Movement of Cracked Silicon Solar Cells During Module Temperature Changes

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***Abstract*—Cracks in crystalline silicon solar cells can lead to substantial power loss. While the cells' metal contacts can initially bridge these cracks and maintain electrical connections, the bridges are damaged by mechanical loads, including those due to temperature changes. We investigated the metallization bridges that form over cracks in encapsulated silicon solar cells. Microscopic characterization showed that the crack in the silicon can immediately propagate through the metal grid, but the grid can maintain electrical contact once the load is removed. We also quantified the movement of the cell fragments separated by a crack as a function of temperature. Cell fragments are free to move diagonally and to rotate, so the change in gap across the crack during a temperature change varies along the length of the crack. In one sample, we showed that a 10 °C temperature change, causing a 2 µm increase in the separation of cell fragments, was sufficient to cause a reversible electrical disconnection of metallization bridging a crack.**

***Index Terms*—photovoltaic cells, metallization, materials reliability, materials testing, image processing**

I. Introduction

PV module packaging materials mechanically protect crystalline silicon solar cells. However, cells can crack during transportation, installation, and service [1]. Cracks can initially be bridged by the cells' metal contacts, allowing current to be collected from broken portions of cells. The initially small effect on performance can become severe when these bridges are damaged by mechanical cycling [2]. Mechanical cycling can include thermomechanical cycling, where the mismatch in coefficient of thermal expansion (CTE) of module packaging materials leads to movement during a thermal cycle [3].

Understanding and quantifying the relative movement of cell fragments is essential to predicting the progress of performance loss in a module containing cracked cells. In this work, we investigate the metal bridges that form across cracks in encapsulated solar cells and the movement of solar cell fragments that these bridges must accommodate.

II. Method

We studied four modules. Module A was a commercial module with 60 156-mm multicrystalline silicon cells. It had been deployed in a utility-scale system for approximately eight years. Modules B and C were single-cell mini-modules made using 156-mm commercial monocrystalline silicon solar cells. They were fabricated using 3-mm float glass, EVA encapsulant, and a PVF/PET/PVF backsheet. Module D was a small (100 mm by 50 mm), low-cost commercial module with a semi-rigid all-polymer package. All of the cells had a silver-based front metallization grid and an aluminum-based rear contact.

Module A was placed in an environmental chamber as its temperature was brought to 0 °C, 20 °C, and 40 °C. Through an aperture in the chamber wall, we collected an electroluminescence (EL) image at each temperature as the module was forward-biased to pass its nameplate I_{sc}.

The cell in module B was intentionally cracked after encapsulation. We used EL imaging to locate the crack and we extracted a sample of cracked cell from the surrounding packaging materials. We used scanning electron microscopy (SEM) to verify that the interior of the sample was free from cracks introduced by the extraction process. We then collected images of front metallization bridging cracks. We used a xenon plasma focused ion beam (FIB) to remove material and collected cross-sectional views.

Cells in modules C and D were unintentionally cracked at some stage of assembly or handling. After locating the cracks using EL imaging, we placed each module on a temperature-controlled stage and collected EL and reflection images from 20 °C to 80 °C on module C and 15 °C to 75 °C on module D. The images had resolution of 4.2 µm per pixel and covered an area of approximately 14 mm by 10.5 mm.

Two-dimensional digital image correlation (DIC) was used to track the movement of features in the reflection images as a function of temperature. DIC has previously been used to measure the movement of solar cells (with a speckled pattern applied) inside a PV laminate [3]. We applied no artificial speckle pattern to the target objects, instead tracking only the native texture of the solar cell front metallization using open-source DIC software [4]. After performing a full-field DIC analysis, we assigned the tracked points to either the upper or lower cell fragment. At each temperature, we derived a similarity transformation to describe the translation, scale, and rotation of each fragment separately. By applying these transformations at the location of the crack, we calculated the relative change in the distance across the crack as a function

