Solar Energy Materials & Solar Cells 294 (2026) 113885

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

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

Stabilization procedures for TOPCon PV modules after UV-induced degradation

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ARTICLE INFO

Keywords:
Photovoltaics
Modules
Degradation
Metastability
UVID
TOPCon

ABSTRACT

The study investigates the stabilization behavior of Tunnel Oxide Passivated Contact (TOPCon) photovoltaic (PV) cell technology following UV-induced degradation (UVID). It focuses on the after-effects of lab-induced UVID, particularly the drastic effects of power loss during dark storage after UV irradiation. To counteract these effects, which are considered as artifacts that do not affect the expected outdoor performance, the paper presents light soaking at 25 °C module temperature as reproducible stabilization procedure for module performance measurements. Considering the increasing market presence of TOPCon-based PV modules and recent reports of, in some cases tremendous extent, UVID in the lab, stabilization after UVID is highly relevant. The study further explores the development of degradation during dark storage over time, different conditions for light soaking, as well as the potential of other approaches: While the repeated flashing is in principle applicable for post UVID-stabilization, current injection procedures showed negligible effect. Interestingly, high-temperature treatment reduces the degradation during dark storage. In that, the study offers insights that may inspire cell-level investigations of degradation and stabilization and improve understanding of underlying mechanisms.

1. Introduction

TOPCon (Tunnel Oxide Passivated Contact) is the new mainstream photovoltaic (PV) cell technology, which is showing higher performances than the conventional passivated emitter rear contact (PERC) technology with competitive cost structure. However, significant degradation due to UV-induced degradation (UVID) has been reported for many commercially available module types [1,2]. While the underlying mechanism is not fully understood [3], first results point towards an issue on cell-level, specifically the passivation layers and the diffusion of hydrogen atoms.

Previous work observed strong power loss, but also recovery of performance in the lab, under light soaking and other conditions [1]. This constitutes a form of metastability, which is especially pronounced after UVID, but needs to be evaluated differently because, as far as currently known, it does not negatively affect outdoor performance.

While the exploration of the underlying degradation mechanism lies out of the scope of this work, it instead focuses on the behavior of modules after lab-induced UVID, which has been shown to be highly dependent on experimental parameters during both aging and subsequent storage, such as operation point, temperature, light and possibly current injection [1]. Specifically, this work focuses on the drastic effects these conditions have on subsequent power measurements with the goal to gain a systematic understanding and define stabilization procedures that allow reproducible module performance measurements.

This is especially relevant for buyers of current PV modules from the market, which are primarily TOPCon-based. Given the concerns about UVID that have emerged over the past few months, there is a demand for reliable and reproducible methods to identify modules that may be vulnerable to UV light exposure in outdoor applications. This work presents those methods.

The results from this work also allows to re-evaluate the drastic power loss observed in previous studies [1–3] in terms of its relevance for the outdoor performance loss. Furthermore, the gained understanding is relevant for sequential testing approaches that combine UV-irradiation with other aging tests, such as sequence C from IEC

This article is part of a special issue entitled: SiliconPV 2025 published in Solar Energy Materials and Solar Cells.

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https://doi.org/10.1016/j.solmat.2025.113885
Received 15 May 2025; Received in revised form 14 July 2025; Accepted 4 August 2025
Available online 26 August 2025
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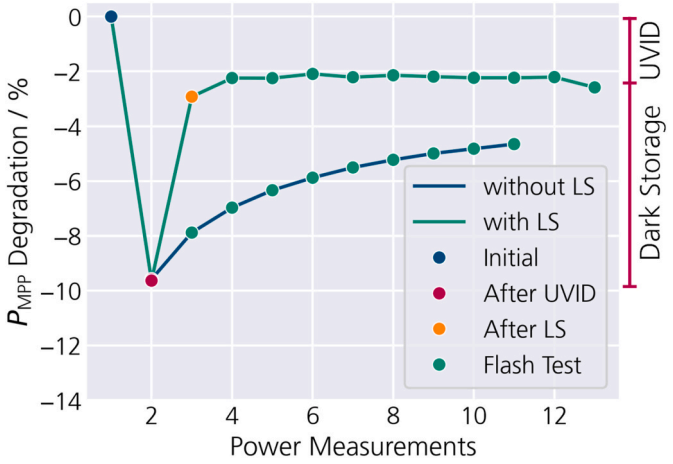

Fig. 1. Degradation and response to repeated flashing with and without prior light soaking (5 kW h/m^2, 25 °C) of one two-cell module.

