

Perovskite Photovoltaic Module Curvature from Lamination Correlates to Operational Stability

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(Received 16 December 2025; revised 18 March 2026; accepted 22 June 2026; published 13 July 2026)

We report on a rapid, nondestructive scanning laser curvature method for directly characterizing an important and unacknowledged factor that can contribute to the stability of encapsulated single-junction and tandem perovskite solar modules, i.e., the curvature from lamination. The ability to directly identify mechanical stresses and their evolution in fully packaged modules provides critical information regarding possible risks for accelerated degradation and failure. We define a metric for the curvature relating the magnitude and variance in front-glass z -displacement to the “flatness” of the module. We also study the effects of package design and lamination parameters—specifically, encapsulant volume, module layout, front- and back-glass thickness, and ribbon placement with the goal of reducing the curvature and the resulting mechanical stress imposed after lamination. Critically, we show that flatter modules show significantly enhanced durability when compared to curved modules, increasing T_{80} by about a factor of 2 from ~ 900 to 1800 h under ISOS-L2 conditions at 65 °C. A direct link between mechanical stress imparted from lamination and chemical degradation mechanisms in modules provides an important design guideline to the community toward robust and reliable perovskite module manufacturing.

DOI: [10.1103/3m96-tfbt](https://doi.org/10.1103/3m96-tfbt)

I. INTRODUCTION

Metal halide-based perovskite solar cells (PSCs) have demonstrated low costs and high performances with an efficiency improvement rate that is unparalleled by any other solar technology [1,2]. Strides have been made in research, and currently the record efficiencies are 27.2% in single-junction devices [3] and 34.9% in tandem with silicon bottom cells, exceeding the detailed balance limit [4].

However, perovskite thin films are vulnerable to degradation from environmental factors, such as oxygen, light, heat, and humidity, which induce various degradation mechanisms [5]. Most solar modules, including silicon and emerging technologies like perovskites, require additional protection in the way of fully sealed glass-glass packaging to prolong device lifetime. Other commercial thin film modules like CdTe also rely on similar encapsulation methods but can withstand high-temperature lamination because of their higher thermomechanical stability. Lamination involves the usage of two key

components: encapsulant material and edge seal. It is important for this encapsulant to have high optical transmittance and conformally cover the thin-film solar module whether it is a single-junction, a two-terminal (2T) or four-terminal (4T) tandem configuration. Additionally, it is critical that an edge seal with a low water vapor transmission rate and oxygen transmission rate creates a tight hermetic seal around the device to prevent the ingress of water vapor and oxygen [6]. The encapsulation also serves to prevent egress of volatile species from the perovskite. The importance of using both encapsulant and edge seal in conjunction was demonstrated in a study by Ulicna *et al.*, where a perovskite module with a polyolefin (POE) laminate and polyisobutylene (PIB) edge seal retained 80% of its efficiency after a year of outdoor testing, whereas those with only the edge seal or an edge seal “blanket” used as an encapsulant started failing after 10 and 100 days, respectively, with the PIB strips promoting degradation pathways [7].

Typically, commercialized silicon/CdTe solar modules are vacuum laminated at temperatures of 150 °C or higher; however, the perovskite can undergo structural changes and degrade into nonphotoactive phases at elevated temperatures even in inert environments [8]. For example, Witteck *et al.* reported laminated PSCs lost 16% of their relative performance when PSCs were laminated at 150 °C for 23 min due to the formation of defects that shunt the device [9]. Therefore, it is important to take encapsulant

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processing temperature and thermal budget into account for perovskite solar modules. Encapsulant selection for perovskites is often governed by chemical compatibility and lamination at lower temperatures due to a limited thermal budget for perovskite-based modules. Among low-temperature encapsulation crosslinking agents, elastomer-based encapsulants like POE and thermoplastic polyurethane offer better moisture resistance, electrical insulation to prevent short circuits, and resistance to UV-related discoloration [10].

Even if all the above properties are satisfied, the encapsulation itself can provide a source for accelerated degradation through mechanical driving forces and stresses that can, in the worst cases, lead to delamination [11]. This can occur due to two reasons: first, the encapsulant material can crystallize as it cools down to room temperature after lamination, leading to warping and the formation of non-crystalline regions. The material shrinkage caused by the molecular structural changes can lead to delamination. Jiao *et al.* saw delamination in perovskite minimodules due to crystallization-induced shrinkage of the encapsulant [12]. Second, the difference in coefficients of thermal expansion (CTE) can lead to volumetric changes in the encapsulant, accumulating thermal stress that eventually delaminates the module if the encapsulant is not sufficiently deformable to accommodate the stress. Some important criteria for encapsulant selection include mechanical properties such as low elastic modulus and curing temperature compatible with underlying layers. Cheacharoen *et al.* showed that using a soft encapsulant with a low elastic modulus can improve the mechanical stability of the module by preventing delamination [13]. Since perovskite films are brittle in nature, thermal cycling can compound the residual stresses from fabrication and induce mechanical damage and performance degradation of the device stack. Even in cases of no delamination, the intrinsic stresses in the perovskite absorber layer can also be detrimental to the phase stability and lead to undesirable ion migration [14].

In a single-junction perovskite or a 4T perovskite-silicon tandem module, the perovskite top cell is deposited directly onto and mechanically constrained by the front glass underneath (Fig. S1 in Supplemental Material [15]) and by the encapsulant on top, which have vastly different mechanical properties. The front glass has a CTE 2 orders of magnitude lower than the encapsulants, leading to competing forces acting on the module [16,17]. When the module cools down to room temperature after being subjected to lamination, the glass prevents the encapsulant from shrinking past a certain point, resulting in curvature since there is a force on the inner side of the glass and none on the outer side, which remains unconstrained. The overflowing of an encapsulant with low viscosity (overflowing the edges) and high elastic modulus (resistant to material expansion/contraction) can also lead to a higher stress on the edges of the modules, which leads to a

significantly “curved” final product [18] and increases the likelihood of a thinner glass breaking [19]. In some studies, laminated silicon modules had a curvature of up to 1.5 mm at the module midpoint from front-glass deformation [20] which generates internal stress and results in a driving force for delamination. Hence, curvature could potentially induce stress in the perovskite device and drive delamination for single junction, 2T, or 4T perovskite-Si tandem modules. We have observed edge cell failure in perovskite modules after accelerated aging when the package is highly convex as shown in Fig. S2 in Supplemental Material [15], which motivated us to systematically study the factors that affect the curvature of the module postlamination [19,20].

