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Discussion

Reliability of tandem solar cells and modules: what's next?

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Hybrid tandem photovoltaic (PV) technology development has gained momentum in the last few years. This has been motivated by a need to push module efficiencies beyond what is theoretically capable with single-junction technologies to further accelerate total global PV deployment. Significant advances have been made with multiple material systems achieving tandem efficiencies over 30% in the last decade. All of the highest record efficiencies have been from laboratory-scale devices, with areas of 1 cm^2 or less. Interestingly, there are multiple material combinations and terminal configurations that have demonstrated promising results. Despite these high laboratory efficiencies, reasonable service lifetimes (a useful operating lifetime of at least 25 years) are needed for tandems to compete with the levelized cost of energy (LCOE) of traditional single junction PV technologies. Existing commercial Si PV products have demonstrated performance in the field with an average of less than 1% relative annual degradation in module and system performance, and many manufacturers now provide 30 year warranties on their products [1].

Without reasonable service lifetimes, tandem PV technologies cannot succeed at a large scale because they won't deliver the necessary performance or financial returns compared to traditional Si or CdTe single junction technologies. In this article, we discuss the basic requirements for integrating multiple tandem cells into modules, and provide suggestions for how reliability studies of tandem cells and modules can learn from prior knowledge in the field of photovoltaic reliability. We will focus on tandems based on metal-halide perovskites (MHPs) and silicon, as this is currently the most prominent combination being explored in the literature and by multiple companies, and has the most challenges associated.

While single-junction technologies (e.g. Si or CdTe), are remarkably durable, with service lifetimes of more than 30 years, reliability issues do still arise. Most modern reliability issues come from the mismatched materials, chemistries, and interfaces of fully packaged modules. For example, traditional monocrystalline silicon based modules are typically packaged using a front cover glass, a thermoset polymer and either a glass or thermoplastic polymer back cover. The layering of these materials creates interfaces which are often mechanically mismatched and the materials themselves are sometimes chemically incompatible, creating electrochemical and mechanical issues during service [2–4].

There are additional reliability concerns in hybrid tandems, regardless of the specific technologies used due to potential interactions between the two sub-modules when combined into a single package. Even if both sub-cells are known to be durable, the additional interfaces in tandem modules introduce new chemical and mechanical considerations. These can all introduce additional degradation pathways. For tandem modules developed using newer technologies, such as those based on MHPs, the reliability concerns become more significant as the MHP devices themselves still currently suffer from short service lifetimes [5].

Little reliability work has been published on hybrid tandem PV devices, so far. Some recent studies have discussed degradation mechanisms of two-terminal (2T) MHP/Si cells, where the sub-cells are vertically connected in series (Fig. 1a). The mechanisms include: potential-induced degradation (PID) (Fig. 1b) [6], interface delamination (Fig. 1c) [7], and light- and elevated temperature-induced degradation [8]. While the knowledge gained from cell-level studies is very important, it is critical that additional studies be performed on modules. Film non-uniformities and defect density are likely going to scale with increased module size. Additionally, the mechanical robustness of

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modules can only be assessed at the appropriate scale. Finally, individual cells have to be electrically interconnected in modules, and each interconnection approach has potential to create reliability challenges.

For four-terminal (4T) configurations, where the two sub-cells are mechanically-interconnected but electrically isolated by an interlayer material (Fig. 1d), additional potential issues could arise which include electrical arcing between the two sub-modules when an interlayer with insufficient voltage breakdown (V_{bd}) properties are used (Fig. 1e). Asperities from the front metallization of a bottom Si cell could also threaten to penetrate the interlayer and cause shorting between the sub-modules when without sufficient thickness or mechanical rigidity. Fabrication processes also become an area of concern, specifically when it comes to lamination using a thermosetting polymer interlayer (e.g. Poly(ethylene-co-vinyl) acetate (or EVA)). Should voids (or bubbles) form at the critical interlayer between sub-modules, the breakdown voltage could be compromised, thus leading to arcing (Fig. 1e).

Packaging architecture and material selection often defines the long-term durability of PV modules. This will also be true of hybrid tandem modules. While many single-junction MHP studies use a package which consists of two pieces of cover glass and a desiccated edge seal with no polymer encapsulant [9], MHP/Si tandems, regardless of architecture, will require a polymer encapsulant to provide mechanical robustness for the Si sub-cells. In addition, chemical compatibility between the encapsulant and absorber will be critical to long-term durability. Some encapsulants, such as those based on EVA, can generate degradation by-products which could have a deleterious effect on the MHP film, or indeed the Si’s passivation in the case of a heterojunction (HJ) cell [10]. This is exacerbated by the need of a hermetically-sealed package for MHPs, where by-products are not able to outgas like they would from a breathable polymer backsheet [11].

The current PV module certification standards, International Electrotechnical Commission (IEC) 61215 [12] and 61730 [13], lay out the minimum requirements for reliability and safety for single junction crystalline Si and thin-film PV technologies. The standards outline a series of accelerated stress tests that screen for early reliability issues in single junction PV modules. It is important to recognize that the accelerated stress tests were developed to target specific, known degradation modes that were observed in field-deployed PV modules. The development of these standards follows the so-called PV reliability learning cycle [1,14]. The basic premise is that a when PV module is deployed in the field for testing, or perhaps as part of a PV installation, and later begins to show a drop in performance or has a visible failure, it is taken from the field and the failure is investigated. Once the root-cause of failure is understood, a new test to screen for the failure in new modules is developed and made into a standard. The current standards for PV module qualification are therefore specific to the technologies that have been tested and may or may not be relevant to newer technologies such as MHPs.

