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Electrical recovery and fatigue degradation phenomena in cracked silicon cells

断裂硅电池中的电力恢复和疲劳退化现象

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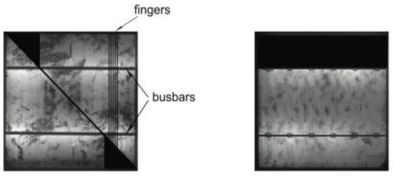
Abstract - **An experimental study based on the electroluminescence technique is herein proposed to demonstrate the existence of a coupling between mechanical deformations and the intensity of the electric field due to cracks in monocrystalline Silicon cells embedded in photovoltaic modules. In spite of the very brittle nature of Silicon, due to the action of the encapsulating polymer and residual compressive stresses resulting from the lamination stage, cracks experience crack closure and contact during mechanical unloading, partially recovering their original electric response. Crack propagation in case of cyclic loading, as, e.g., in the case of vibrations due to transportation and use, have also been reported for the very first time. The research results pinpoint the need of improving electric predictions based on the estimation of inactive cell areas since worst case scenarios not accounting for electro-mechanical coupling are too conservative.**

Keywords – **Photovoltaics, Cracks, Fatigue, Electromechanical coupling**

I. INTRODUCTION

Photovoltaic (PV) modules are supposed to have a lifetime longer than 20 years under the exposure to environmental conditions like temperature variations, wind vibration and snow pressure. Thermo-mechanical loads induce stresses into the components of the module, especially into the crystalline Silicon (Si) solar cells, which are affected by cracking [1-9]. Cracks on the millimetre or centimetre size are mostly invisible by naked eye but they can be localized according to the electroluminescence (EL) technique [10]. Such cracks can lead to electrically inactive cell areas, thus reducing the power output of the module. For instance, cracks inserted in solar cells by the application of a uniform pressure to simulate snow can lead up to 1.5% of power loss [3]. After the subsequent application of 200 humidity freeze cycles according to standard specifications [11], such cracks propagate, the electrically disconnected areas increase in size and up to 10% of power loss has been reported [3]. Potentially, if a crack crossing conductor (called finger) is sufficiently open, then the finger may fail and the electric flow to the busbar can be interrupted. Therefore, portions of Si cells can be potentially deactivated by cracks and their impact on power-loss reasonably depends on their inclination and position with respect to the busbars, see Fig. 1a,b. For instance, a crack parallel to the busbar on the upper side of the cell could lead up to 25% of electrically inactive area (Fig. 1b). According to this pure geometrical criterion which does not take into account neither physical mechanisms such as thermo-mechanical deformation, nor the fact that the cells are embedded in the composite PV module, worst-case scenarios have been predicted by considering all the experimentally detected [3] or the numerically simulated [8] cracks as perfectly insulated lines.



(a) 6% of potentially inactive cell

(b) 25% of potentially inactive cell

Fig. 1, Amount of potentially inactive cell areas depending on the orientation of the crack with respect to the busbars [3,8] (a,b).

In reality, it is reasonable to expect intermediate configurations where cracks may partially conduct depending on the relative crack opening displacement at crack faces. In analogy with the cohesive zone model used in computational fracture mechanics to depict crack growth in crystalline materials [12,13], where cohesive tractions opposing to the relative displacement of the crack faces are decreasing functions of the opening and sliding displacements, an electric flux dependent on crack opening might be postulated. A very

