Solar Energy Materials & Solar Cells 108 (2013) 78–81

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

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

Broken metal fingers in silicon wafer solar cells and PV modules

Pooja Chaturvedi *, Bram Hoex, Timothy M. Walsh

Solar Energy Research Institute of Singapore, National University of Singapore, Singapore

ARTICLE INFO

Article history:
Received 7 May 2012
Received in revised form
3 September 2012
Accepted 7 September 2012
Available online 6 October 2012

Keywords:
Silicon wafer solar cells
Broken metal fingers
Electroluminescence
Mechanical load test
PV modules
Thermal cycling test

ABSTRACT

Photovoltaic (PV) modules undergo accelerated aging tests as part of the certification procedure in order to confirm that they are not susceptible to the most common failure mechanisms that would strongly reduce their lifetime in the field. Though not yet part of the standard test sequence, it is well known that silicon camera based electroluminescence (EL) imaging would be a good addition to the test sequence as it enables the identification of defects in PV modules such as micro-cracks and poor electrical contact that will limit the lifetime of the module in the field, but do not necessarily result in a power reduction of more than 5% that would have them fail the certification tests.

After IEC tests, we observe two distinct types of dark areas in the EL images of silicon wafer based PV modules, irregularly shaped regions which are the result of cracks in the silicon wafers, and regular rectangular shaped areas which we postulate are due to broken front grid fingers.

In order to identify the mechanism responsible for the dark rectangular regions in the EL images of silicon wafer based PV modules, we investigate a soldered solar cell which exhibits similar rectangular dark areas in its EL image. SEM microscopy reveals that the dark areas in this cell are due to broken fingers caused by contraction of the tin during the soldering process. We hypothesise that a similar mechanism is responsible for the dark rectangular areas seen in the EL images of silicon wafer based PV modules after the accelerated aging tests.

1. Introduction

The majority of the photovoltaic (PV) module types has to undergo accelerated aging testing in order to qualify for International Electrotechnical Commission (IEC) or Underwriters Laboratories (UL) certification that is a prerequisite before selling these modules on the global market. Many modules fail these accelerated aging tests [1–3]. A failure is defined as a power loss of more than 5% after the accelerated aging test. Electroluminescence (EL) imaging is a simple yet powerful tool which is well known for its use in quality control in PV module manufacturing [2–4]. The additional information provided by EL imaging can be useful for failure analysis. It was shown, for example, that EL imaging can be used to qualitatively assess the failure modes after the dynamic load test [5]. The spatially resolved information provided by EL imaging is much more useful than *I–V* data alone, because *I–V* parameters typically cannot give information about the root cause for the power degradation of the module. Moreover, EL imaging can detect defects in the PV module that will reduce its lifetime in the field such as micro-cracks and poor electrical contacts. A detailed study on crack formation after the mechanical load test demonstrated that many cracks, about 50%, were found parallel to the busbars, thus causing maximum degradation in cell and overall module performance [6]. In addition EL imaging was also used for quantitative analysis of PV modules, e.g. the measurement of voltage distribution and determination of the spatially resolved series resistance [7,8].

In this work we observe two distinct types of dark areas in silicon wafer based PV modules after accelerated aging tests—namely irregularly shaped areas which we attribute to (micro) cracks in the silicon wafers, and regular rectangular areas which we attribute to broken front grid fingers.

2. Experimental

As part of the certification process for PV modules, they are subjected to several types of accelerated aging tests. These tests are defined in the relevant international standards, such as IEC 61215 edition 2 [9]. The main accelerated aging tests are thermal cycling, mechanical load (static and dynamic), damp heat and humidity–freeze.

During the mechanical load test, the PV module is subjected to three cycles of 2400 Pa uniform load, applied for 1 h sequentially to the front and the back surface [9]. If the module is going to be rated to withstand heavy accumulation of snow and ice, an optional 5400 Pa weight is used. The purpose of this specific test in the IEC standards is to determine the ability of the module to withstand wind, snow, or ice loads [9].

