Presented at the 46th IEEE Photovoltaic Specialist Conference, June 18 2019, Chicago

Electroluminescence-Testing Induced Crack Closure in PV modules

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Abstract — **Electroluminescence (EL) measurements of PV modules with cracked cells have showed some open cracks to close arbitrarily from day to day even though these modules are stored in a controlled, stressor free laboratory environment – constant temperature and no mechanical load. We have found that variations in current and temperature generated from resistive heating during EL measurements strongly influence crack closure. Because crack closure can lead to some gain in maximum power, we consider the ramifications for IEC standards, namely that performing EL measurements before I-V measurements may lead to inflated results.**

Index Terms — **Electroluminescence, Current measurement Current-voltage characteristics, Solar Panels, Photovoltaic cells, Waste heat, Heating, Thermal expansion, Stress, Strain.**

I. Introduction

Crack opening and closure in silicon solar cells is a complex and sometimes reversible process. It is generally understood that environmental stressors such as wind loading and snow loading can not only create cracks but also cause them to open over time leading to power degradation as sections of encapsulated solar cells become detached from the power generation circuit [1]. Since the flow of current is stopped at the boundaries of these detached areas (open cracks), they remain dark during EL measurements [2].

On the other hand, EL imaging studies have also showed that some open cracks can close during temperature cycling from -10°C to 85°C while others remained open. Oddly enough, these cracks remained closed when cycling the temperature back from 85°C to -10°C [3]. Furthermore, even without a significant change in the ambient temperature, many research groups and testing labs have observed cracks shifting from open to closed in EL images taken a few days apart. Minute mechanical loads or vibrations produced during module handling have been considered as a potential reason for these seemingly random crack closures.

In addition, we have previously reported on similar unstable behavior of cracks during mechanical loading using the *LoadSpot* tool [4]. Right after a front side load was applied and removed, EL images captured some cracks closing although the overall trend showed crack opening due to the tensile stress generated from the bending. Alternatively, some closed cracks opened after a positive pressure cycle producing compressive stress although the overall trend did show crack closing.

Because these fluctuations in the state of cracks can affect the module maximum power, this work seeks to identify contributions from the electroluminescence test itself to crack instability and implications for standard reliability testing.

II. Experiment

To understand the effect of EL imaging on cracks, we use three monocrystalline 60-cell modules, which are initially without cracks. Our experimental setup includes a Sinton Instruments FMT-350 tunnel simulator for IV measurements used in combination with an integrated mechanical load tester and high-resolution EL camera system from BrightSpot Automation. The *LoadSpot* mechanical load tester performs standard IEC static and cyclic mechanical loading sequences using vacuum and air pressure, leaving the front surface of the module unobstructed to enable both I-V characterization and EL imaging during loading.

We started by obtaining EL and IV data on all three modules before creating cracks using a static front side load of approximately 4000Pa. This load was chosen for this specific module under test in order to obtain > 50% of cells cracked while minimizing the number of cracked cells that would completely shatter. We then performed both EL (at 0.1*Isc and 1*Isc) and IV measurements at 0 and -1000Pa. Next, to start opening cracks, we subjected each module to 1000 cyclic loads (7cycles/min) at +/-1000Pa load amplitude according to the IEC 62782 standard. We took IV and EL measurements at 0Pa and -1000Pa loads every 200 cycles. Last, we exposed all three modules to 50 Thermal Cycles (TC50) and 10 Humidity-Freeze cycles (HF10). Fig. 1 shows the state of the cracks after TC50 and HF10 for the three modules.

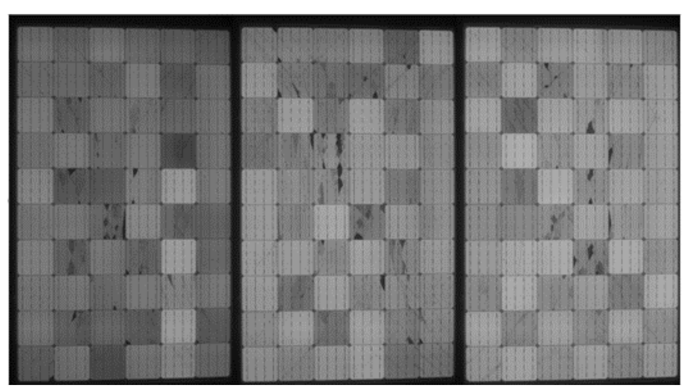

Fig. 1. Low current EL images of modules under test taken after static loading, cyclic loading, and TC50/HF10, showing a large number of open cracks