Existing measurement techniques to measure curvature include surface profilometry, which is limited in that it can typically only map displacement vs distance in one dimension (either x or y). Optical sensors can provide more data and measure the surface of the module, but these measurements use a change in curvature to measure stress through Stoney’s equation and are not suitable for measuring stresses resulting from layers thicker than a few microns. These techniques are not designed to map deformation in modules since there are mm-scale-thick encapsulant sheets and back glass involved in the stack. Studies have used simulated models to quantify stresses and strains in a photovoltaic module that evolve during manufacturing [21,22]; however, these numbers cannot replace real experimental data due to uncontrolled variables and processing parameters that can affect the module. Differences arising from lamination stress, nonuniform geometry, and time/temperature-dependent properties of encapsulants are nearly impossible to replicate in models; hence, there is a need for a system that rapidly measures the module curvature.

Here we report a method to accurately measure the displacement of a laminated photovoltaic module using a laser-based displacement sensor and a moving stage. Using the results, we directly map the bowing, which will be referred to here as “displacement” of the package that affects the resulting mechanical stability of the perovskite top cell. We develop a system to quantify curvature and define it as the displacement difference between the center and edges of the module and use these numbers, as well as the uniformity seen in the 3D displacement map, to categorize the extent to which packages are “flat” and “curved/bowed.” We investigate the effects of laminate thickness, lamination pressure, back glass thickness, ribbon placement, and jig height on the flatness of the package and correlate this to module stability under accelerated light/heat or thermal cycling tests.

II. METHODOLOGY

For the purpose of this study, semitransparent perovskite top cell modules were used to investigate the effects of lamination. The cell stack was deposited onto an

ITO-coated front glass with $130 \times 130 \times 1.1$ mm dimensions (100×100 mm aperture area) to fabricate a module with the following architecture: Glass/ITO/HTL/Perovskite/ETL/IZO/Encapsulant/Glass. For the laminate, we used different amounts of TPO encapsulant which were cut up into smaller sheets using a laser cutter. A butyl rubber edge seal was applied to seal all four sides of both the back and front glass, with a 2–3 mm gap along two parallel edges. The two pieces of glass were placed so that the gaps are perpendicular to each other, meaning that an area adjacent to each corner only has half the edge seal thickness of the rest of the module. A visual representation of this is given in Fig. S3 in Supplemental Material [15]. Teflon jigs of 2, 3, 5.1 and 5.8 mm heights were used to constrain the package and prevent edge seals from being pushed out. In addition, a thin Teflon sheet above and below the package prevented undesired adhesion to the laminator after encapsulation. The standard module configuration when laid down was flush with the 5.1 mm jig while it would protrude outward for the lower jig heights. Pictures of the setup are shown in Fig. S4 in Supplemental Material [15]. We also included soldered indium bus bars on the front glass with 0.5-cm-wide and 2-cm-long metal ribbons/tabs exiting the module to serve as electrical connections. Detailed lamination conditions for each package described in the tests are included in Table S1 in Supplemental Material [15].

The modules were laminated using a Bent River bladder laminator. Using the jigs above, this has the capacity to laminate 16 130×130 mm modules at a time; but to avoid additional uncontrolled variables, we used the same position and laminated one module per run. The pins were lowered to allow uniform pressure to be applied to all spots, and the system waits to achieve the target temperature of 130°C unless stated otherwise. This temperature is ideal for allowing the encapsulant to melt and edge seal to soften and flow. The package was held at the target temperature for 8 min after which the target pressure of 12 psi (unless stated otherwise) was achieved and held for 5 min. The total lamination process took approximately 15 min and the temperature, pressure vs time profile is shown in Fig. S5 in Supplemental Material [15].

The flatness of the laminated module was measured using a glass displacement sensor from global sensor manufacturer SICK AG. It uses a laser beam and measures the displacement between the detector and the reflected surface. We set the laser power to a high enough value to make sure the detector always measured the displacement of the top glass surface and did not record any back surface reflections. We set an extremely large threshold of 3000 mm so the system can also return accurate displacement measurements over highly reflective regions such as the indium bus bars. The sensitivity and gain on the sensor were set to a value to get the maximum output. The module was placed on a stage and positioned so that the bottom-

right corner aligns with the (0, 0) coordinate given to the measurement system. The system takes an input of the length and width of the module in the software (we used 120×120 mm) and then moves the stage across the entire package in a serpentine pattern and stores the displacement at each coordinate point. The sensor takes a programmed number of measurements and calculates the mean and standard deviation. The mean value is stored as a value if the standard deviation is less than what the user has defined in the program. For our measurements, we set the standard deviation at 0.05 mm to get the most accurate results and account for any irregularities in the reflected beams or the module surface. We used a linear speed of 7.85 mm/s for the stage and defined the step size as the length/width of the module divided by the number of grid points, which is a user-defined parameter and was set at 15. This generates a map of deflection vs position for the front surface of the package, which is then plane leveled using linear least squares. The module is then flipped over to measure the displacement of the back glass. Results are superimposed on a singular 3D (x, y, z) graph by leveling this plane via linear least squares and then reflecting the measured plane across the x (direction of flip) and z axis. The system is not sensitive to module alignment, meaning if it is not lying flat on the tabletop, it will continue to measure as usual, and the results will not be affected.

The modules were degraded on a custom system [23] using resistor loads, which have been shown to be a good approximation for maximum power point tracking [24] under ISOS conditions. Modules were kept at 65°C under white light illumination, and its spectrum is shown in Fig. S6 in Supplemental Material [15].

