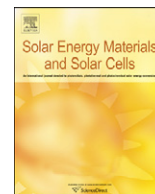




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Effects on amorphous silicon photovoltaic performance from high-temperature annealing pulses in photovoltaic thermal hybrid devices

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ABSTRACT

There is a renewed interest in photovoltaic solar thermal (PVT) hybrid systems, which harvest solar energy for heat and electricity. Typically, a main focus of a PVT system is to cool the photovoltaic (PV) cells to improve the electrical performance; however, this causes the thermal component to underperform compared to a solar thermal collector. The low temperature coefficients of amorphous silicon (a-Si:H) allow the PV cells to be operated at high temperatures, which are a potential candidate for a more symbiotic PVT system. The fundamental challenge of a-Si:H PV is light-induced degradation known as the Staebler–Wronski effect (SWE). Fortunately, SWE is reversible and the a-Si:H PV efficiency can be returned to its initial state if the cell is annealed. Thus an opportunity exists to deposit a-Si:H directly on the solar thermal absorber plate where the cells could reach the high temperatures required for annealing.

In this study, this opportunity is explored experimentally. First a-Si:H PV cells were annealed for 1 h at 100 °C on a 12 h cycle and for the remaining time the cells were degraded at 50 °C in order to simulate stagnation of a PVT system for 1 h once a day. It was found when comparing the cells after stabilization at normal 50 °C degradation that this annealing sequence resulted in a 10.6% energy gain when compared to a cell that was only degraded at 50 °C.

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1. Introduction

Photovoltaic solar thermal (PVT) hybrid systems have been shown to be more efficient at solar energy collection on the basis of exergy, energy and cost [1–7]. Most current PVT systems are based on crystalline silicon (c-Si) photovoltaic (PV) materials, whose performance declines with increasing temperature by 0.04%/°C [8]. Thus, these PVT system designs are primarily focused on cooling the c-Si PV cells to maximize the electrical gain, while the extracted thermal energy is viewed as a secondary benefit [7]. The result of this design focus is that the thermal component of the PVT system significantly underperforms when compared to standard solar thermal collectors [9–12]. Focusing the design on only maximizing solar electrical output thus prevents the PVT system from being optimized.

A potential solution to this challenge is to use a PV material that can operate at high temperatures without substantial performance losses. One such promising material is hydrogenated

amorphous silicon (a-Si:H), which has a temperature coefficient of only $-0.01\%/^{\circ}\text{C}$ [8], a quarter of that of c-Si. A fundamental challenge recognized shortly after the discovery of the a-Si:H PV cell was light-induced degradation of the a-Si:H PV performance known as the Staebler–Wronski effect (SWE) [13–17]. SWE causes defect states to form in the a-Si:H material when exposed to sunlight, which lower the efficiency of the PV cell. For commercial high-quality a-Si:H materials, these defects saturate after a long (~ 100 h of continuous 1 sun) illumination and the efficiency of the cell is considered stabilized at this point [18–20]. This stabilized state is known as the degraded steady-state (DSS). Fortunately, SWE is reversible and the a-Si:H PV cell efficiency can be returned to its initial state if the cell is heated to 150 °C for 4 h as the defect states are annealed [13,20–22]. Various schemes have been devised to take advantage of thermal annealing in a-Si:H, such as removing the entire PV array and annealing them in an air oven at lower temperatures (e.g. at 80 °C) over extended times [23]. In addition, it has been found that a-Si:H PV performs better at high temperatures since the optoelectronic properties of a-Si:H materials [24–26] stabilize at a higher efficiency [18,27]. In a solar thermal flat plate collector the temperature can easily reach over 100 °C and even climb higher than 200 °C if the system is stagnated [28]. Thus an opportunity exists to deposit a-Si:H

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directly on the solar thermal absorber plate [29,30] where the cells could reach the high temperatures required for annealing. This suggests that a-Si:H would be an excellent choice of PV material for a PVT system and that careful control of the temperature of the thermal side of the PVT could be used to introduce thermal annealing pulse cycles to raise the overall PV electrical conversion performance.

This paper explores this potential and reports on a series of experiments in which a-Si:H based PV cells were exposed to high temperature pulse annealing cycles for which the temperature and duration were determined by the potential stagnation conditions in a PVT system. The results are discussed to determine the value of utilizing a scheme of thermal cycling in PVT systems to maximize the overall solar energy harvested.

2. Materials and methods

The a-Si:H PV cells used in this study were fabricated by an AKT plasma enhanced chemical vapor deposition (PECVD) chamber. The i-layers of thicknesses 210, 420, 630 and 840 nm were deposited by ThinSilicon in the following bottom up structure as can be seen in Fig. 1: AGC float glass (3 mm)/SnO₂:F (700 nm)—textured fluorinated tin oxide/Ag (200 nm)/AZO (100 nm)/n-a-Si:H (25 nm)/i-a-Si:H (210–840 nm)/p-a-Si:H (15 nm)/ITO (70 nm).

The following sections describe the various methodologies required to complete and acquire the data for this study.