TABLE I
SUMMARY OF EXPERIMENTS

Experiment 1 *60-cell module* ***EL current***	**Experiment 2** *60-cell module* ***No current, Heating***	**Experiment 3** *60-cell module* ***Photocurrent, Heating***	**Experiment 4** *60-cell module* ***Brace, Cont. EL current***	**Experiment 5** *60-cell module* ***Brace, EL current***
			1. EL @ 0m, 20.6°C	
1. EL @1A, 30s, 25°C	1. EL @1A, 30s, 25°C	1. EL @1A, 30s, 25°C	2. EL @ 03m, 24.1°C	1. EL @1A, 30s, 25°C
			3. EL @ 07m, 28.0°C	
2. EL @ 9A, 10s, 25°C	2. **Outdoor,** *Open-circuit*	2. **Outdoor,** Short-circuit	4. EL @ 14m, 31.6°C	2. EL @ 9A, 10s, 25°C
			5. EL @ 23m, 33.9°C	
3. EL @ 1A, 30s, 25°C	3. EL @ 1A, 30s, > 40°C	3. EL @ 1A, 30s, > 40°C	6. EL @ 33m, 35;0°C	3. EL @ 1A, 30s, 25°C
			7. EL @ 43m, 35.3°C	

According to the methodology described in the literature [5], the state of the cracks can be determined by making low current EL measurements at about 10% of the short-circuit current Isc. Additionally, low current measurements do not heat up the cells and therefore do not affect cracks.

In order to explain the effect of EL testing on open cracks, we compare low current EL images obtained before and after a relevant stressor typically experienced during module testing. In this work, the two main stressors of interest include current and temperature. We seek to understand both their individual and combined effects. Thus, experiment 1 considers the effect of a brief (10s) but high current (~Isc) representative of a standard EL measurement. Because the current is brief in time, the measured module temperature does not change significantly (≤ 1°C). As a result, the current is expected to be the main contributor to any changes. Experiment 2 seeks to determine the effect of temperature alone. Therefore, in between the low current EL measurements, the module is heated up outside in the sun while in open-circuit, preventing current flow. The combined effect of increasing module current and module temperature is examined in experiment 3 by placing the module outside in the sun again but this time in a short-circuit configuration with a high photocurrent current flowing. This will help us determine whether placing the modules under illumination, which are regular operation conditions for PV module operation in the field, also causes cracks to close. Experiment 4 is the indoor and alternative to experiment 3 and consists of pumping a high forward-bias current into the module for an extended period of time while relying on resistive heating to heat up the module from room temperature to near the nominal operating cell temperature (NOCT). Last, in experiment 5, we investigate this effect of EL testing on a cracked module retrofitted with a backside brace that presses strongly on the backside on the module. Because there is a compressive force on the cells forcing open cracks to close up [6-7], one might expect that standard EL testing will have little effect on the state of the cracks, especially at the center. Table 1 shows a summary of the experiments. Likewise, the module used in experiment 4 also has a backside brace.

III. RESULTS

The results for Experiment 1 are matching for all three modules. After a high-current EL measurement at ~Isc for 10 seconds, most of cracks in the low-current EL images below that were initially partially open (darker gray areas) are now more closed (lighter gray area) although the module temperature remained essentially constant (±1°C). Fig. 2 depicts that result for one of the modules. This indicates that high currents play a role in EL testing induced crack closure.