III. RESULTS AND DISCUSSION

Module curvature was measured with a glass displacement sensor that relies on the laser triangulation measurement involving an angular calculation to measure the distance between two points. The laser light is projected onto the object and the reflected beam is mapped to a position. The displacement is measured through triangulation of the light source, a point on the measured object, and the image received by the detector as shown by the arrows in Fig. 1(a). The measurement is driven by the Gaussian distribution read by the detector in Fig. 1(b), and it repeats the measurement until the desired standard deviation value is achieved. The top side of the front glass is measured and then the module is flipped over to measure the bottom of the back glass. For our system, y axis is considered parallel to the scribe lines while the x axis is perpendicular. Data are stored in two 2D plots which map the displacement (z axis) vs the width (x axis) and displacement vs length (y axis) of the module. A 3D plot, like the one shown in Fig. 1(c), is also presented, showing the width (x), vs length (y) vs displacement (z) for both the front and back glass. We quantified curvature of the

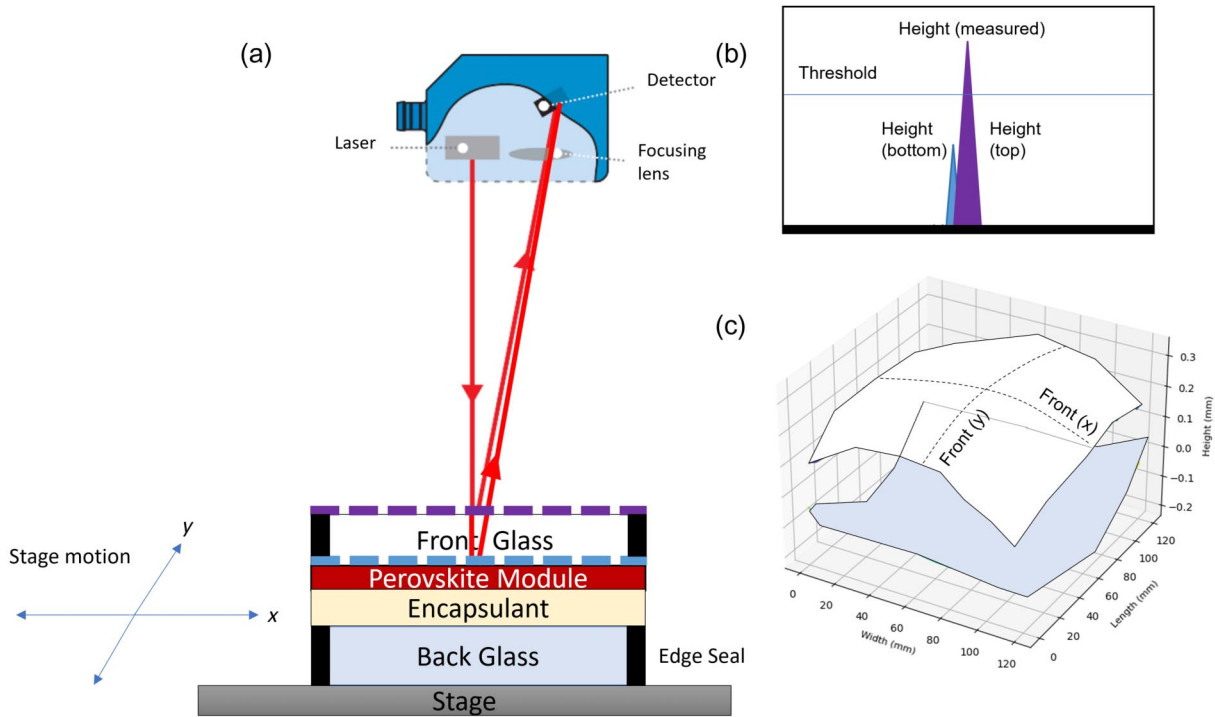


FIG. 1. (a) The displacement sensor setup for measuring photovoltaic module curvature with the laser detector hanging fixed overhead, while the stage moves in the x and y direction to measure across the module (b) the signal read by the detector showing reflection off the top of the front glass, bottom of the front glass (c) the 3D plot from the system showing the curvature of the front glass and back glass.

package by averaging the difference in displacement between the edges and the center of the module [60 mm point for both the length (y) and width (x)] as shown in Fig. S7 in Supplemental Material [15]. Since the system takes measurements for a 15-by-15-point grid, all x and y values are averaged to obtain the curvatures measured for the x and y axis.

Ultimately, the goal was to develop strategies to reduce the resulting displacement and curvature so that the perovskite device has the lowest mechanical driving force and to minimize the possibility of delamination and mechanical stress-induced degradation. Relevant accelerated stability tests to probe mechanical integrity for PV modules includes IEC 61215-MQT11 which involve several tests including thermal cycling of the samples from -40 to 85°C for 200 cycles, referred to as TC200. Materials expand at high temperatures and contract when they are cooled down but since the active layers comprising the solar module, glass, encapsulant, and interconnects all have different CTE values, changes in volume occur at different rates, leading to tensile or compressive forces acting on the layers.

We performed electroluminescence (EL) imaging before and after thermal cycling to track defects from these thermomechanical stresses. Before the thermal cycling, the modules showed dimming in some of the cells in Fig. 2(a) but likely due to nonuniform coating or

improper scribing. The more warped package with front-glass displacement values above $100\ \mu\text{m}$ depicted in Fig. 2(c) shows damage to the edge cells (visible in the feathering pattern in Fig. 2(b)). Since EL differs from photoluminescence imaging (Fig. S8 in Supplemental Material [15]) by charge injection, a dark region seen only with EL signifies a charge transport issue. This damage seen in the dim cells here could possibly be damage from delamination to one or more of the device layers. This effect was only seen in the edge cells and corroborates the observation in Fig. S1 in Supplemental Material [15], where visual edge cell failure is observed.