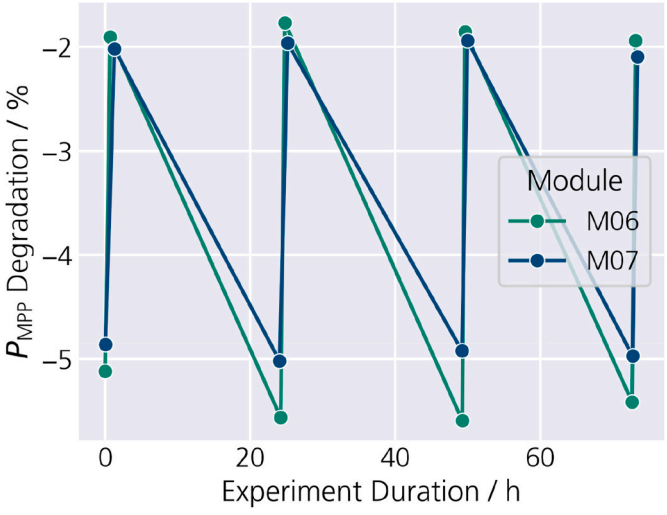

Fig. 2. Two-cell module performance during repeated degradation (in dark storage) and stabilization by lightsoaking.

61215–2, in which UV stress is followed by tests such as thermal cycling and humidity freeze. In this case, both can be expected to change the measured performance, even without the presence of UVID.

2. Methods

If not stated otherwise, the modules used in this paper are full sized commercial glass-glass modules with TOPCon cells from a Tier 1 manufacturer based in China. Small-scale modules had been produced at Fraunhofer ISE from commercial TOPCon cells of another Tier 1 manufacturer with two cells per module. The used encapsulant did not contain a UV blocker. Modules and cells were independently acquired on the market during the second half of 2023, meaning that the cells in the small-scale modules did not match the cells in the full-size modules.

UV-testing was done by exposing the modules to UV-A fluorescent tubes as the light source according to IEC 61215–2:2021, MQT 10, with a total dose of 60 or 120 kW h/m^2.

Post-UVID stabilization was carried out using a AAA-graded solar simulator inside a climate chamber. The module was exposed to an AM1.5 spectrum with an irradiation 1000 W for 5 min at 25 °C module temperature. A duration of approximately 10 min passed between stabilization in the climate chamber and power measurements in the flasher.

If not stated otherwise, power measurements were carried out on a AAA-classified flasher by Pasan. Small scale modules were measured using a table flasher by EternalSun with 10 s interval between individual measurements.

In the multiflash experiment, measurement systems with a flash duration of 80 ms and 10 ms, by Pasan and Halm, respectively, were used. The IV curve was traced in three sections, i.e. six flashes per power measurement. Both systems used an interval of 30 s between the individual flashes.

3. Results

3.1. Degradation and stabilization after UVID

Based on previous findings, we divide the causes for power loss after UV-testing into two categories: Firstly, UV-induced degradation (UVID) damages the cell and is presumed to be non-recoverable. Secondly, modules after UV-testing exhibit a dark storage power loss, which typically reduces module performance (mostly voltage) during storage under dark or low-light conditions. As mentioned above, little is known about the underlying mechanism of this loss during dark storage. However, fact that a similar behavior was also observed in experiments on bare cells hints at a process on cell level, which is presumably independent of the encapsulant and other module components. In the context of this work, the state after light soaking is defined as stabilized, meaning that the performance is not affected by metastability such as the dark storage effect. This presumably corresponds to the outdoor degradation, considering the light irradiation outdoors.