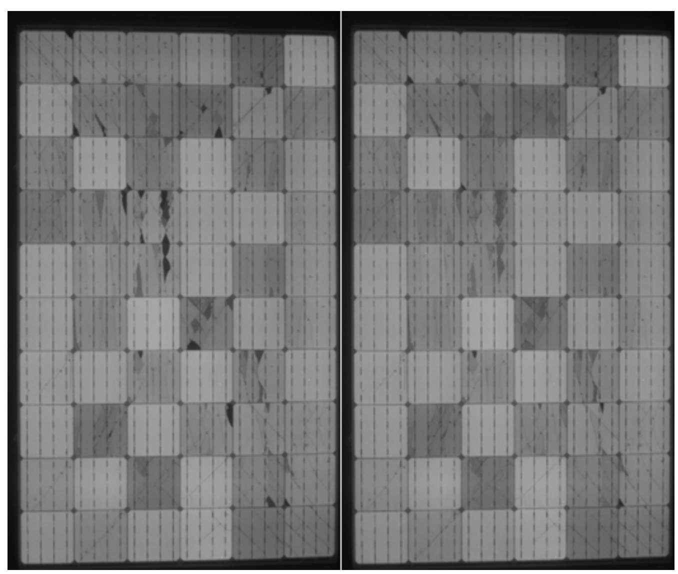

Fig. 2. **Experiment 1**: Low current EL images before (left) and

after (right) a single high current standard EL measurement at 9A for 10 seconds at 25°C.

In experiment 2, we manage to change the temperature of the module without high-current flow by putting the module outside in an open-circuit configuration. In this instance, we did not observe any of the cracks closing as shown in Fig. 3. This result seems to suggest that the module temperature alone (without high current flow) is not a critical factor in EL testing induced crack closure. Cracks seemed to open further. A similar dependence of EL images on temperature was recently reported at the 2018 NREL Module Reliability Workshop [3].

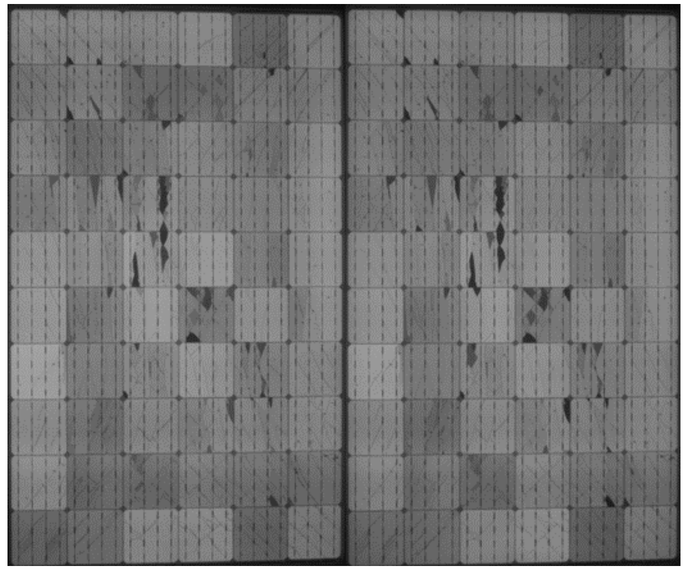

Fig. 3. **Experiment 2**: Low current EL images before (left) and after (right) outdoor exposure while in *open-circuit*. Temperatures above 40°C were reached.