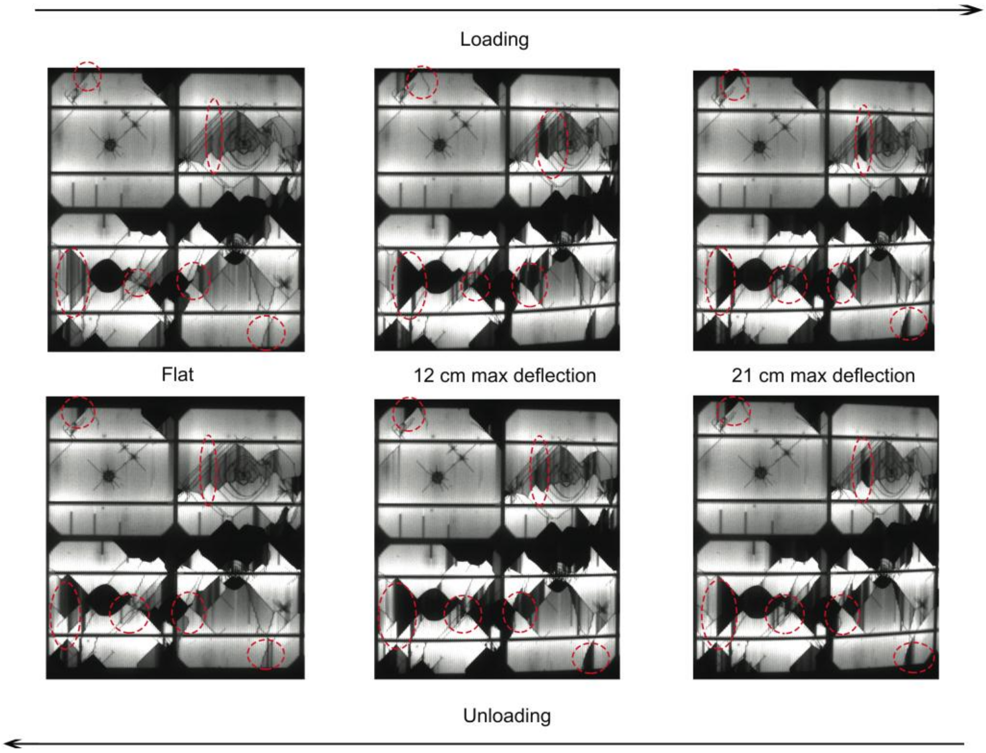


Fig. 2, Evolution of Electroluminescence (EL) signal during bending loading and unloading for different deflections.

preliminary experimental observation supporting coupling effects due to cracking regards the highly oscillating electrical response in time of a PV string containing a cracked cell, depending on the cell temperature [7].

II. EXPERIMENTAL TESTS

The evidence of coupling between thermoelastic and electric fields has important consequences from the modelling point of view. At present, electric models of solar cells do not consider this form of coupling induced by cracking.

In the most refined versions [14,15], a discretization of the solar cell is made in the plane and a two-diode model is applied to each node of the mesh to predict the electric response of the semiconductor. In case of hot spots, however, it was indeed necessary to modify the value of the series resistance in the nodes close to a crack. Hence, to achieve a predictive stage useful for power-loss predictions and durability assessment of PV systems exposed to environmental loads, series resistance values used as input of the circuit model should be related to the thermoelastic stress state in the solar cell.

To make an insight into this phenomenon, a three-point bending test with a mid-span displacement control on a rectangular PV module has been performed by monitoring cracking at different deformation levels by taking EL images. A semi-flexible module made of 2 columns of 5 monocrystalline Si cells (156x156 mm wide) is used. This type of module, which has a certain degree of flexibility, can be used in many applications where the substrate we would like to bond the module is curved. The partially symmetric arrangement of the layers through the thickness (0.265 mm of polyethylene terephthalate, 0.600 mm of epoxy-vinyl-acetate, 0.166 mm of Silicon, 0.400 mm of epoxy-vinyl-acetate and 0.345 mm of backsheet) leads to Silicon cells just above the neutral axis of the cross-section. Therefore, although large transversal displacements are imposed to the thin plate, tensile stresses inside Silicon are moderate and comparable with those experienced in classical PV modules under conventional bending tests. In those composites, having a thick glass cover (4 mm) and an unsymmetric structure, Si cells are much more distant from the neutral axis and therefore are subjected to a tensile stress state comparable with that simulated in the present test, in spite of the much lower inflections induced by environmental loads [4,8].

To create pre-existing cracks and study their evolution depending on the imposed flexure, moderate impacts have been made with PMMA balls of 4 cm of diameter at a velocity of 6 m/s. In this way, cracks are introduced by an indentation effect. The EL image of four solar cells in the middle of the panel and in the initial flat reference configuration is shown in Fig. 2. Location of impacts can be clearly distinguished by the circular dark spots from where diagonal cracks depart. These patterns are completely invisible by naked eye and can only be determined by the EL technique. Most of them are inclined at

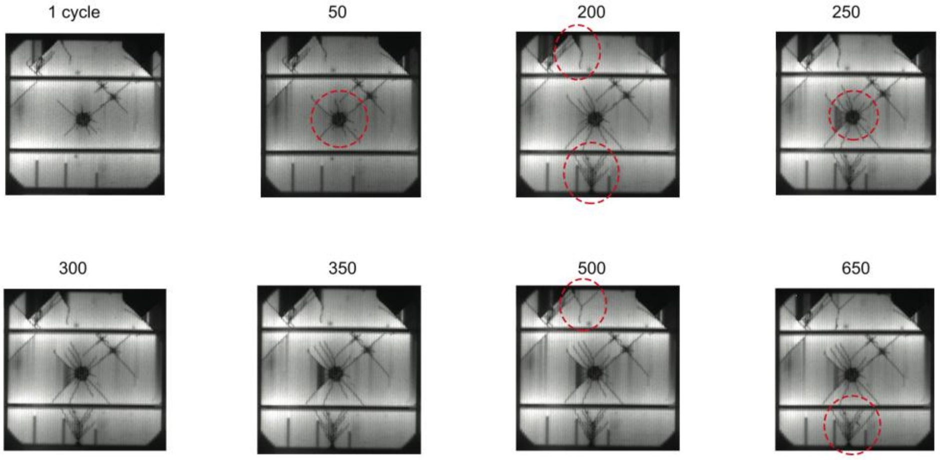


Fig. 3, Fatigue propagation of cracks, EL images at the maximum deflection point of the module (21 cm), for different loading cycles.