During the measurements of TOPCon modules after UV-testing, it quickly became clear that the performance was unstable. An example is shown in Fig. 1, where a 2-cell module was subjected to a UV aging test (120 kW h/m^2), resulting in more than −8 % power loss. This loss, however, did not remain stable, but instead diminished upon repeated flashing (blue line). Consequently, the module could be stabilized by continuous light soaking at 1000 W/m^2 for only 1 min, raising the module performance back to around −2 %. Present results on TOPCon modules indicate that light soaking is a very effective stabilization method, meaning that additional flash testing after LS for 1 min generally does not lead to further performance gain. The difference in operation point during light soaking, namely maximum power point tracking (MPP), open- (OC) and short circuit (SC) was thereby found to be negligible (not shown).

Reportedly, UV light is mainly responsible for the power gain during LS [4]. Considering the work flow of UV-testing and performance measurements, this means that the modules are presumably in a stabilized state right at the end of the UV test, but cannot directly be

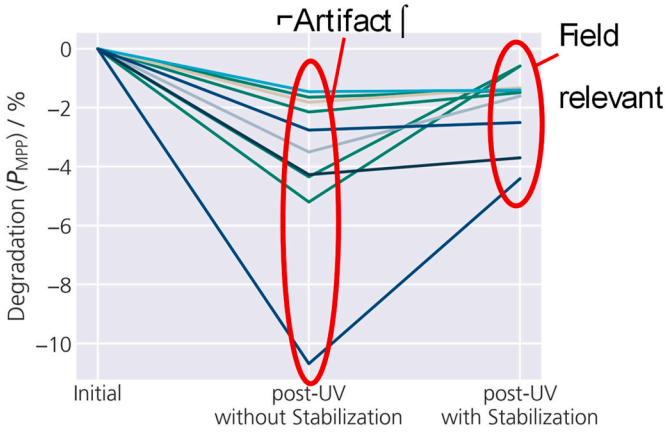

Fig. 3. Degradation (P_{MPP}) after UV test and subsequent light soaking. Color code: module types.

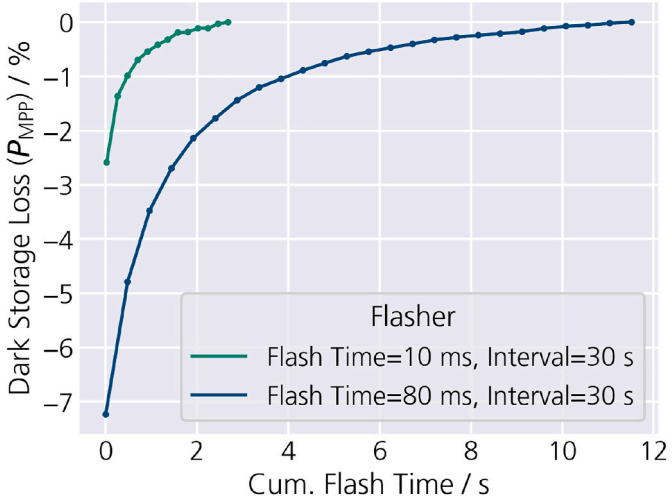

Fig. 4. Development of performance (P_{MPP}) during stabilization after UVID and dark storage by repeated flashing "multiflash" with two different flash durations. The module was previously subjected to a UV irradiation of 120 kW h/m^2 and varying dark storage times.

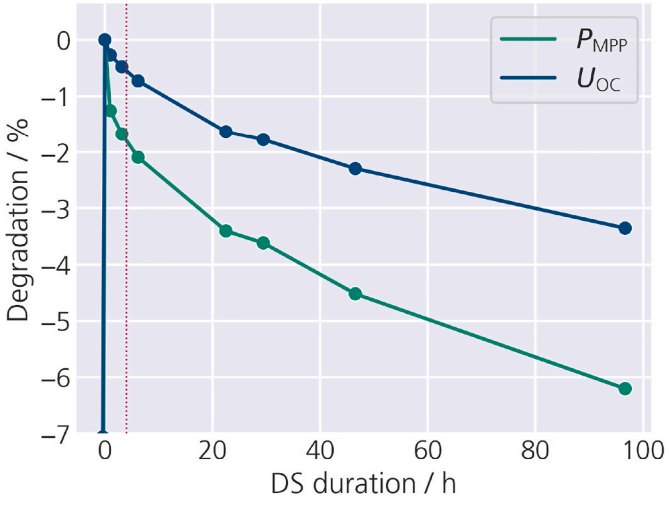

Fig. 5. Development of P_{MPP} and V_{OC} upon dark storage after UVID testing and lightsoaking. The vertical red line indicates 4 h of dark storage after lightsoaking.