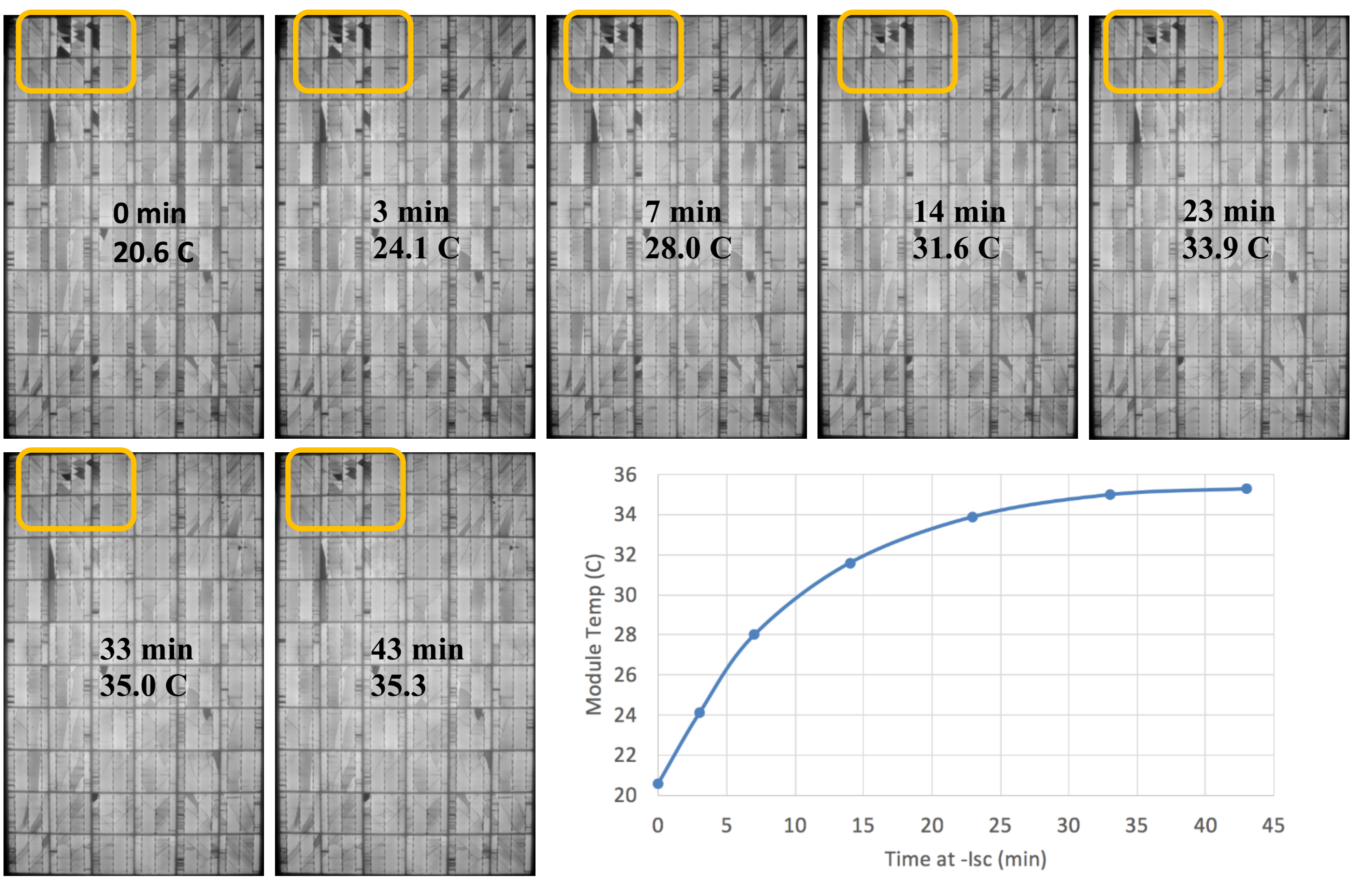

Fig. 5 **Experiment 4:** EL images taken during a continuous high *forward-biased current* for a period of 45 min. Temperatures above 35°C were reached.

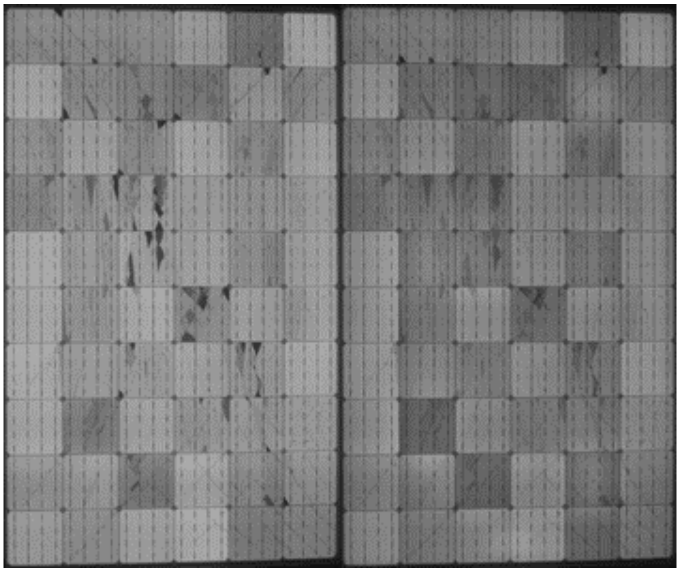

Fig. 4. **Experiment 3**: Low current EL images before (left) and after (right) outdoor exposure while in *short-circuit*. Temperatures above 40°C were reached.