The bottom row in Fig. 2 includes EL images from the module that had a low curvature with displacement values lower than $50\ \mu\text{m}$ as shown in Fig. 2(f). After 200 cycles, there was no damage seen in the EL images in Fig. 2(e) and the dimming of the cells only indicates a perovskite nonuniformity because it was also seen in Fig. 2(d). These results along with JV characteristics of the modules prethermal and postthermal cycling (Figs. S9 and S10 in Supplemental Material [15]) support our hypothesis that the curvature of the perovskite device affects the stability of the perovskite module and can accelerate mechanical failure if it is beyond a certain threshold.

We were then motivated to study strategies to mitigate this curvature, which include the following approaches: (i) tuning the encapsulant volume, (ii) adjusting the

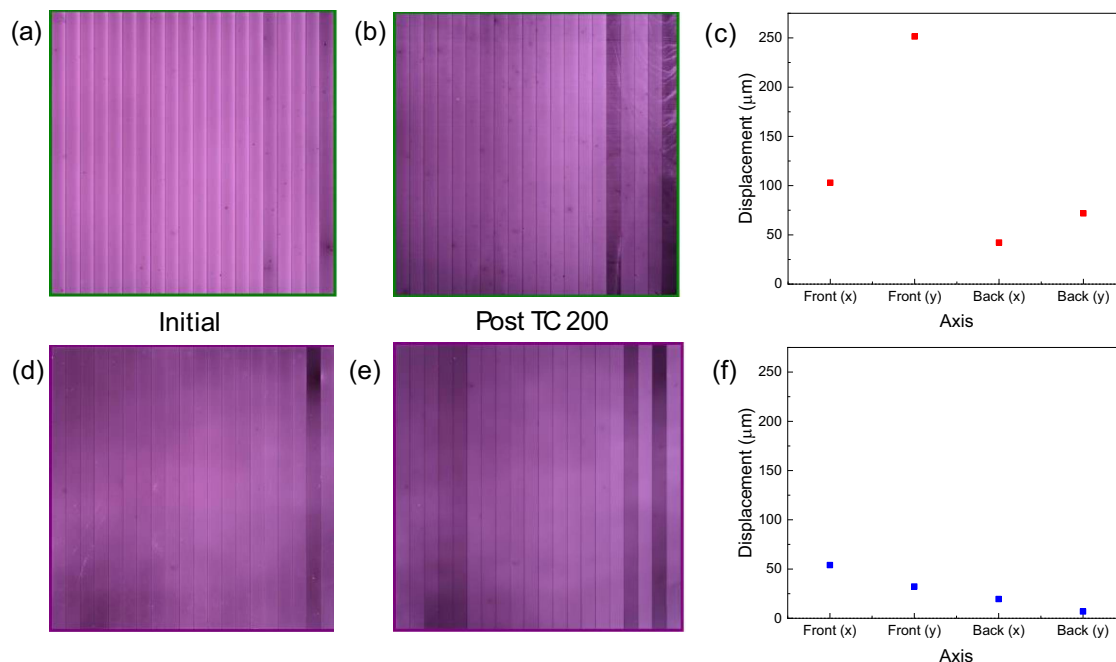


FIG. 2. EL imaging of a warped package (a) before and (b) after 200 thermal cycles, and for a “flatter” package (d) before and (e) after 200 thermal cycles. (c) and (f) show the curvature of the module before cycling.

pressure transfer via jig height, (iii) changing glass thickness, and (iv) modifying the placement of the ribbons used for electrical connections.

A. Strategies to reduce front glass curvature and resulting stress on perovskite

1. Package fill: Amount of encapsulant used

Our first study tuned the volume of encapsulant used since we hypothesized that as a first-order approximation, the glass curvature was directly proportional to the amount of encapsulant being used to laminate the module. When there is an excess of encapsulant, the first-order effect is the higher volume of material leads to a more obvious displacement in the front and back glass. We varied the encapsulant amount by cutting up 5 g encapsulant sheets and seeing how increasing the number of sheets used correlates to the flatness of the module. With 2 sheets (0.8 mm thickness), the front glass is concave in the x direction (perpendicular to scribe lines), with an $83.6 \mu\text{m}$ displacement but relatively flatter in the y direction (parallel to scribe lines) with a $45.5 \mu\text{m}$ displacement possibly due to the edge seal (0.9 mm) making the module edges thicker than the center as evident in the 3D plot shown in Fig. 3(a).

The back glass was relatively flat and was less affected by the lamination process, an effect which we attributed to the higher thickness (2 mm compared to the 1.1-mm-thick front glass) leading to increased rigidity. When the encapsulant volume was increased to three sheets, as shown in Fig. 3(b), the displacement in the y direction

was $282 \mu\text{m}$ with the module bowing outward, and there was a slightly convex curvature seen in the back glass while the x direction had a lower displacement value of $75.7 \mu\text{m}$. Increasing the number of sheets to 4 led to a convex shape in both the x and y directions with displacement values of 315 and $179 \mu\text{m}$, respectively, for the front glass, showing that there was excess encapsulant leading to “bloating” effect in the center of the front glass which is visible in Fig. 3(c).

The encapsulant volume clearly plays a key role in curvature, but it is also important to explore how the encapsulant flows under different lamination conditions to find out why the modules were more bowed in one direction than the other.