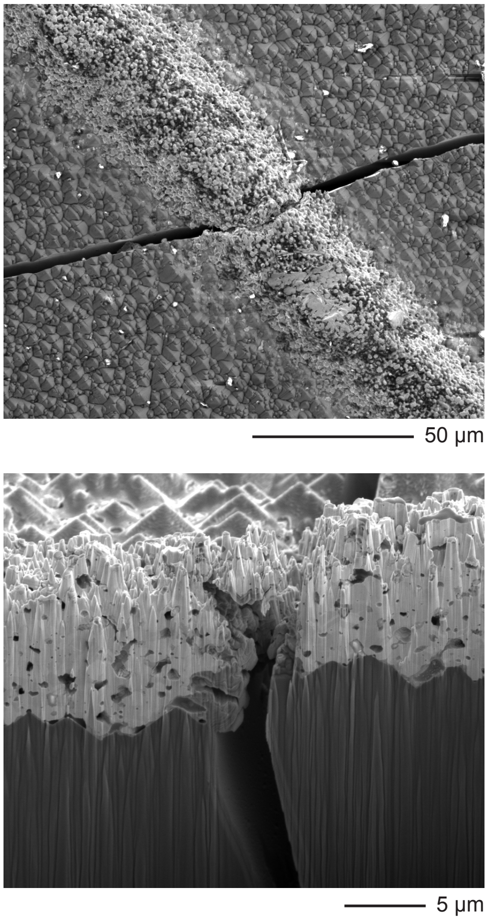

Fig. 1. SEM images from a solar cell that was cracked and then removed from module B. The images show a line of silver metallization (top) bridging the crack and a cross-sectional view of the same line (bottom). While there is little or no visible contact, this line continued making electrical contact after the crack was formed.

of temperature.

To confirm the displacements measured on multiple grid lines at once, we examined a single grid line with 0.2 µm per pixel resolution at 20 °C and 80 °C. This pair of images was compared by fitting a pair of similarity transformations to corresponding keypoints from above and below the crack.

III. Results and discussion

Fig. 2 shows EL images of a single cell in module A as a function of temperature. Selected areas of temperature-dependent disconnection at cracks are highlighted. The horizontally streaked appearance of these areas shows that individual front grid lines have been disconnected. It has been shown that the aluminum back contact (not the silver front grid) controls the degradation of contact across a crack in a module subjected to artificial mechanical cycles [5]. Our results show that this is not universally true and that, in the case of our field-weathered module, front silver grid is controlling the loss of contact.

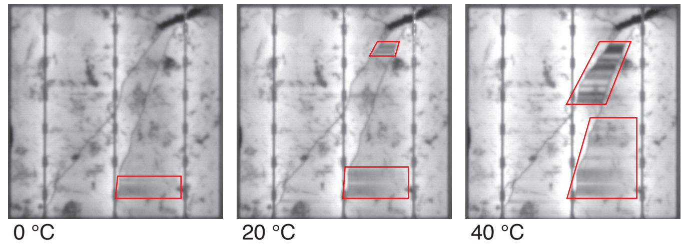

Fig. 2. EL images of one cell in module A are shown as a function of temperature. Selected areas with temperature-dependent disconnected front grid lines are highlighted with red boxes.

Fig. 1 shows SEM images of one of the metal lines crossing a crack in module B. EL images showed that the line continued making electrical contact even after the formation of the crack, despite the crack having propagated from the silicon through the silver line. This suggests that a crack can immediately sever a metallization line, which can then reestablish contact when the load is removed. The images also show that the crack was not fully closed at room temperature and contained some debris that may have been responsible for holding the crack open. Future models of damage and failure of metallization at cracks may need to consider these effects.

The displacements across the crack in module C are illustrated in Fig. 3 and plotted in Fig. 4. As the module packaging materials expanded and softened at high temperatures, the cell fragments moved apart. The fragments shifted diagonally and rotated slightly relative to each other as they moved apart, so at elevated temperature the relative separation between the fragments varied along the length of the crack. Maximum total displacement across the crack at 80 °C, relative to 20 °C, varied from 4 µm to 2 µm in the region we studied. EL images showed that there was no electrical continuity across this crack at any temperature.

Higher-magnification reflectance images of the crack intersecting the grid line at the center of Fig. 3 are shown in Fig. 5. These images show the same movement, with substantial components both parallel and perpendicular to the grid line, that was derived from the larger-field images. Relative displacements across the crack, computed from these higher-magnification images, are plotted using circular markers in Fig. 4 and show close agreement between the two techniques.