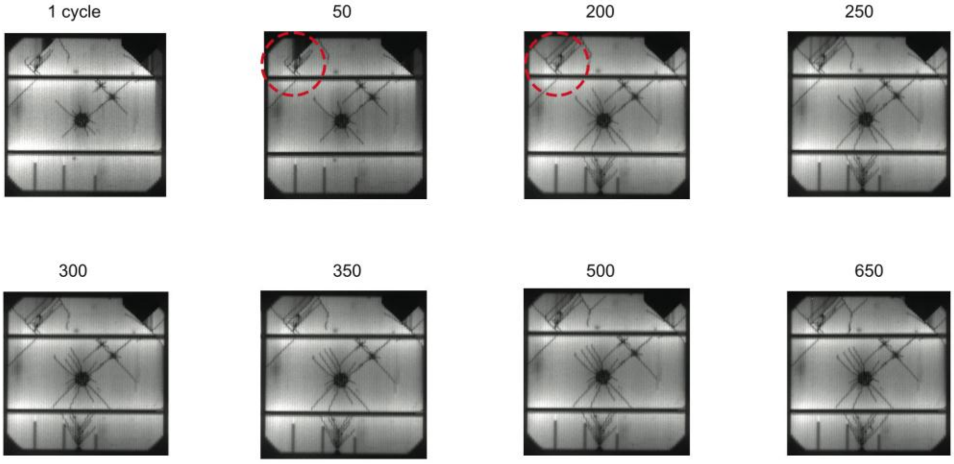


Fig. 4, Fatigue propagation of cracks, EL images of the unloaded configurations (flat, no deflection), for different loading cycles.

±45°, consistently with the 111 crystallographic plane of cubic face centred monocrystalline Silicon. In some cases, large electrically insulated cell portions, appearing as dark areas, are present. Other portions, circled with dashed lines, show regions isolated by cracks but still partially conducting from the electrical point of view. As expected, this can be explained by the fact that their crack opening is smaller than a critical value for complete electric insulation.

Due to a thermo-elastic mismatch between Silicon and the thermoplastic materials composing the module, a compression state in the cell is present in the unloaded configuration. This is the result of cooling down the module from the stress-free condition at the lamination temperature of 150 °C to the ambient temperature [16]. Finite element computations estimate a shortening of each cell of about 0.1 mm. Therefore, a tensile axial displacement of that amount is necessary in bending to open initially compressed cracks.

By increasing the bending deflection (upper row in Fig. 2, loading direction from left to right), cracks open and additional insulated dark areas appear, thus confirming that the electrical behaviour of cracks does depend on the elastic deformation. Very interesting is the unloading stage (lower row in Fig. 2, unloading direction from right to left), where cracks come into contact and conduct again. Hence, although globally the amount of damage is increased during the cycle since the final EL image is darker than before, an electric recovery phenomenon due to crack closure is reported.

III. FATIGUE DEGRADATION AND ELECTROMECHANICAL COUPLING

The evolution of degradation by increasing the amount of bending cycles (from zero to a maximum deflection of the module of 21 cm per cycle) has also been monitored and it is shown in Fig. 3, where EL images of a significant cell of the module have been recorded at the point of maximum deflection for 1, 50, 200, 250, 300, 350, 500 and 650 cycles. During the first 50 cycles we report a propagation of cracks around the dark central point of impact. Crack propagation further takes place from 50 to 200 cycles, with the appearance of new cracks from the lower border of the cell, originating from an edge crack. No crack propagation takes place from 200 to 250 cycles, although the EL intensity between diagonal cracks diminishes, thus implying a material degradation and a reduction of electric conductivity across the cracks. This trend continues further by increasing the number of cycles, with also further crack propagation (cycle 300) and coalescence of two propagating cracks (cycle 350). At 500 cycles, a new crack is originated from an initial one on the upper side of the cell as a result of a crack-branching mechanism. After the appearance of this new crack, the dark EL area just on the left of it becomes conductive again. This can be explained as the effect of the phenomenon of strain localization, popular in brittle materials, which corresponds to a stress relief in the surrounding cracks when a major crack propagates [12]. Therefore, with the appearance of a new crack, the previous one in the surrounding is relaxed and it experiences a reduction of its relative opening displacement.

