Solar Energy Materials & Solar Cells 111 (2013) 82–89

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Review

Systematic investigation of cracks in encapsulated solar cells after mechanical loading

Martin Sander [a,*], Sascha Dietrich [a], Matthias Pander [a], Matthias Ebert [a], Jörg Bagdahn [a,b]

[a] Fraunhofer Center for Silicon Photovoltaics, Walter-Hülse-Str. 1, 06120 Halle (Saale), Germany
[b] Anhalt University of Applied Sciences, Photovoltaic Materials, Bernburger Str. 57, 06366 Köthen (Anhalt), Germany

ARTICLE INFO

Article history:
Received 15 October 2012
Accepted 11 December 2012
Available online 22 January 2013

Keywords:
Cracks
Electroluminescence
Mechanical loading
Thermal loading

ABSTRACT

Mechanical and thermal loads on photovoltaic modules (PV modules) lead to mechanical stresses in the module parts and especially in the encapsulated solar cells which can break under a certain load. To investigate the development of cracks in encapsulated solar cells, a novel approach was developed that systematically analyzes the influence of the load direction on the crack directions. For this purpose an experiment is established that tests specimens on smaller scales under well-known boundary conditions. The cell cracks are statistically evaluated and the fracture stress can be compared directly for different crack orientations or different cell types. The test setup is expected to be suitable to systematically investigate the behavior of new cell or module designs or to act as a quality assurance test.

For the investigated cells a loading parallel to the busbars causes cracks at lower load magnitudes than a loading perpendicular to the busbars and different cell types show different fracture strength values. The findings can be transferred to full scale modules by calculating a probability of failure for each solar cell. This allows an interpretation of many effects that were observed in full scale PV modules and allows design optimization for reduced cell breakage rates.

Contents

1. Introduction

Photovoltaic modules (PV modules) are supposed to have a lifetime of more than 20 years under various environmental conditions like temperature changes, wind load, snow load, etc. Such loads induce mechanical stresses into the components of the

* Corresponding author. Tel.: +49 345 5589 416; fax: +49 345 5589 101.
E-mail address: martin.sander@csp.fraunhofer.de (M. Sander).

0927-0248/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2012.12.031

module, especially into the crystalline solar cells, which show cracks frequently [1–3]. The cracks are mostly invisible for optical inspection (naked eye) but can be identified using electroluminescence [4]. Thus they are often called micro-cracks even though their dimension is on millimeter or even centimeter scale [5,6]. The cracks can lead to isolated cell areas, thus causing reduced power output of the module [5,6].

According to IEC 61215 full scale PV modules are tested mechanically by applying a uniform area load on the horizontally mounted PV module. Typically after this mechanical load test the cells of the PV modules show a characteristic crack pattern that corresponds with observations on PV modules in the field, too. These characteristic crack directions can be found for both mono-crystalline and multi-crystalline cells [7].

The crack orientation in the cells and the spatial distribution of cracks in the module varies over the cell position [7]. This indicates a non-uniform stress distribution and different stress directions in individual cells in the PV module under mechanical loading. To analyze this in more detail some preliminary mechanical considerations on the stress distribution in full scale PV modules are discussed in Section 2.

To get more information about the mechanics of crack development and crack growth in encapsulated solar cells, tests of mini-modules under well-known boundary conditions are performed. The loading conditions are derived from the stress analysis in full scale PV modules.

The experimental approach and the test setup is described in Section 3. Cracks after mechanical loading are investigated systematically and different types are identified in Section 4. They are evaluated according to their relative frequency of occurrence in PV modules and the fracture stress for different cell types is determined. These results can be transferred to full scale PV modules by using finite element analysis (FEA). Using this approach adjustments in module mounting or module design can be made to reduce cell cracks and to increase module reliability.