Next, in experiment 3, the modules is exposed to sun while the connectors are shorted allowing for current flow. These results are presented in Fig 4. In this instance, we module heats up due to both the radiation from the sun as well as resistive heating. Under these conditions, open cracks were observed to partially close. Additionally, we obverse a slight darkening of the EL images after the outside exposure due to an increased module temperature, which in turn reduces the voltage drop across the cells. Because the EL intensity is directly proportional to the voltage, the image looks darker.

Fig. 5 shows the results for experiment 4. In this case, a continuous forward-bias 9A current is applied to a module with a backside brace, and the temperature is measured versus time using an IR thermometer (Etekcity #774) pointed at the center front side of panel. The measured temperature reaches 35°C due to resistive heating alone. The backside brace puts the cells in compression and therefore partially closes open cracks except at the edges. In the area enclosed in the orange square, where the influence of the backside brace is lowest, the EL images (taken with a 24-megapixel BrightSpot EL camera system) show that open cracks are closing over time. The temperature reached is still lower than NOCT in the field.

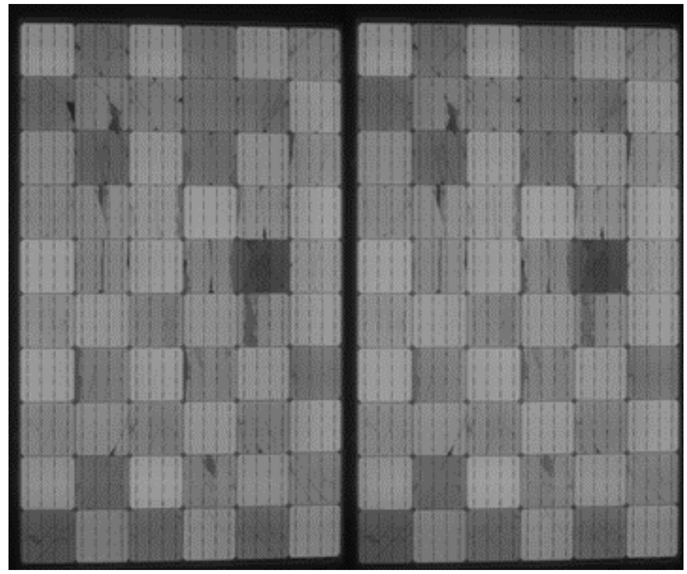

Fig. 6. **Experiment 5**: Low current EL images before (left) and after (right) a single high EL measurement at 9A for 10 seconds at 25°C. The module was mounted with a *backside brace* before cyclic loading and environmental chamber testing.

Last, experiment 5 allows us to investigate how much additional crack closure a module with a backside brace would experience during a standard high-current EL testing for few seconds. The initial low-current EL image on the left in Fig. 6 shows an improvement due to the brace with many cracks showing a mid-gray shade as opposed to normally much darker shades without the brace. The final low current EL testing on the right in Fig. 6 shows in general no significant changes in the state of the cracks with few exceptions. The first cell (left most) in the second row from the top completely closes; this is can explained by the fact that the pressure from the brace is mostly affecting cells at the center of the module where the pressure is higher as opposed to cells on the outer edges. Two other cells (row 6 & column 5 or row 9 & column 4) although not being on the outer edges experience slightly lighter shades after the EL imaging, signifying that cracks are closing a bit more even in the presence of the compressive force from the brace.

IV. Analysis

The experiments can be placed into one of the following groups in order to make the distinction between the heating mechanisms involved and the areas affected.

A. Heating just the metals with a current

From experiments 1 and 5, a standard EL measurement with a current injection level of approximately Isc for a short duration of approximately ~10s does not generate a measurable change in the overall module temperature. However, open cracks are partially closing as a result. This is observed in low-current EL taken before and after the standard EL measurement. This leads us to believe that during standard EL measurements, transient thermomechanical effects from resistive heating mostly localized to the encapsulated solar cell are responsible for the closing of the cracks. Furthermore, from experiment 5, a standard EL measurement at high-current injection levels has very little influence on the state of the cracks at the center of the module due to the backside brace. With the application of the backside brace, most of the cell already experience a large enough compressive stress causing open cracks to close partially at the outset. Only cells toward the edges might experience a further minor change to a lighter shade where the compressive stress is reduced. A standard EL measurement seems to have an effect comparable to a temporary compressive load on the encapsulated cell. These cracks were observed to take couple of days to reopen.