2. Pressure transfer: Adjustment of jig height

Lamination pressure is also an important parameter that affects module curvature since it can affect how the encapsulant flows during the process, and an uneven application of pressure can lead to more warpage due to nonuniform encapsulant thickness. We wanted to study how the distribution of pressure affects the glass displacement. During standard lamination without a jig, as the laminator membrane exerts pressure on the front glass during lamination, the encapsulant and edge seal flow outward. There is a concentration of stress at the edges of the module where the bladder impinges on the glass. This leads to bending of the edges during the high-temperature curing with the package being much thicker at the center than at the edges. The need for a jig or some sort of frame

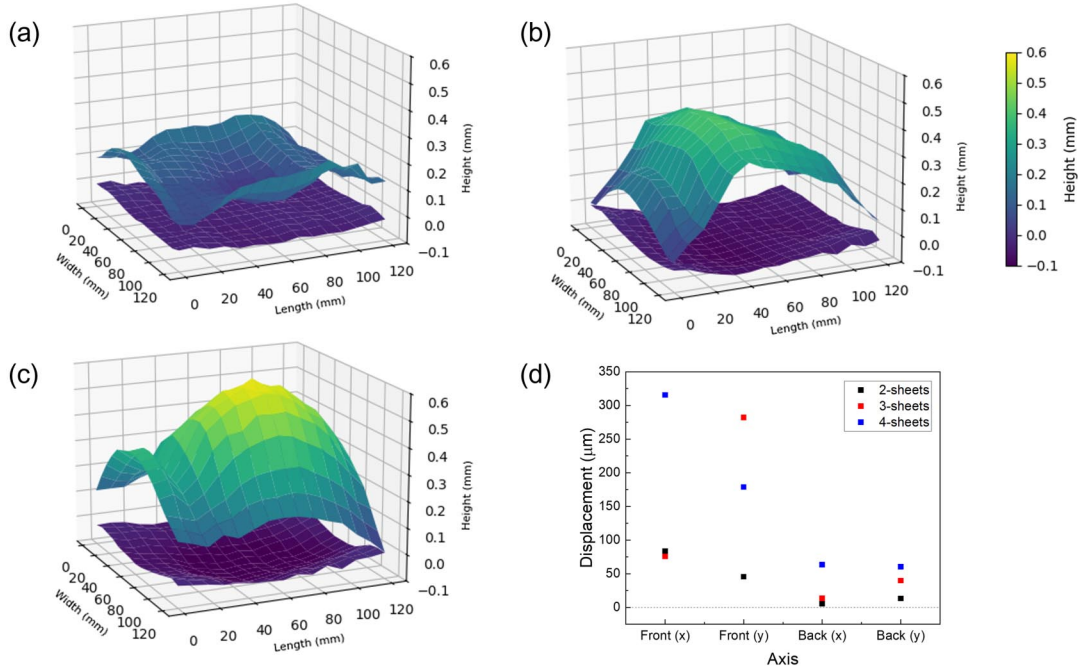


FIG. 3. (a) The displacement measurements from modules laminated with (a) 2 sheets (10 g), (b) 3 sheets (15 g) and (c) 4 sheets (20 g) of encapsulant (d) shows the 2D displacement values for the front and back glass for all three conditions on the same scale.

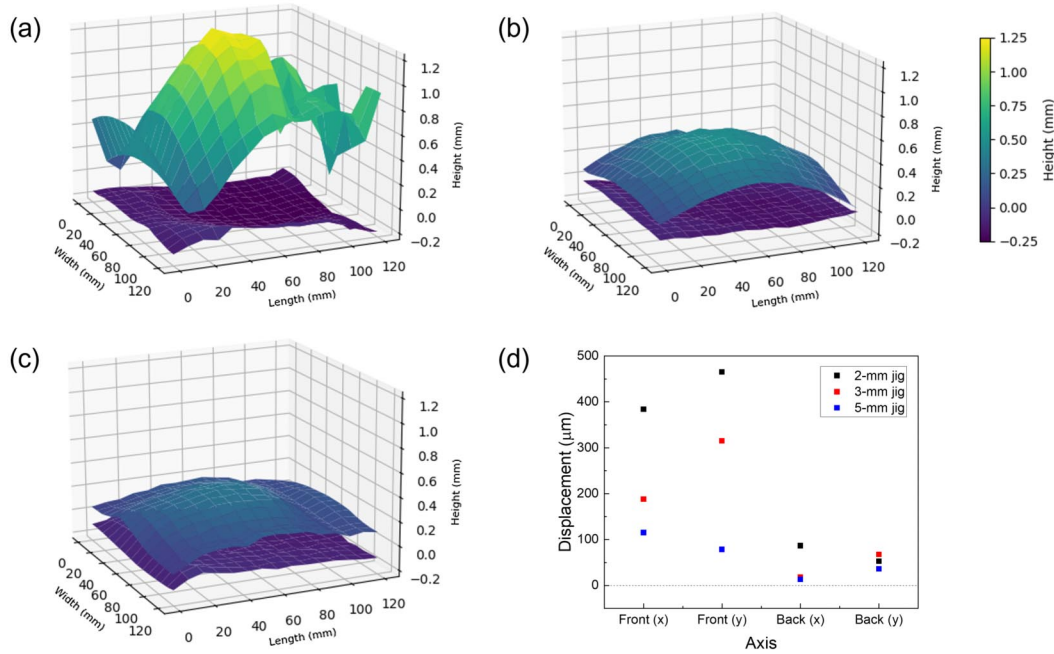


FIG. 4. Laminating modules using a jig heights of (a) 2 mm, (b) 3 mm, and (c) 5.1 mm showing an inverse relationship between jig height and front glass curvature (d) shows a plot of the 2D displacement values for the front and back glass for all three conditions on the same scale.

to constrain the module arises to prevent encapsulant from flowing out [18], which is what we implemented in this study. We used three different jig heights to study how the flow of encapsulant and edge seal changed, as observed in the displacement measurements.