measured due to the elevated temperature around 60 °C according to standard [5]. During cooldown to 25 °C standard conditions, the module may be subjected to storage at dark or low-light conditions, during which the performance drops below the stabilized state, causing the need for a subsequent stabilization method such as light soaking.

Generally, the dark storage effect can be reproduced multiple times on the same module with interim stabilization (Fig. 2).

As a consequence of these findings, the degradation during dark storage between UV aging and power measurement can be interpreted as an artifact that only affects lab measurements, but not the outdoor performance. It can further be presumed that previously published UVID results [1,2] were often negatively affected by additional degradation during dark storage between UV aging test and power measurements for different times and at different light conditions, rendering these datapoints basically meaningless., Only the measurement after light soaking is reproducible and a meaningful reference point (Fig. 3).

Considering the field-performance of a module affected by UVID, these results further suggest that a very short time of light irradiation (i.e. early morning minutes) should suffice to revert any possible effects of dark conditions over night and thereby stabilize the module performance with high effectiveness. Therefore, we generally recommend using the recovered state (i.e. after light soaking) as reference when evaluating power loss after UVID, including for modules that were previously exposed in the field.

Taking these considerations into account the UVID-induced performance loss appears significantly weaker after light soaking, but some module types still degrade significantly more than −2 %. Considering a UV-dose of only 60 or 120 kW h/m^2, which can be reached by two years or less, depending on the location of exposure, this exemplifies the need for UVID testing of current commercial TOPCon modules.

As discussed above, one of the earliest observations of the metastability happened upon repeated flasher measurements. As subsequent trials showed, a similar approach could also be used to completely stabilize the modules in a so-called "multiflash" approach (Fig. 4). The module, which had previously been subjected to a UV irradiation of 120 kW h/m^2 and dark storage, required only a few seconds of cumulative light exposure inside the flasher to stabilize. However, the net time in the flasher was significantly prolonged by a 30 s delay between the flashes, which is required for technical reasons. The data nevertheless demonstrates the potential of this method, which could be adapted for stabilization by using a different spectrum with higher UV content and does not necessarily require a high-quality light source as in this

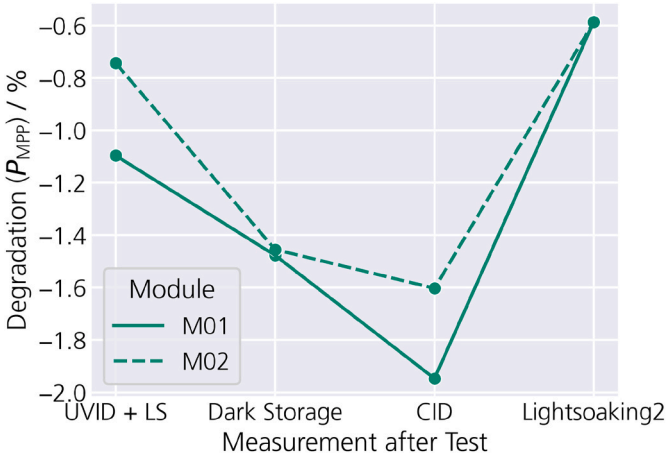

Fig. 6. Current injection (CID) on full-sized module after UVID and dark storage did not lead to performance increase or stabilization.

experiment. An interesting finding was that the required cumulative irradiation for stabilization strongly depended on the duration of the individual flashes: At 80 ms individual flash duration, the module required around 9 s of cumulative light exposure to stabilize from −2.5 %, while only around 3 s were required with 10 ms flashes. The underlying reason for this phenomenon remains unknown; however, it may hint towards a transient nature of the light stabilization effect.

