Temperature-Dependent Light-Stabilized States in Thin-Film PV Modules

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Temperature-dependent light-stabilized states in thin-film PV modules

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***Abstract*—Thin-film photovoltaic modules are known to exhibit light-induced transient behavior which interferes with accurate and repeatable measurements of power. Typically power measurements are made after a light exposure in order to target a "light state" of the module that is representative of outdoor performance. Here we show that the concept of a unique light state is poorly defined for both CIGS and CdTe modules. Instead we find that their metastable state after a light exposure can depend on the temperature of the module during the exposure. We observe changes in power as large as 5.8% for a 20°C difference in light exposure temperature. These results lead us to conclude that for applications in which reproducibility and repeatability are critical, module temperature should be tightly controlled during light exposure.**

***Index Terms*—Metastability, transient, photovoltaic, solar, light soak, thin film, characterization, measurement**

I. Introduction

Thin-film photovoltaic modules are widely known to exhibit light-induced reversible changes in their current-voltage (IV) characteristic and associated power [1], [2]. These changes complicate the repeatable and accurate measurement of modules' power output in the metastable state that is relevant to field operation.

Typically, modules are exposed to either simulated or natural sunlight for a period of time in order to bring them into a metastable state representative of their outdoor performance. For the purposes of this discussion, we refer to such procedures as "stabilization procedures." A widely (though not exclusively) held assumption in the PV community is that there is a true, well-defined "light state" of the module which is the electrical performance state of the module after an arbitrarily long light exposure.

However, it is important to consider the role of temperature during light-based stabilization procedures [3]. Here, we show that the final metastable state of a module, as measured at room temperature (RT) after a light exposure can depend on the temperature of the module during stabilization.

Our results have important implications for applications where agreement between different test laboratories is critical. For example, the existing qualification standard for thin-film PV modules, IEC 61646, specifies a module temperature range of 40–60°Cduring light exposure. In addition, a draft of an update to that standard (which will be incorporated in future version of IEC 61215) proposes an allowed range of 25–85°C. This is largely due to practical consideration for the ability of test labs to promptly execute the tests. However, our results show that such large temperature ranges can be problematic in the presence of ill-defined temperature-dependent light states.

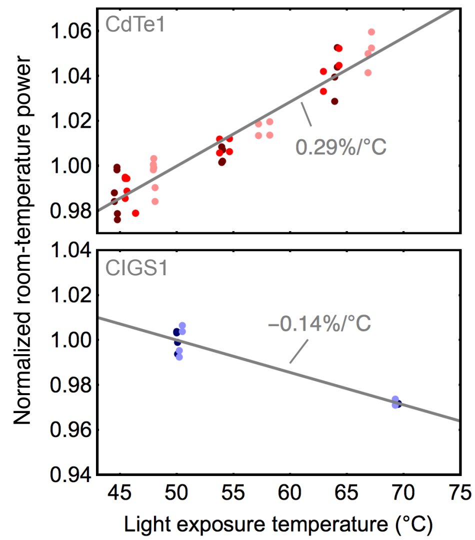

Fig. 1. The room temperature (RT) power, temperature corrected according to the manufacturer specifications and normalized, plotted vs. the back-of-module temperature during the preceding light exposure. The different shades indicate different samples. Both the 30-minute and 60-minute measurements are shown, which improves confidence that the results are not an artifact of measurement during rapid transient changes to the modules.

II. Method

We exposed a variety of thin-film PV modules to simulated sunlight in a light-soak chamber at a series of different temperatures. We made room temperature measurements of their current-voltage (IV) curves between these light-exposure steps. For each step, the modules were exposed until their observed power output was stable.

We investigated four different commercial thin-film module models: two CIGS module models referred to throughout as CIGS1 and CIGS2, and two CdTe module models referred to as CdTe1 and CdTe2.

Each light-exposure step was carried out under simulated sunlight in a light-soak chamber. Back-of-module temperature was controlled with closed-loop modulation of cooling fans controlling the flow of outside air through the chamber. An array of metal halide lamps was used as the light source in the chamber. The modules were loaded at maximum power, with IV curves measured every 5 minutes. Each exposure proceeded until the in situ IV curves indicated that power was changing at a rate of $< 1\%/(20\ \mathrm{kWh/m^2})$.

The modules were cooled to room temperature with the chamber fans, which took approximately 20 minutes. Room-temperature IV curves were then collected using a long-pulse solar simulator at 30 minutes, and again at 60 minutes, following the end of light exposure. Module temperatures for the room-temperature (RT) IV curves were 23±3°C. Taking two IV curves improves our confidence that the modules were not being measured during a rapid thermal or electrical-state transient.

After the RT IV curves were collected the modules were returned to the light-soak chamber for the next temperature step. Temperatures were repeated within the sequence to investigate whether any observed changes were reversible. An example of a typical test sequence is:

1) Initial RT IV
2a) Light exposure at 50°C
2b) Measure RT IVs
3a) Light exposure at 70°C
3b) Measure RT IVs
4a) Light exposure at 50°C
4c) Measure RT IVs

III. Results and discussion

We observe that, for some module types, the electrical performance state reached with light exposure is strongly dependent on module temperature during the exposure. The effect was strongest in CIGS1 and CdTe1. The effect of light exposure temperature on the normalized RT power for these modules is shown in Fig. 1. For CdTe1 we observe that higher temperatures during light exposure led to higher performance in subsequent RT measurements. For CIGS1, we observe the opposite, that higher light-soak temperature reduced room temperature power. For a 20°C variation in the temperature of the preceding light exposure, the performance changes we observe would lead to a 2.8% variation in power for CIGS1 and a 5.8% variation for CdTe1.