When the bladder inflates to apply pressure to the module during lamination, the pressure is unevenly distributed, and the bladder pushes down on the edges of the module for a lower jig height as shown in Fig. S11 in Supplemental Material [15]. We see in Fig. 4(a) the edges

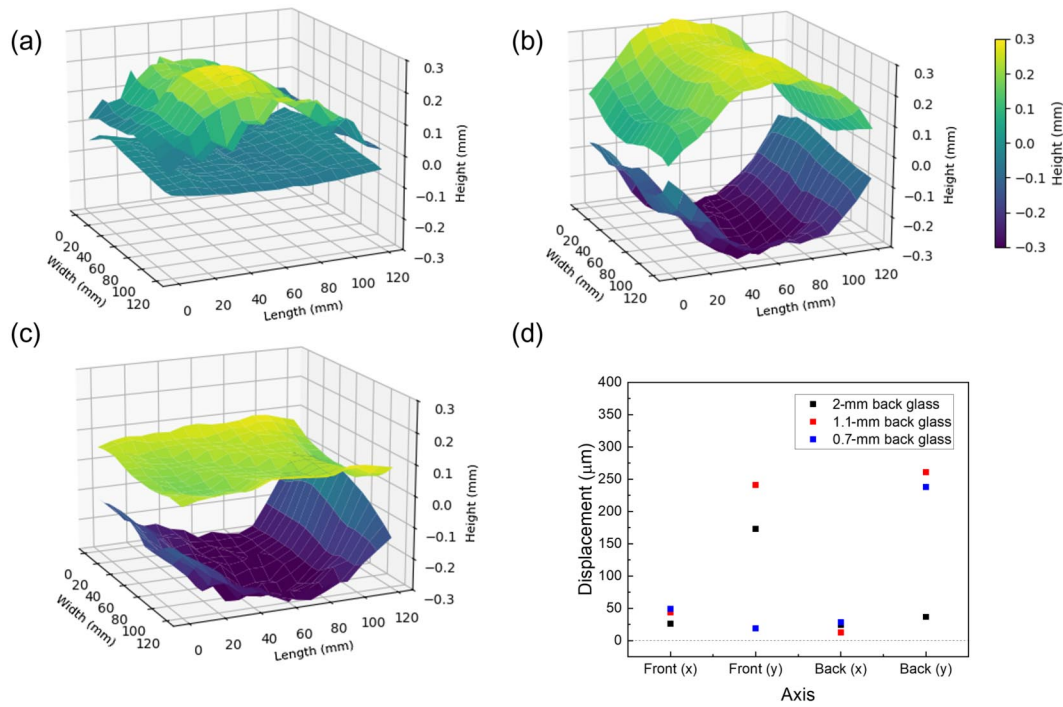


FIG. 5. Varying back glass thickness from (a) 2 mm, (b) 1.1 mm to (c) 0.7 mm to shift the neutral axis upwards. (d) Shows the 2D displacement values for the front and back glass for all three conditions on the same scale.

of the front glass are deformed in an asymmetric manner with a jig height of 2 mm and show dramatic displacement variations of $384\ \mu\text{m}$ in the x direction and $466\ \mu\text{m}$ in the y direction for the front glass. However, using a 3-mm jig height leads to less pressure on the edges and more on the center of the module as depicted in Fig. 4(b). The displacement of the front glass slightly reduces to $188\ \mu\text{m}$ and $315\ \mu\text{m}$ for the x and y axis respectively. The curvature is lower when we use a 5.1-mm jig height because our module is of comparable height with the jig which helps distribute pressure more evenly pushing the encapsulant and PIB to an equilibrium level. We measured front glass displacements of $115\ \mu\text{m}$ and $78.5\ \mu\text{m}$ for the x and y which is also evident in the much flatter 3D displacement plot in Fig. 4(c). Figure 4(d) makes the contrast between the front-glass displacements much more apparent and shows how the jig height is inversely proportional to the measured curvature value. After determining these effects from the encapsulant, we next set out to study how tuning the glass thickness plays a role in curvature.

3. Neutral plane engineering: Back glass thickness

In all the packages tested so far, the front and back glass differed in thickness (1.1 and 2 mm respectively) and the neutral axis—the point at which bending is symmetric—was located within the back glass itself. As such, we consistently observed a less bowed back glass regardless of the encapsulant volume and jig height. Our goal was to reduce the curvature on the front glass since this is where

the perovskite is located. As such, we explored the effect of moving the neutral plane toward the front glass by reducing the back glass thickness. With a 2-mm-back glass, the neutral axis is below the front glass, and this is where the bending of the module is centered when the pressure is applied as depicted in Fig. S12 in Supplemental Material [15]. This leads to a bigger force acting on the front glass, resulting in a larger measured curvature which was $26.2\ \mu\text{m}$ in the x direction and $173\ \mu\text{m}$ in the y direction, as seen in Fig. 5(a). Whereas, when we used a symmetrical configuration using a back glass of the same thickness as the front glass, the front and the back glass bowed by equal amounts, and there was a convex shape seen on both sides with displacement values of up to 241 and $261\ \mu\text{m}$ in the front and the back glass. The corresponding 3D plot in Fig. 5(b) looks like the module is much thicker but because both the front and back glass experienced an identical force on them, they were both similarly convex. However, using a back glass that is thinner than the front glass (0.7 mm) shifted the neutral axis upward and into the front glass itself; hence, we saw a larger bowing effect in the back glass in Fig. 5(c). The displacement was 28.3 and $238\ \mu\text{m}$ in the back with a much flatter front of 49.2 and $18.9\ \mu\text{m}$ in the x and y -direction respectively. The jig height was lowered to 3 mm when we reduced the back glass thickness to maintain a uniform pressure transfer as identified in the previous section. We hypothesize the curvature values are larger in the y direction because of indium solder along the