Compared with stabilization by light soaking, the degradation in dark storage proceeds significantly slower (Fig. 5), but still sufficiently rapid to potentially influence performance measurement results. Because, similar to UV-tests, typical light soaking procedures result in elevated module temperatures around 60 °C, a time for cooldown can be required after light soaking to avoid measurement uncertainty related to numerical temperature correction. While the maximum allowed time between light soaking and subsequent power measurement is currently discussed in the context of creation of IEC TS 63624–1 "Test methods for UV-induced degradation -Part 1: Crystalline Silicon", the example shows that a time as short as 4 h can lead to significant degradation and should be reduced as much as possible. In the context of this study, we prevented this issue by carrying out the light soaking while controlling the module temperature to 25 °C in a climate chamber, allowing to carry out power measurements at standard conditions within minutes after light

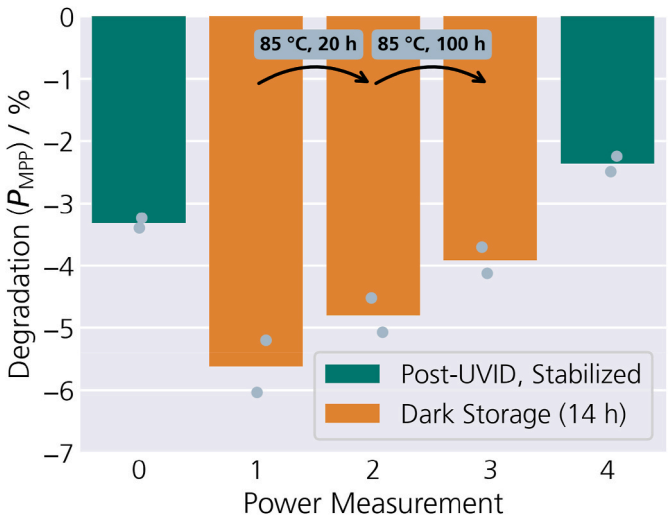

Fig. 7. Post-UVID degradation experiment on two two-cell TOPCon PV modules after light soaking: Degradation was caused by dark storage for 14 h after light soaking. The grey dots indicate individual power measurements (P_{MPP}) and the bars the mean degradation.

soaking.

In some reliability testing approaches, e.g. testing for light-induced degradation and light and elevated temperature-induced degradation, current injection can be used as alternative to light soaking. This is often a preferred method because light soaking capacity is typically limited by the irradiance area. Further advantages of current injection could be an easier temperature control during the test. When we applied this technique as candidate for stabilization after UVID testing, however, it had only a negligible effect: In an experiment on two full-sized modules that showed around −1.5 % degradation (P_{MPP}) after UVID and subsequent dark storage, current injection of I_{SC} in forward bias direction for 100 h at 25 °C did not result in a performance increase or stabilization (Fig. 6). In both cases, a subsequent exposure to 1 min of light soaking raised the module performance significantly. It remains possible that current injection using different parameters or time scales could stabilize modules after UVID, but based on the results so far the potential for a wide-spread usage seems low. However, the limited effect of current injection also means that electroluminescence measurements can be used to investigate the state of PV modules without interfering in the state of stabilization, as light IV measurements would do (Fig. 8).

Another interesting finding relates to the effect of temperature on the degradation in dark storage. These experiments were carried out on modules that underwent repeated cycles of dark storage and light soaking (comparable to Fig. 2), to show reproducible degradation (to around −5.5 %) and stabilization (to around −3 %), However, after treating the modules at 85 °C for 20 or 100 h, the modules showed a trend of significant decreasing degradation in dark storage (power measurements 2 and 3 in Fig. 7). While this finding might not be helpful for refining procedures for UVID testing or stabilization, it can possibly hint at the underlying mechanisms or a possibility to reduce dark storage degradation during the cell production step.