Results from testing on module D, the specimen with all-polymer packaging, are shown in Fig. 6 and Fig. 7. As with module C, the expansion of the module packaging materials at elevated temperatures pulled the cell fragments apart. Diagonal and rotational movement led to displacements that varied along the length of the crack. Because of the much higher CTE of polymers compared to glass, the displacements were approximately five times larger in module D than in module C. Maximum total displacement across the crack at 75 °C, relative to 15 °C, varied from 11 µm to 19 µm in the region we studied.

The EL images in the right column of Fig. 6 illustrate that the movement of broken cell fragments during thermal

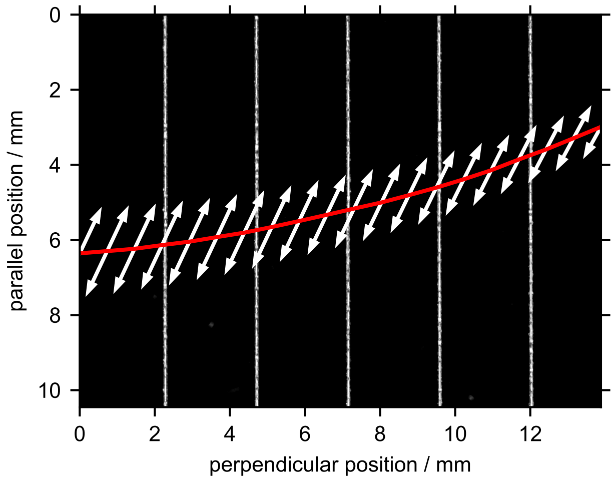

Fig. 3. A reflection image of module C, with the crack highlighted in red. The relative movement between the cell fragments from 20 °C to 80 °C is shown with white arrows that are each magnified by 500×.

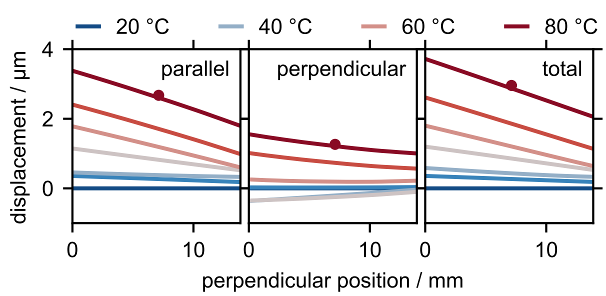

Fig. 4. Measured displacement across the crack in the cell of module C, relative to the 20 °C state, is plotted for different temperatures. The components of displacement parallel (left) and perpendicular (center) to the metallization lines and the total (right) displacement are shown. The circular markers show the displacement measured across a single grid line using a higher-magnification view.

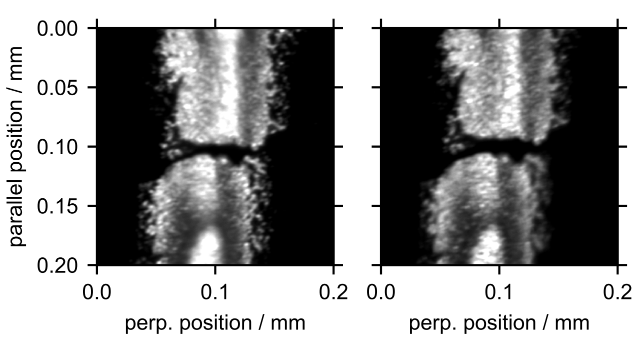

Fig. 5. Reflection images of a single grid line crossing the crack of the cell in module C at 20 °C (left) and 80 °C (right). The shift between the cell fragments is visible, with substantial displacements both parallel and perpendicular to the grid line.