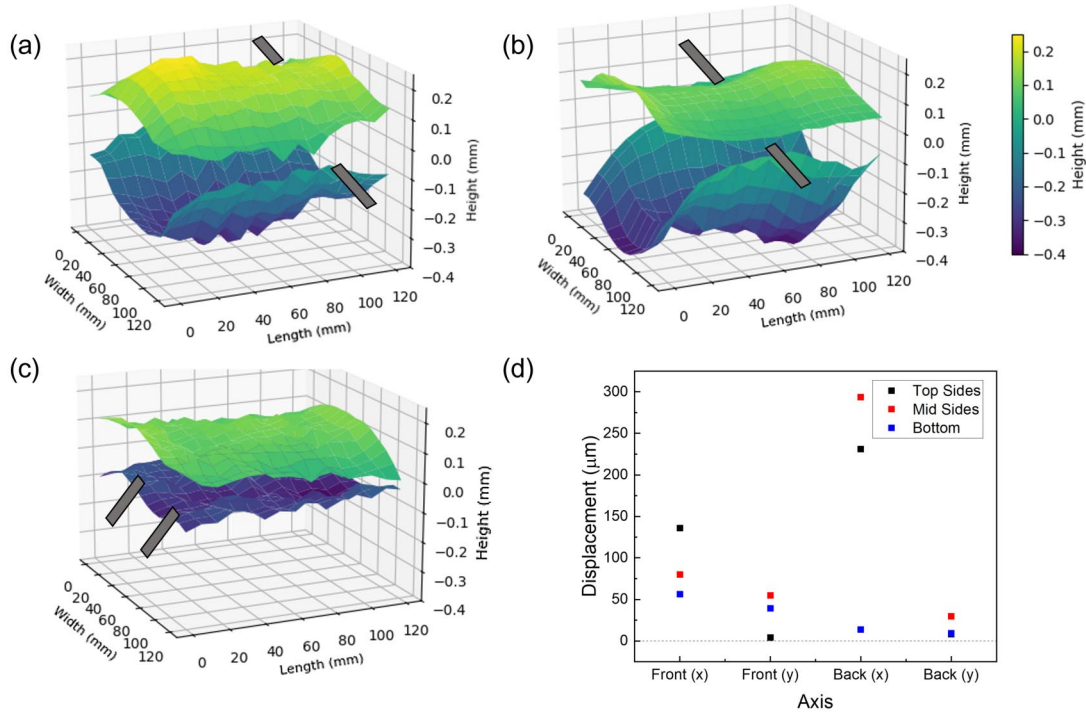


FIG. 6. Changing the placement of the ribbons from (a) top of the sides to (b) middle of the sides, and (c) bottom of the module affects the conduction of heat and hence the melting of the encapsulant (d) shows the 2D displacement values for the front and back glass for all three conditions on the same scale.

length-side edges of the module acting as an additional source of stress on the encapsulant and therefore the glass. This hypothesis motivated us to pursue our final variable to study how tuning metal ribbon design with its comparably high thermal expansion stiffness affects module curvature.

4. Package configuration: Busbar placement

Based on our observation that a thinner back glass with 0.7 mm thickness minimized the front-glass curvature, we continued with this design selection for the final set of experiments. From all the materials involved in the lamination process, the metallic ribbons have the largest thermal expansion stiffness which is a product of the Young's modulus and CTE, making it the largest material contributor within the package to thermal stress [25]. This combined material property is a measure of how resistant the material is to thermal expansion and can lead to more deformation in the surrounding layers. Since these ribbons are approximately 0.5 cm in width and only in contact with a small area of the package, their effect is localized. We soldered the ribbons to indium busbars on both sides of the perovskite module before lamination. When the ribbons are placed on the sides, near the top of the module, they lead to warping of the top edge and sides of the module due to the heat being conducted along the x direction as the module cools down. This resulted in displacement values of 136 and 4.24 μm in the front glass and 231 and 8.1 μm

in the back glass for the x and y axis, respectively, as shown in Figs. 6(a) and 6(d). Placing them in the middle can lead to even more warping and bloating in the middle of the package for the back glass with 294 μm displacement in the x direction was observed in Fig. 6(b). We discovered that having the ribbons come out of the bottom of the module resulted in the flattest packages because the effects from the thermal expansion stiffness of the ribbon are limited to the edge of the module. The front glass showed displacement values of 56.1 and 39.2 μm while the back glass was displaced by 13.7 and 9.22 μm in the x and y direction, respectively, and the 3D plot in Fig. 6(c) shows a very flat package.

Our studies found that several factors affect the glass curvature in a glass-glass laminated configuration. The knee-jerk response would be to link curvature changes to the lamination temperature and pressure settings; however, the displacement values have more to do with the mechanics of rigid bodies and heat transfer. The point of application of the force from the laminator, as well as the neutral axis of the stack, is important to consider in order to understand where the curvature comes from and how it is propagated. The conduction of heat within the module and how encapsulant bonding is facilitated is also a significant contributor to the flatness of the laminated package. As the module cools down, the metallic elements such as busbars and ribbons resist contraction due to their high thermal expansion stiffness, making the area around