Fig. 2 shows example RT IV curves for CIGS1 and CdTe1. We observe that for CdTe1, both the fill factor (FF) and open-circuit voltage V_{oc} are affected, while for CIGS1, the FF is most strongly affected. There are a variety of physical mechanisms to which light-induced transients are attributed in the literature [1], [2], [4]–[6]. Many such mechanisms involve light-driven changes in the occupation of defect states in the bulk or at interfaces. Such changes, particularly at interfaces, are associated with change in FF. Since trap occupation is fundamentally a thermal phenomenon, these explanations are consistent with the results reported here.

We find that the changes due to temperature during light exposure are reversible. This is apparent from Fig. 1, which shows measurements after repeated temperature steps. Any hysteresis in Fig. 1 is small compared to the overall change. The reversibility is further illustrated in Fig. 3, which shows both the pre-light-soak RT power measurement (step 1) and the RT power measurements after a warm-hot-warm sequence of light exposures (steps 2–4). In Fig. 3, steps 2 and 4 are measurements made after warm exposures with a module temperature set point of 50°C. Step 3 is a measurement made after a hot light exposure with a set point of 75±5°C. For

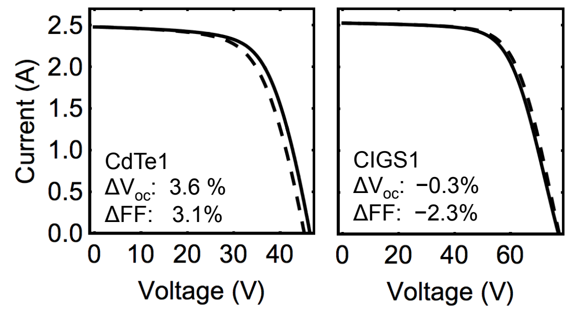

Fig. 2. Example room temperature IV curves taken after a warm light exposure (dashed, temperature set point of 50°C) and a hot light exposure (solid, temperature set point of 70°C). The differences in V_{oc} and FF relative to the warm-exposure curve are indicated.

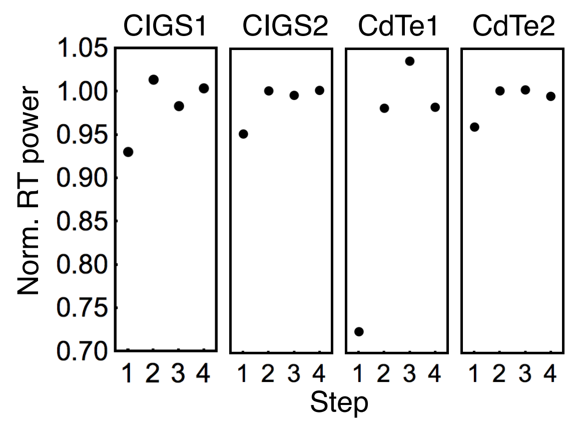

Fig. 3. Sequences of RT power measurements made on one each of the four types of modules. Step 1 is a measurement made before light exposure. Steps 2 and 4 are measurements made after warm light exposures (set point of 50°C). Step 3 is a measurement made after a hot light exposure (set point of 75±5°C). Step 1 indicates that all modules showed some degree of initial light-induced transient. Module types CIGS1 and CdTe1 showed substantial temperature dependence in their light-exposed states, (see Fig. 1). This is apparent here in the variation seen in steps 2–4. The relative repeatability between steps 2 and 4 indicates the reversibility of the light-soak temperature effects.

CIGS1 and CdTe1, we see from steps 2 and 4 that transitions between the temperature-dependent states are reversible.

Step 1 in Fig. 3 also shows that all four module types exhibited an initial gain in power after light soaking. In the case of CIGS2 and CdTe2, there was not a substantial temperature dependent effect. It is also interesting to note that the magnitude of the initial power gains in CIGS2 and CdTe2 are less than those of CIGS1 and CdTe1, respectively. In the cases of CIGS1 and CdTe1, the initial transients are both positive, but then the modules exhibit opposite light soak temperature-dependence. These results highlight that the existence, sign, and magnitude of the light-stabilized state temperature-dependence cannot be trivially derived from the initial transient behavior. Furthermore it underscores that the temperature dependence is product-specific, and not a universal property.

IV. Conclusion

We have shown that the light-stabilized state of some CIGS and CdTe modules depends on the modules' temperature during light exposure. Thus there does not, in general, exist a well-defined "light-state" for some types of thin-film module. It is important to note that these effects are not universal; we also tested CIGS and CdTe modules for which such temperature effects were not substantial.

The existing standard for light stabilization as described in IEC 61646 allows a 20°C range in temperature, which based on our observations can lead to greater than 5% variation in the power of the final light-stabilized state. Thus we conclude that when repeatability is critical, module temperature should be carefully controlled during light exposure.

However repeatability is not always the most important metric. For some applications, the field performance may be of greatest interest. The electrical state realized in a tightly controlled chamber may not be representative of that realized outdoors. When it is critical to understand the outdoor performance of a module, deployment in a similar environment may give more accurate results. However, the effects described here are expected to add uncertainty to translation of such results to other environments.

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