2. Stress conditions in full scale PV modules

The strain and stress distribution of the cross-section of a PV laminate is depicted schematically in Fig. 1a for a uniaxial bending around the y-axis. Compression stress at the top side of the glass and tension stress at the bottom side is induced in the x-direction. The cells are placed at the bottom side of the module. Thus tension strain from the bottom side of the glass is transferred to the cells via the encapsulant. The material properties of the encapsulant have an influence on the transferred stress into the cells. This stress is superimposed with the bending stress of the cell itself. The highest tension stress occurs at the bottom side of the cells leading to breakage of the silicon as shown by Dietrich et al. [8].

To analyze the stress distribution in full scale PV modules under a uniform area load, a finite element simulation has been set up that includes all relevant materials and layers. Due to the symmetry, a simulation of a quarter of the module with appropriate boundary conditions meets the requirements. Fig. 1b shows the first principal stress at the bottom side of the cells of a standard PV module with an aluminum frame which is clamped with four clamps at the long edges. Additionally, the representative direction for the first and the second principal stress for each cell is depicted by arrows. The arrow size represents the stress magnitude. With these information the characteristic crack pattern of PV modules after mechanical load test can be explained well in a qualitative way. Despite the large variety of crack orientations classified by Köntges et al. [9], in the following it is assumed that the crack orientations can be condensed to cracks parallel, perpendicular and 45° to the busbars, because all other classes are found to be combinations of these.

It is obvious that most of the cells show a biaxial stress distribution and the first and second principal stresses are aligned predominantly in the x- and y-directions. Here cracks either parallel or perpendicular to the busbars can be observed, in which cracks parallel to the busbars may lead to isolated areas and therefore to power loss of the PV module [7,9]. In particular the four cells in the corners of the module show a 45° stress direction and the highest stress magnitude. This is the position where most of the PV modules show cracks under 45° after mechanical loading [7].

The non-uniform stress distribution and different stress directions make it difficult to estimate the fracture stress for an individual cell or to set up a reliability concept for the cells in a PV module just by performing standard mechanical load tests on module scale.

3. Experimental approach

To achieve an improvement in mechanical characterization of encapsulated solar cells, a new experimental approach is chosen that investigates cracks systematically according to their direction. For first investigations the influence of stresses in the x- and y-directions is analyzed. Fig. 2 shows schematically the experimental approach for investigation of mechanical loading. For this purpose test specimens on smaller scales (mini-modules) are exposed to defined loads and are characterized by electroluminescence.

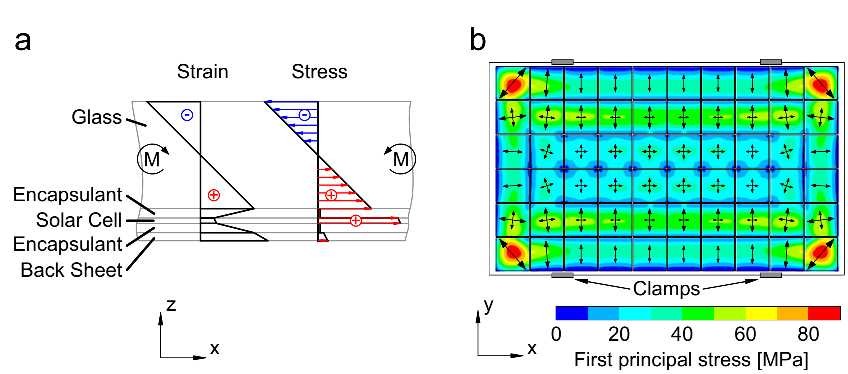

Fig. 1. (a) Schematic strain and stress distribution for a PV laminate during bending around the y-axis [8]. (b) Standard PV module with a clamped aluminum frame under 5.4 kPa area load. The color code represents the magnitude of the first principal stress at the bottom side of the cells and the representative direction for the first and the second principal stress is depicted by arrows. (For interpretation of references to color in this figure caption, the reader is referred to the web version of this article.)