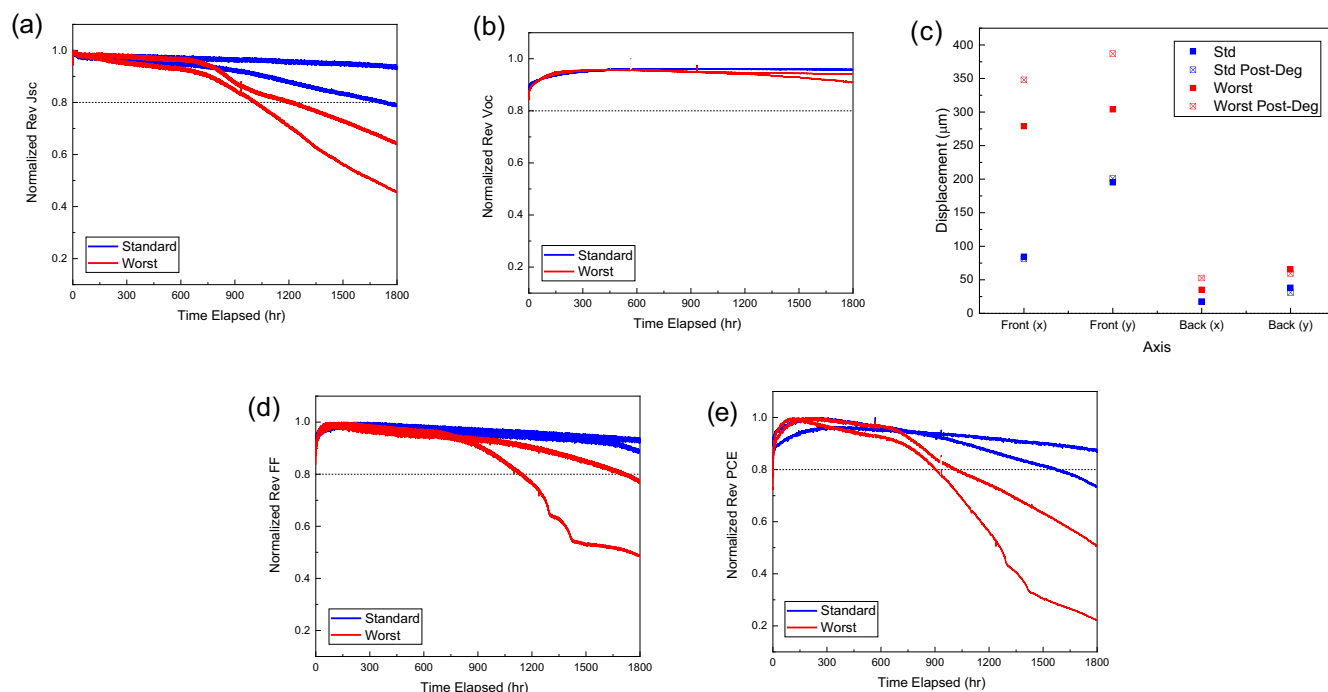


FIG. 7. Testing how the curvature affects stability of the perovskite module under ISOS-L2 at 65 °C by measuring (a) current density J_{sc} , (b) open-circuit voltage V_{oc} , (d) fill factor FF, and (e) power conversion efficiency PCE. The reverse scan parameters were normalized to their peak value. A standard and worst lamination recipe was used to produce “flat” and “curved” packages respectively with (c) their averaged curvature values before and after the degradation testing.

them shrink more leading to more warpage in the x direction. We identified four lamination parameters to be the most critical when it comes to minimizing the curvature of the front glass where the perovskite module is located:

- (1) Encapsulant volume: Tuning the amount of encapsulant to the jig height and edge-seal thickness prevented “bloating” of the module. Sufficient encapsulant is needed to ensure uniform bonding; however, adding too much encapsulant increases the curvature of the front glass.
- (2) Lamination pressure: The use of a jig or frame can prevent encapsulant from overflowing, and the jig height should be optimized so it is aligned with the glass-glass layup to ensure uniform pressure is acting on the front of the module and avoid the “pinching effect” where edges experience a larger force.
- (3) Neutral axis: Using thinner back glass relative to the front glass shifted the neutral axis upward and reduced the front-glass curvature.
- (4) Ribbon placement: The placement of the ribbons also affects how the encapsulant flows and cross-links leading to a change in the curvature. This can also have implications on a four-terminal tandem module where the silicon subcell facilitates conduction of heat throughout the encapsulated package.

To establish a link between module curvature and stability, we conducted accelerated aging on modules laminated using two conditions to generate either a curved or a flat module. This was to validate that cell failure happened much earlier for modules that had a significant curvature in the front glass. For the worst/curved (highest front glass curvature) lamination, we used a high temperature of 150 °C, 14 psi, encapsulant volume of 20 g, and a 3-mm jig for nonuniform pressure transfer to maximize the front-glass curvature. The standard/flat lamination condition included a recipe of 130 °C, 10 psi and 15 g of encapsulant and a 5.1-mm jig. We used a 2-mm-back glass for all laminations. The curvatures were measured for each of these modules and for the curved module, the front glass displaced by 279 and 304 μm in the x and y direction, whereas the flat lamination recipe resulted in a front-glass displacement of 84.3 and 195 μm in the x and y direction shown in Fig. 7(c).

We used the ISOS-L2 protocol which includes exposure to 1-sun illumination at 65 °C temperature and continuously logged the JV characteristics every 15 min using the setup described in methods. The curved module showed an initial PCE drop of 20% right after lamination due to the high lamination temperature but later recovered after a light soak as shown in Fig. S13 in Supplemental Material [15]. We used T_{80} or the time it takes for the module to drop below 80% of peak PCE as the standard for tracking failure; and the curved module started failing under testing

after 1000 h as seen in Fig. 7(e), while the flat module held up until at least 1800 h (one standard module did not cross T80). The loss of J_{sc} drives the PCE loss as seen in Fig. 7(a) where the value dropped below 80% in 1000 h for the worst-case recipe. The V_{oc} did not change much for either one of the lamination conditions, but the fill factor (FF) dropped at a faster rate for the worst recipe. Since there was no loss in V_{oc} [Fig. 7(b)] but a drop in fill factor (FF) [Fig. 7(d)], we posit that faulty top contacts due to possible delamination in the curved module drove the failure mechanism as opposed to increased bulk/surface recombination from degradation processes. Further support for the hypothesis of contact delamination/damage is in the J_{sc} loss following a pattern similar to that of PCE. Degradation testing exacerbated the curvature for the highly curved module and the displacement values increased for the front glass as seen in Fig. 7(c). There was only a nominal change in the displacement values for the flat module laminated using the standard recipe. This provides evidence that a highly curved package does affect the long-term stability of the module and although the high lamination temperature might have created some degradation pathways in the perovskite, delamination of the contacts/top layers was most likely due to the curvature and lead to edge-cell failure.

IV. CONCLUSION AND OUTLOOK

Our study was intended to establish a method to measure photovoltaic module curvature and also emphasize the importance of tracking it for long-term stability. We have developed a measurement protocol to quantify the curvature of a laminated module, which correlates with the film stresses imposed on the perovskite stack. Our results identify a correlation between module curvature and perovskite module stability through ISOS-L2 testing and thermal cycling. The flatter packages retained T_{80} for 1800 h under 1-sun at 65 °C and they also showed no damage to the top layers after 200 thermal cycles.

We also note that the method is generalizable and can also be used to measure the curvature of encapsulated single-junction or two-terminal perovskite-tandem modules or other thin-film solar modules (i.e., CdTe) at the m² scale. This opens an opportunity to use this technique as a screening tool for module durability and as a quality-control check during manufacturing to screen for early-stage failure detection.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement No. DE-EE0010502. The views expressed herein do not

necessarily represent the views of the U.S. Department of Energy or the United States Government.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

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