distributed in the range 22.1–30.7% with accumulated solar irradiance larger than 350 kWh/m². Thus, the outdoor light-induced degradation ratio for these modules is higher than their indoor light-induced degradation ratio (15.9–24.3%). The higher outdoor light-induced degradation is mainly due to the lower module temperature during the outdoor exposure than the module temperature of 50°C during indoor light soaking. In the meantime, the modules fabricated with the low deposition rate have the relatively lower outdoor light-induced degradation ratio distributed in the range 10.5–21.4%, which shows the lower deviation from the indoor light-induced degradation ratio (12.2–17.8%). In the case of the sample H4, the outdoor exposure test with accumulated irradiance of 437.7 kWh/m² was subsequently performed after the indoor light-soaking test for 481 h. The outdoor exposure causes the further degradation by 6.9%, which results in the total degradation ratio of 27.6%. Considering the difference in the outdoor light-degradation ratios between the samples H4 and H8, it can be concluded that the pre–indoor light-soaking test for 481 h does not give any noticeable impact on the result of the outdoor exposure test with accumulated irradiance of 437.7 kWh/m². From the comparison between the samples having the same initial P_{max} value of 121.6 W, the sample H10 exhibits the higher light-induced degradation ratio of 30.7% than the sample L8 (21.4%) as a result of the outdoor exposure with accumulated irradiance of 353.1 kWh/m². Moreover, the sample L6 has highest stabilized P_{max} of 102.9 W (corresponding to aperture-area η_{sta} of 7.6%) among our a-Si:H single-junction PV module products that passed IEC 61646 and IEC 61730 thin-film module certification tests from UL, USA. As the multichamber PECVD systems with two p-chambers, six i-chambers, and the two n-chambers were used, the thickness of the deposited layers was controlled within a tolerance of ±10% from the target thickness. Thus, initial V_{oc} can be enhanced with the increase in the thickness of the p-layers [11]. On the contrary, the increased thickness of the i-a-Si:H absorber can enhance initial J_{sc}. If an a-Si:H single-junction PV module has higher initial P_{max} due to a thicker i-a-Si:H absorber, lower stabilized P_{max} can be possible because of a more severe light-induced degradation of FF [19]. Therefore, some PV modules show lower stabilized P_{max} after the outdoor exposure test despite higher initial P_{max}.

Table 2. Outdoor exposure test results of the a-Si:H single-junction PV modules fabricated with different deposition rates of i-a-Si:H.

| Deposition rate (nm/sec) | Sample | P_{max} (W) | Accumulated irradiance (kWh/m²) | Light-soaked P_{max} (W) | η_{sta} (%) | Δη/η_{sta} (%) |
|-------------------------|--------|------------|-------------------------------|------------------------|------------|----------------|
| High (0.35)             | H4*    | 119.4      | 437.7                         | 86.4                   | 6.4        | 27.6           |
|                         | H6     | 111.9      | 437.7                         | 87.1                   | 6.4        | 22.1           |
|                         | H7     | 116.8      | 437.7                         | 89.0                   | 6.6        | 23.8           |
|                         | H8     | 119.9      | 437.7                         | 83.3                   | 6.1        | 30.5           |
|                         | H9     | 120.7      | 353.1                         | 87.7                   | 6.5        | 27.3           |
|                         | H10    | 121.6      | 353.1                         | 84.3                   | 6.2        | 30.7           |
| Low (0.20)              | L6     | 115.0      | 541.3                         | 102.9                  | 7.6        | 10.5           |
|                         | L7     | 120.5      | 353.1                         | 100.4                  | 7.4        | 16.7           |
|                         | L8     | 121.6      | 353.1                         | 95.5                   | 7.0        | 21.4           |
|                         | L9     | 122.8      | 353.1                         | 98.8                   | 7.3        | 19.5           |

All the modules were measured under the STC conditions. *The outdoor exposure test was performed after the indoor light-soaking test for 481 h.
counterparts, and thus the additional balance of system (BOS) due to lower stabilized $P_{\text{max}}$ cannot be neglected. The indoor light-soaking test is still a useful method to evaluate the research and development (R&D) of thin-film Si solar cells as well. From our results, however, it is inferred that both the IEC 61646 indoor light-soaking test and the IEC 61646 outdoor exposure test with >60 kWh/m$^2$ local irradiance would not be adequate for the determination of the nominal-rated power of the thin-film Si terrestrial PV module products. It was suggested that it took about 2 years until the performance of a-Si:H single-junction PV modules became stable in the outdoor environment [26, 27]. Besides, there is the seasonal fluctuation of the outdoor performance for a-Si:H single-junction PV modules originating from the effects of thermal annealing and light soaking [27, 28]. Thus, a long-term outdoor exposure test is highly requested for the evaluation of thin-film Si multijunction PV modules including any a-Si:H-based absorber as well as the a-Si:H single-junction PV modules. Here, we propose the outdoor exposure test not less than 350 kWh/m$^2$ in order to determine the nominal-rated power of the thin-film Si PV module products. It should be noted that some fabricated modules show the tendency that lower stabilized $P_{\text{max}}$ results from the outdoor exposure test despite higher initial $P_{\text{max}}$. Therefore, the optimum thickness of the a-Si:H absorber [29, 30] that governs the production throughput must be determined via the long-term outdoor exposure test. It is also desirable that any sensitive production process for the initial performance of thin-film Si PV modules such as deposition conditions for the i-a-Si:H absorber, buffer layer at an interface, and intermediate reflector should be designed based on the results of the long-term outdoor exposure test.

**Summary**

We have investigated the stabilized performance of the encapsulated a-Si:H single-junction PV modules fabricated with the different deposition rates of i-a-Si:H. The light-induced degradation of the modules demonstrates different behaviors depending on the light-soaking environment. The modules deposited with the conventional deposition rate of 0.20 nm/sec have a small increase in the light-induced degradation in the outdoor exposure test compared with the light-induced degradation in the indoor light-soaking test. However, the modules deposited with a high deposition rate of 0.35 nm/sec demonstrate a notable difference in the light-induced degradation ratio between the indoor and outdoor tests. It is also to be noted that some modules have the trend that higher initial $P_{\text{max}}$ stimulates the higher light-induced degradation, and thus leads to lower stabilized $P_{\text{max}}$.
Therefore, we propose that long-term outdoor exposure tests should be not less than 350 kWh/m² to determine the nominal-rated power of thin-film Si PV module products. In addition, it is desirable that all processes, including the deposition rate of i-a-Si:H, should be designed based on the long-term outdoor exposure behaviors, instead of the indoor light-soaking behaviors based on IEC61646.

**Conflict of Interest**

None declared.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Image of an a-Si:H single-junction module.