The damp heat test, Module Qualification Test (MQT) 13 from IEC 61215–2, is regularly used to evaluate the stability of packaged MHP devices which have known sensitivities to water. The damp heat test exposes modules to 85% relative humidity (RH) and 85°C for an extended period of time[15]. This test was originally developed to assess the susceptibility of Si PV modules to corrosive degradation mechanisms which, at the time, had been observed in fielded modules. For a MHP device that has been packaged using an appropriate edge seal moisture barrier, the damp heat test is then only testing the quality of the package and its ability to prevent moisture ingress, and is not directly assessing the perovskite’s resilience to moisture. Additionally, there may be tests that are missing from the standards that would be necessary to adequately assess the reliability of MHP modules. It has been demonstrated in the literature that MHPs are particularly sensitive to light exposure at elevated temperatures for extended durations [16–18]. There are currently no published standards that would appropriately screen an MHP-based PV module for this degradation.

Broadly speaking, degradation modes fall into three categories; electrical, chemical or mechanical. And more often than not, degradation mechanisms are driven by a combination of these categories. Some of the MQT’s in the IEC standards could appropriately assess some of the issues which have been outlined in the paragrpahs above. IEC 61215–2 MQT 21, the potential-induced degradation (PID) test, which is driven by electrochemical degradation stressors, drives any potential mobile ions which can subsequently impact the sub-cells within a packaged module. IEC 61215–2 MQTs 11, 16 and 20: the thermal cycling test, static load and mechanical load tests, respectively, would likely be appropriate for evaluating adhesion between MHP layers and between MHP/Si interfaces in the case of a 2T, which are mechanical However, since these MQTs were developed with specific degradation modes of Si PV modules in mind, there are likely degradation modes or mechanisms that could not be identified by the current standards and will not be identified until they are deployed in the field Fig. 2.

Tandem PV modules have great potential to make a significant impact on the total deployed PV capacity. However, de-risking this emerging technology is a complex challenge due to the myriad materials and design choices which can each influence reliability and service life. Fortunately, there are already decades of knowledge and experience in PV design, reliability and testing that can be leveraged to accelerate our understanding and qualification of tandem modules. To move tandem technology forward, it is critical that reliability testing of modules, and not just cells, becomes a focus for the tandem research community. Sharing reliability and field-performance data of tandem devices, and validating results with independent third-parties, will enable the reliability learning cycle to progress faster, speeding up the time frame for deploying tandem PV technologies and creating clean electricity for the planet.

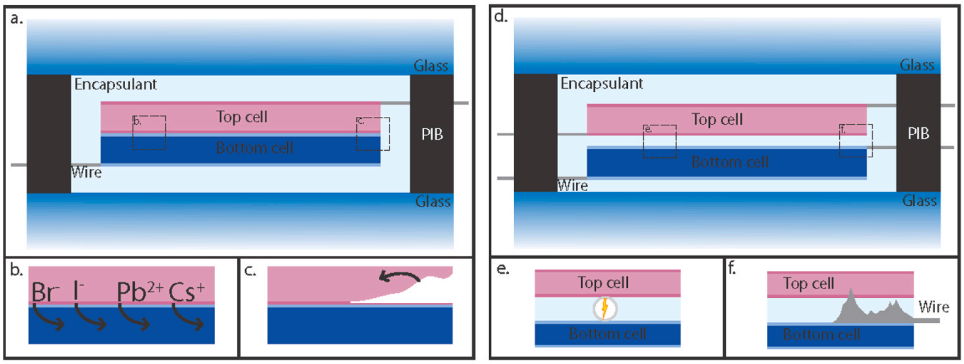

Fig. 1. Cross-sectional schematic of a fully packaged (a-c) fully integrated 2T tandem module and (d-f) 4T mechanically-stacked tandem module. (b-c) schematic of failures in 2T tandems: (b) PID and (c) interface delamination. (e-f) schematics of failures in 4T tandems: (e) arcing between sub-modules and (f) shorting between submodules.

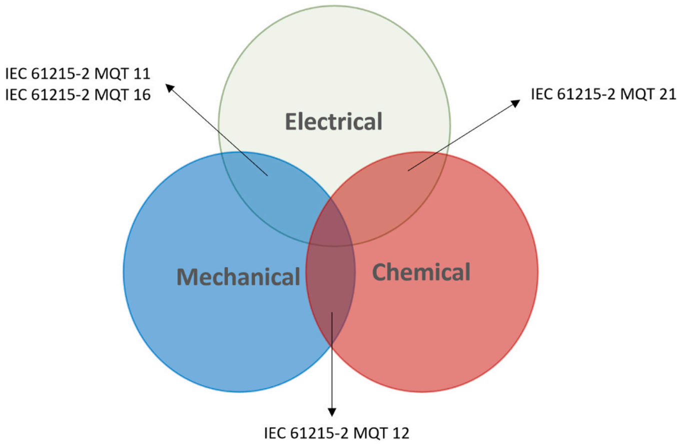

Fig. 2. The three broad categories of degradation modes and how they can overlap. Arrows indicate the IEC Module Qualification Tests which fit into the relevant categories, and could be suitable for capturing degradation modes in tandem PV modules without a prior knowledge of the degradation mechanism.

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.

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