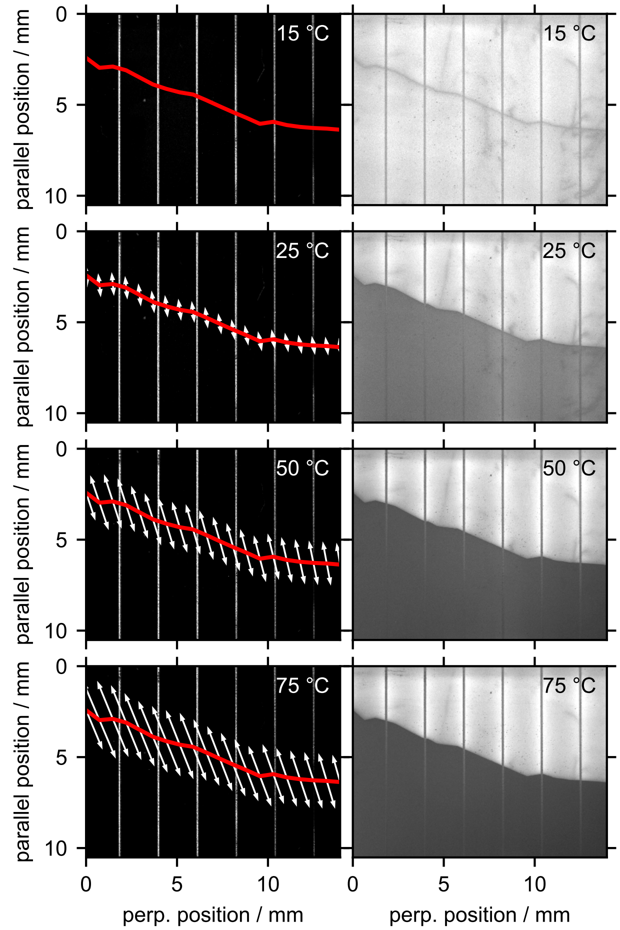

Fig. 6. Reflection images (left) and EL images (right) from module D. The crack is highlighted on the reflection images in red. The relative movement between the cell fragments from 15 °C to 75 °C is shown with white arrows that are each magnified by 200×. The EL images show that the movement of cell fragments causes electrical disconnection of the metallization bridging the crack. The brightness of each EL image has been uniformly adjusted to highlight this change.

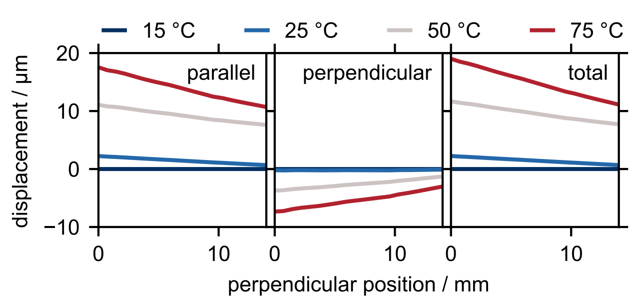

Fig. 7. Measured displacement across the crack of the cell in module D, relative to the 15 °C state, is plotted for different temperatures. The components of displacement parallel (left) and perpendicular (center) to the metallization lines and the total (right) displacement are shown.

expansion was responsible for the loss of electrical contact in metal lines bridging the crack. This disconnection became apparent beginning at 25 °C, where there was a maximum total displacement across the crack, relative to 15 °C, of only 2 μm. At the stage of damage present in module D, this disconnection was reversible and we repeated it several times. This reversible disconnection can also occur in conventional, glass-based PV module packages.

IV. Conclusion

Cracked crystalline silicon solar cells can lead to reduced PV system power output. Metallization lines that initially bridge the cracks are damaged by mechanical and thermomechanical cycling. We showed that a crack in silicon can immediately propagate through a metal line. Initially, the cracked metal line re-established electrical contact when the load was removed. We also measured the movement of cracked cell fragments inside of PV modules as a function of temperature. As temperature increased, these fragments shifted and rotated. The resulting increase in the gap across the crack varied along the crack's length and had substantial components both perpendicular and parallel to the metallization lines. On the areas we examined, a 60 °C temperature increase caused the gap across the crack grow by up to 4 μm in a glass-based package and up to 20 μm in an all-polymer package.

Predicting the increase in power loss due to cracks over time is not currently possible. Future efforts to this end will rely on models of the accumulation of damage to metallization lines bridging cracks. This damage accumulates as a result of relative movement of cracked cell fragments. In this work we have quantified this movement as a function of temperature for the first time, using techniques that can easily be applied to large-area commercial PV modules

Acknowledgment

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

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 Number 34357.

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