4. Summary and outlook

We examined the stabilization behavior of Tunnel Oxide Passivated Contact (TOPCon)-based modules after UV-induced degradation (UVID). Light soaking at 25 °C module temperature is presented as the optimal method currently available, since it allows subsequent measurement at standard test conditions. This result is particularly relevant because it contributes to reproducible and field-relevant UVID test procedures for current TOPCon PV modules, for which we currently recommend screening against UVID sensitivity. Beyond this, we also recommend the consideration of stabilization when evaluating field-aged modules and test results in combined aging test sequences that contain UV irradiation, such as IEC 61215-2 sequence C.

However, the requirement of light soaking in a climate chamber might pose limits to some testing houses. The option to use the conventional light soaking at elevated temperatures also reduces the influence of dark storage but cannot prevent degradation during the short cooldown time required before the power measurement at 25 °C. This demonstrates the need for a less elaborate method, hopefully to be developed in the future. Based on the presented findings and current knowledge, this could be based on irradiation with a different light source, intensity or frequency (“multiflash”), while we showed that the application of current injection is less promising.

Although this study did not focus on investigating the underlying mechanisms, the general behavior of slow degradation during dark storage and rapid stabilization upon illumination is reminiscent of the behavior observed in ALD-coated AlO_X passivation layers on lifetime samples [6]. Furthermore, the peculiar reduction of degradation in dark

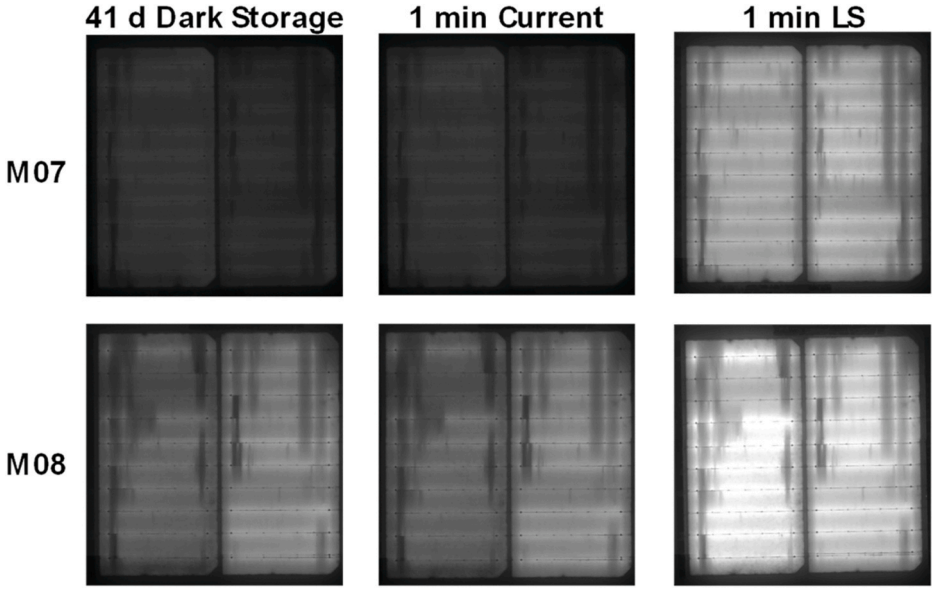

Fig. 8. Electroluminescence measurements on two-cell modules after dark storage, current injection and light soaking.

storage upon high-temperature treatment may hopefully inspire cell-level investigations of degradation and stabilization, thereby contributing to the understanding and potential modelling of underlying mechanisms at the cell level.

CRediT authorship contribution statement

Paul Gebhardt: Writing – original draft, Visualization, Validation, Project administration, Data curation, Conceptualization. **Esther Fokuhl:** Validation, Project administration, Conceptualization. **Sumeet Santosh Mujumdar:** Writing – review & editing, Investigation, Data curation. **Hyrie Frey:** Writing – review & editing, Investigation, Data curation. **Angelika Beinert:** Writing – review & editing, Project administration, Conceptualization. **Achim Stöhr:** Writing – review & editing, Investigation, Data curation. **Martin Kaiser:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization. **Ingrid Hädrich:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was funded by the German Federal Ministry for Economic Affairs and Climate Action in the projects GagaRIn (03EE1133A), MoQa (020E-100550326) and Quelle (03EE1172E).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solmat.2025.113885.

Data availability

Data will be made available on request.

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