B. Heating up the whole module with a current

Experiment 4 provides similar results at the center of the module where the partially closed cracks due to a backside brace remained unchanged. However, in this case, a large forward-bias current is applied, not for just a few seconds, but continually for more than 45 minutes. This causes the overall temperature of the module to increase continually up to 35°C. The continuous current produces large resistive heating that is no longer localized only to the encapsulated solar cell. The temperature of the glass, EVA, and backsheet are also increasing significantly. Many open cracks inside one of the cells at the edge, where the compressive stress is smaller, gradually close up as the panel warms up. Crack closure seems to be more related to the change in the overall module temperature. One possible explanation relates to the EVA becoming less stiff at higher temperature, which in turn allows thermomechanical effects from the resistive heating to produce larger movement due to the expansion of the metals at a given current injection level, thus allowing the cracks to further close in the metals.

C. Heating up the whole module using the ambient temperature as well as the metals with a current

The explanation in the previous section (IV.B.) can also help understand Silverman's results [3] obtained at high and low-current injection levels as the ambient temperature was ramped to up 85°C. The EVA is increasingly less stiff, allowing thermomechanical stresses from high-current measurements to cause the metal to expand further with the increasing temperature and thus to continually close cracks. Going from high temperatures to low temperatures does not change the state of the crack since additional high-current measurements during ramp down are keeping these cracks closed. Additionally, going from 85°C to -10°C in just a few hours puts the encapsulated cells in a higher compressive state as the entire module bends towards the backsheet, effectively freezing the cracks in a closed state. We observed such temperature-dependent out-of-plane displacement in modules installed in the field when subjected to daily temperature cycling between daytime and nighttime [1]. Thus, low-current EL images do not show an opening of the cracks in the course of decreasing temperatures.

Additionally, experiment 3 combines both high current and an increase in the overall module temperature. Based on our current understanding, these conditions would result in crack closure. This is exactly what the low-current EL images taken before and after sun exposure while in short-circuit reveal (connectors are shorted allowing a large current to flow).

D. Heating up the whole module using only the ambient temperature

Similarly, although the overall module temperature changes from 25°C to 45°C in experiment 2 from being exposed to the sun while in open-circuit, low-current EL images before and after sun exposure did not result in much crack closing, but rather crack opening. The low-current EL measurement did not produce enough thermomechanical stresses to overcome the open cracks for the given EVA stiffness at 45°C.

V. Finite Element Model

To confirm our understanding, we created a model using Abaqus unified FEA platform from SIMULIA of a coupon comprising glass, EVA encapsulant, a silicon wafer with an aluminum BSF layer, three Cu ribbons on top and bottom of the solar cell, and a backsheet. The moduli of elasticity for both the EVA and the backsheet were defined to be temperature-dependent. To mimic the case of a 60-cell module, we introduced a 3A current of at one end of each ribbon connected to the aluminum BSF layer, for a total of 9A. The current is then exiting on the other side of the solar cell at the opposite ends of the ribbons. A potential of 0V (ground) is applied to the electrode on the n-type region of the device. This corresponds to the forward bias condition experienced during EL imaging. The ambient temperature was set to 25C and indoor wind speed set to less than 0.3 m/s. This value is within the targeted range of 0.1–0.3 m/s for indoor air speed usually implemented in buildings according to the ISO7730 standard for ergonomics of the thermal environment. We then estimated the heat transfer coefficient between the coupon and air to be 15.7 W/(m^2·ºK) based on Romary et al [8]. Because the Abaqus solver is limited to only to a basic Joule heating model for heat generation, it is inadequate for P-N junctions, which involves numerous thermal processes other than Joule heating. Anyhow, we are working under the assumption that if we are able to match the thermal profile that the coupon experiences during normal operation, then we can generate accurate thermomechanical stress/strain fields as well as displacements. Our approach to estimating the thermal losses in the silicon solar cell was to determine experimentally first the module steady-state temperature due to a constant high current, then set it as the target temperature for silicon in our model, and backsolve for the effective resistivity ρ. From experiment 4, we know the steady-state temperature of a module with 9.5A of current running continuously though it is about 35°C. Setting that cell temperature as a target for the silicon temperature in our coupled electrical-thermal-structural model, we were able to lock onto an effective resistivity for the silicon after several iterations. We found that an effective resistivity of 0.33 Ω-cm for the silicon layer produced the desired outcome.