2.1. Light-induced degradation

A Newport class AAA solar simulator was used to apply AM1.5 1 sun illumination to the PV cells until a DSS was reached. Degradation temperatures were maintained with a Chemat Technology Inc. hot plate attached to a Cole Parmer Digi-Sense k-Type temperature controller. A k-type thermocouple was placed beside the cell to monitor and maintain surface temperature at the desired temperatures of 25 °C (standard testing conditions for PV), 50 °C (representative operating temperature for PV) or 90 °C (representative of operating temperatures for solar thermal systems) during the degradation. PV Measurements *I*-*V* Curve software K2400 *I*-*V* was used with a Keithley 2000 multimeter and a Keithley 2400 source meter to measure the current-voltage output of the cells. An Autolt macro was implemented to run the program to take the measurements at desired intervals.

2.2. Spike annealing at the DSS

After reaching the DSS, the cells were exposed to a thermal annealing cycle (spike annealing) with a set point of 100 °C for 1 h. This test was to simulate stagnation of the thermal component of the PVT system. The 100 °C was determined as feasible by

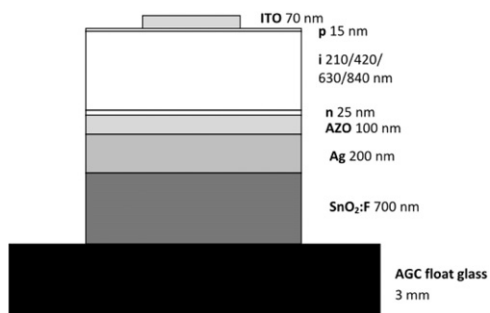


Fig. 1. Composition and structure of the a-Si:H solar photovoltaic cells used in this study.

experimentally simulating stagnation using a test rig containing the PV cell array used in this study. It should be noted that this value is conservative due to the nature of the areas around the test cells, which were highly reflective. The 1 h annealing time was considered a short enough period of time to not greatly affect the thermal system performance, but long enough to ensure a substantial annealing of the SWE defect states in the PV cell. The PV cell was then allowed to cool to its degraded temperatures of 90, 50 and 25 °C and remained at these temperatures for at least 10 min to obtain an accurate temperature correlation.

2.3. Spike annealing cycle

Following the methods outlined in Sections 2.1 and 2.2, a spike annealing cycle test was completed on a 12 h cycle. The cell was degraded at 50 °C for 10 h and 45 min, at which time the surface temperature of the cell was raised to 100 °C over approximately 15 min and was maintained at that temperature for 1 h and then allowed to cool naturally to 50 °C. It should be noted that the typical operating temperature for a PV module is 50 °C [31].

3. Results and discussion

It is known that a-Si:H PV when degraded at higher temperatures will stabilize at higher efficiencies, as can be seen in Fig. 2 showing the normalized maximum power (P_{max}) with a 630 nm i-layer thick a-Si:H cell degraded at 25, 50 and 90 °C [19].

From Fig. 2, it can be easily determined that running an a-Si:H cell at higher temperatures will increase the energy output of the cell due to the earlier occurrence of the DSS. This supports the concept of using a-Si:H in PVT systems as a-Si:H cells stabilize at higher efficiencies at higher operating temperatures. However, it would be more beneficial to the overall energy conversion if the cell could retain its initial efficiency rather than operate at the DSS lower efficiency. In order to test if this was possible, high-temperature annealing pulses (or spike annealing) were investigated. The spike annealing process was applied to the stabilized cells of the temperature series found in Fig. 2 and the results are shown for degradation temperatures of 25, 50 and 90 °C, respectively, in Figs. 3–5. In each graph, the fill factor (FF), maximum power and annealing temperature profile are plotted as a function

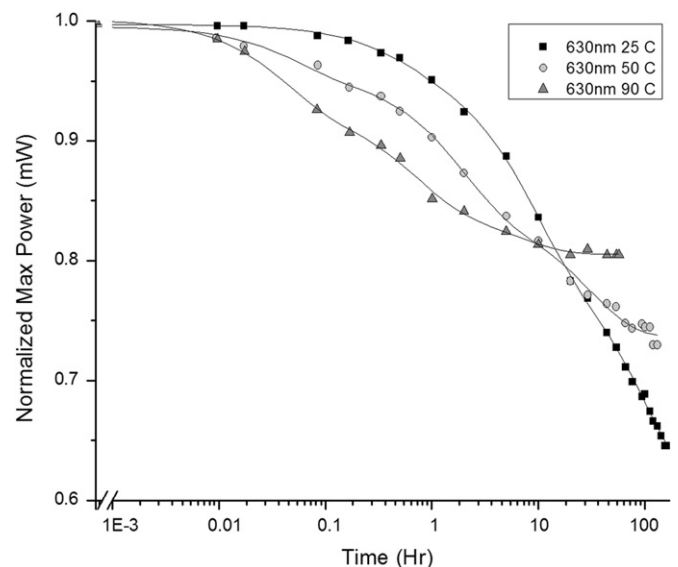


Fig. 2. A normalized temperature series of 25, 50 and 90 °C degradation under 1 sun for a PV cell with an i-layer thickness of 630 nm.

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