The analysis of the EL images in the undeformed stage at the end of each set of cycles (Fig. 4) shows again the phenomenon of electrical recovery due to crack closure already noticed in the case of the first cycle. In these images, strain-localization can be noted by comparing EL images for 50 and 200 cycles, see the circled areas. The propagation of a diagonal crack to the left relieves the deformation in the Silicon area, the diagonal crack on the right experiences a reduction in crack opening and the EL image of Si above it becomes brighter.

A quantitative analysis of EL images can be performed by associating a value ranging from 0 to 1 to the grey-scale intensity of each pixel of the digital photo. Values of EL close to unity correspond to very bright Silicon areas, whereas values close to the opposite extreme are dark "electrically inactive" zones. Hence we can determine for each EL image the frequency histograms by computing the percentage of pixels with a given EL intensity with respect to the total number of pixels. At maximum deflection (Fig. 3), the histogram is particularly skew-symmetric, with a long tail for EL intensities less than 0.5 (Fig. 5). Moreover, although the difference between EL images by increasing the number of cycles is apparently marginal, i.e., only a few cracks propagate and some regions become darker, the EL histograms quantify the fatigue degradation trend. By increasing the number of cycles, in fact, the EL histogram shifts to the left. For high EL intensities, the pixel percentage is diminished by increasing the number of cycles. Exactly the opposite trend takes place in the low EL intensity range, i.e., more pixels become darker (Fig. 5).

IIII. Discussion and Conclusions

The experimental results herein presented show that, due to the encapsulation of Si cells into a ductile polymeric material, coupling between the electric response measured by EL images and the elastic deformation field takes place due to cracking. Therefore, the worst case scenario of considering all the detected cracks as perfectly insulated ones has to be considered with care, since more complex degradation phenomena occur in reality. In particular, we have shown the appearance of electrical recovery due to crack closure and residual thermo-elastic stresses, fatigue crack propagation, crack branching and crack coalescence, stress relief and recovery in the EL signal in case of strain localization induced by crack propagation of existing cracks or by new crack nucleation. It has to be remarked that all of these phenomena are impossible in stand-alone Si cells which are very brittle and display a different behaviour as compared to Silicon at the micro-scale, like that used for MEMS [17]. Therefore, modelling of Si solar cells behaviour by neglecting their embedding into a composite is meaningless in case of PV applications. Of course, this introduces additional complexity due to the very different size-scales and thicknesses of the various PV layers which require the use of multi-scale computational strategies.

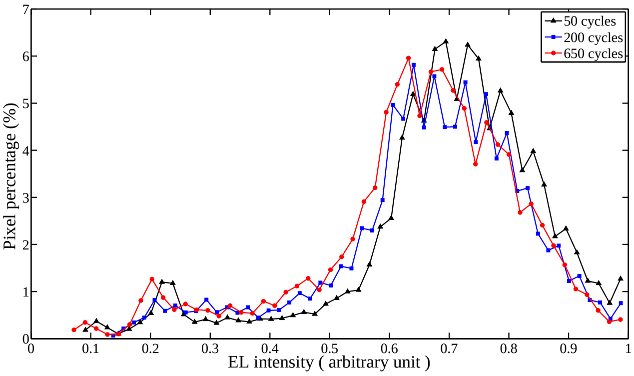


Fig. 5, EL frequency histograms for different number of bending cycles at maximum deflection. Note the shift of the histograms to the left by increasing the number of cycles, a trend consistent with the progression of fatigue damage.

The reported results have general implications for any kind of conductive material embedded into a ductile polymeric one, see, e.g., graphene layers dispersed into a polymeric matrix [18]. In other words, the global behaviour cannot be predicted from the mechanical properties of the individual constituents, but it comes out as the result of the interaction of the system's components, a feature typical of complex systems.

The present results pinpoint the need of modelling thermo-electro-mechanical coupling effects in polycrystalline Silicon solar cells embedded in PV modules, requiring the development of multidisciplinary research involving electronics, materials science and computational mechanics. From the industrial and engineering point of views, the present results imply that the quasi-static application of very high distributed pressures as requested by qualification standards [11] is not enough if we are interested in evaluating the actual degradation rate and possibly infer about the lifetime of produced PV modules. In fact, other unexpected forms of damage, like fatigue crack propagation, are indeed possible due to the composite structure of the module and can be induced by very common sub-critical loads like vibrations due to transportation or wind gusts, phenomena not yet characterized so far.

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