Using this effective resistivity for the silicon layer, we consider two cases with transient currents more representative of EL measurements considered in this work. Because running these transient cases on the full coupon would dramatically increase the complexity of the problem, we opted for using a simplified structure consisting of just the silicon, aluminum, and the ribbons. The first case consists of a low-current EL test at room temperature (1A for 30s at 25°C). The second case consists of a high-current EL test at room temperature (9A for 10s at 25°C), Steady-state results are presented in Fig. 7.

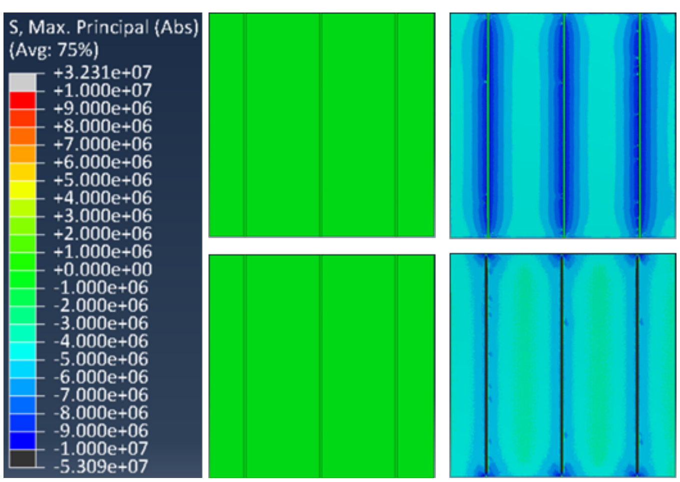

Fig.7. First principle stress map of a solar cell during EL imaging. (Top left) aluminum backside after 1A for 30s, (Top Right) aluminum backside after 9A for 10s, (Bottom left) silicon sun-side after 1A for 30s, and (Bottom Right) silicon sun-side after 9A for 10s. The compressive stress reaches up to 50Mpa for the 9A case while << 1MPa for the 1A case.

The results in Fig. 7 show significant compressive stress in the backside aluminum layer as well as the front side metallization and the front surface of the silicon layer after running 9A for 10s. The aluminum was found to expand 20µm in each direction within the XY plane (U_1 and U_2) from initial dimensions 156mm x 156mm to 156.02mm x 15.02mm. This is significant because the electrical functionality of the solar cell is primarily depending on the crack propagation through the metal, not the silicon [8]. If a cell was cracked right through its center resulting in two equal sections of dimension 156mm x 78mm, then based on the average strain produced from a 9A current for 10s, each section could expand by 5µm on either side of the crack and easily bridge a significantly wide crack.

Additionally, silicon has a smaller coefficient of thermal expansion and resists the expansion of aluminum; therefore, it causes the aluminum to experience compressive stress. At the boundary between the aluminum and the silicon, the opposite is true in the silicon, which experiences tensile stress. As the aluminum expands, it also causes the cell to bow in a concave manner toward the sunny side. On the other side of the neutral axis at the top of the silicon, the silicon experiences compressive stress due to the bend. The bend produces a total out-of-plane displacement (U_3) from the center to each corner of approximately 2.58mm. Such large displacement is capable of generating significant movement and causing the metals to reconnect.

Furthermore, the largest compressive stresses occur in the metals and reach up to 50MPa. We recently reported similar compressive stress levels in solar cells located mid-distance between the center and the edge in a standard 60-cell module subjected to a uniform backside 2000Pa load [6]. Such compressive stress was found to be large enough to close cracks successfully.

In reality, the cell is not freestanding, and the rest of the module materials will strongly limit the expansion of the aluminum and the bending of the cell. Therefore, these effects are expected to be smaller in the encapsulated case. Nevertheless, the results for the transient cases provide valuable insight into mechanisms leading to crack closure.

VI. Discussion

Most modules pass IEC qualification testing associated with mechanical durability, which requires no more than 5% power loss after the specified test sequence. One important question is whether a module that should have failed qualification testing instead passed because of electroluminescence-testing induced crack closing. To answer that question, we must assess how much power can be gained due to electroluminescence induced crack closing. The goal is to understand exactly how much power is gained due to this effect at STC (1000W/m^2). For the

EL measurements and IV measurements at STC, we used a Sinton FMT350 tunnel flash tester.

The testing sequence used to evaluate power gain due to closing cracks was:

1) Low-current EL measurement (1A for 30s)
2) IV measurement at STC (1000W/m^2)
3) High-current EL measurement (9A for 10s)
4) Low-current EL (1A for 30s) – verify crack closure
5) IV measurement at STC (1000W/m^2)
6) Compare Pmax obtained before and after EL measurements

Fig. 8 displays the maximum power Pmax obtained at STC. Pmax for two of the modules, module 1 and module 2, did not show much improvement. On the other hand, module 3 showed a gain of 2% or 5W absolute power. In fact, the IV curve of module 3 showed current mismatch. Under these conditions crack closure seems to affect Pmax even more. For modules 1 and 2, we suspect that the initial IV measurement at STC ran high enough current (multiple millisecond pulses with current higher than the short-circuit current at STC) to be able to close cracks and therefore mask this effect.

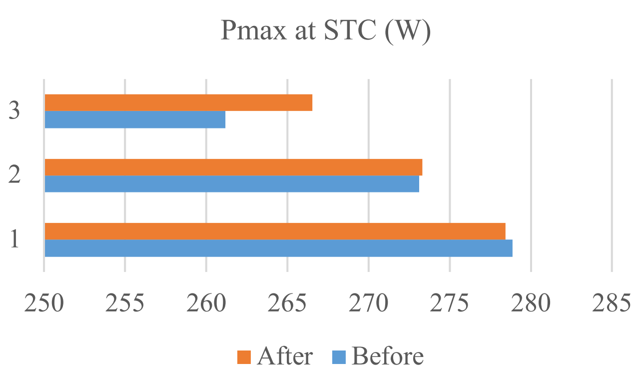

Fig. 8. Pmax before and after high-current EL testing for the three modules under test.

The improvement in Pmax of module 3 is proof that EL-testing induced crack closure can have implications for standard reliability testing of PV modules. If after IEC61215 certification testing, a panel is degraded by 6% when measured at 25°C, perhaps including EL testing before IV testing will bring the degradation down by 2% below 5%. The same argument could be made for temperature variations during testing. IV results of panels having cells with open cracks are also likely giving “worse” results at room temperature than they would if temperature-corrected for performance at higher temperatures. Since official IV testing allows for correction within a range of module temperatures (25C +/-2C), if a panel is degraded by 5.1% when measured at 25°C, conceivably testing at 27°C and correcting to 25°C might bring the degradation down below 5%. Therefore, modules with cracked cells may “benefit” by being tested at the upper allowable temperature. Standard testing protocols might need to be revised in order to prevent this effect from affecting pass or fail conditions. It is also our experience that EL-testing induced crack closure is a temporary effect. Days after the high-currents are removed and internal components of PV modules are allowed to cool back down to room temperature, cracks tend to open up again.

Beyond reliability testing of PV modules in the lab, there is the reality of the field. Experiment 3 in this paper includes the effect of the modules under illumination as in regular PV module operation in the field. A similar effect on open cracks as in the case of EL testing was observed. This crack “closure” effect happens on its own at high currents; this implies that laboratory test conditions at 25°C to be a worst-case scenario that does not typically happen in the field. Additionally, because EL testing is often performed at room temperature indoors or at nighttime, often below room temperature, much EL data is giving “worse” results than would be the case during typical panel operation. This emphasizes further the need to consider how IEC tests can be applied in a more consistent and reproducible way when testing modules with cracks.

VII. Conclusion

EL testing can cause open cracks to close partially, resulting in some power gain. The generated compressive stress in the metals because of Joule heating is between 50MPa, which can be large enough to close a crack. Performing EL testing at elevated temperatures also causes more cracks to close. Normal module operation in the field on a sunny day was also shown to close cracks. These results have implications for the standard reliability testing of PV modules with cracked cells. Standard testing protocols might need to be revised in order to prevent this effect from affecting pass or fail conditions, or at the very least to be applied in a more consistent and reproducible way. These results also have implications for academic research. When studying crack opening and closing, we need to be aware of this effect and try to test under similar temperatures and currents.

VIII. Acknowledgements

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 DE-EE0008152.

IX. Disclaimer

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