During the thermal cycling test, the PV module is subjected to a temperature profile of −40 °C to +85 °C for 200 cycles, with a

* Corresponding author. Tel.: +65 65161150; fax: +65 67751943.
E-mail address: pooja.chaturvedi@nus.edu.sg (P. Chaturvedi).

0927-0248/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2012.09.013

maximum ramp rate of 100 °C/h. This test can potentially result in thermo–mechanical stresses in the cells and module due to different thermal expansion coefficients of the various materials within the laminate. The solder joints between the tin-coated copper ribbons and screen-printed silver busbars of the cell are particularly susceptible to stress during thermal cycling. Therefore, the purpose of this test is to verify the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by repeated changes of temperatures [9].

The EL imaging setup used in this study consists of a thermoelectrically cooled silicon camera, an optical lens, and a mounting frame for PV modules housed inside a dark room. The module was connected to a power supply [Thurbly Thandar Instruments, CPX 400 A] that was positioned outside the dark room. A silicon based electron multiplying charge coupled device camera [EMCCD, Andor, Luca (R)], with a resolution of 1004 × 1002 pixels was used to image the EL signal from the PV modules and cells. The electron multiplication in the Si sensor results in a much better signal-to-noise ratio than is possible with conventional CCD cameras. The working distance between the module and the camera was about 3 m with a resolution of 1.6 mm/pixel on the image. During the measurement, the modules were forward biased with a voltage that resulted in a current approximately equal to the module's short-circuit current (I_{sc}) under one-sun illumination.

Finally, a scanning electron microscope (SEM, Carl Zeiss, Auriga) was used for imaging a soldered silicon wafer solar cell which displayed similar dark rectangular areas in the EL measurement.

3. Results

PV modules were imaged using EL before and after each of the IEC test branches. For some types of accelerated aging tests, namely thermal cycling and mechanical loading, the difference in EL images before and after the tests was found to be significant.

3.1. Mechanical load test

The initial EL image in Fig. 1(a) shows a relatively uniform EL intensity from the PV module. However, after the mechanical load test (with 2400 Pa uniform load) many cells in the module have a lower EL intensity compared to the image taken prior to the test, even though an identical forward bias current was flowing through each solar cell. This is illustrated in Fig. 1(b). The EL signal is determined by the separation of the electron and hole quasi Fermi levels, the internal voltage, at that point [10]. A higher relative EL intensity implies a higher internal voltage, and vice versa. The internal voltage at a specific point can be low due to the low quality of the diode or due to a local high series resistance at that point in the PV module (e.g. caused by broken contact fingers).

In Fig. 1(b) two different types of dark regions are observed in the EL image of the module after mechanical load testing. The first type of dark regions are irregularly shaped (for example in the upper left and upper right cells in the picture). These dark regions are due to cracks in the silicon wafer solar cells. The second type of dark regions are rectangular (or square) in shape (highlighted by the white rectangles in the picture), and extend from one of the busbars of the cells. It is hypothesised that these rectangular dark regions are due to metal fingers which are broken at the busbar.

As seen from Table 1, the maximum output power (P_{mpp}) and fill factor (*FF*) of the module after mechanical load test decreased by 3.6% and 3.0% respectively, while the open-circuit voltage (V_{oc}) and the I_{sc} largely remain unaffected in this experiment. Hence this module still passes this IEC test, as the power reduction is less than 5%. However, the EL image clearly detects severe damage of the module after the mechanical load test that potentially results in a failure if the module is, for example, subsequently exposed to thermal cycling.

3.2. Thermal cycling test

Fig. 2 compares the initial EL image of the PV module with one taken after the thermal cycling test. In the image taken after the

Table 1
Electrical parameters for the module before and after mechanical load and thermal cycling test.

Parameter/Test	Mechanical load		Thermal cycling	
	Before	After	Before	After
Open-circuit voltage (*V*)	36.9	36.7	36.8	36.8
Short-circuit current (*A*)	8.44	8.42	8.64	8.55
Maximum output power (*W*)	236	228	241	226
Fill factor (%)	75.9	73.7	75.6	71.2

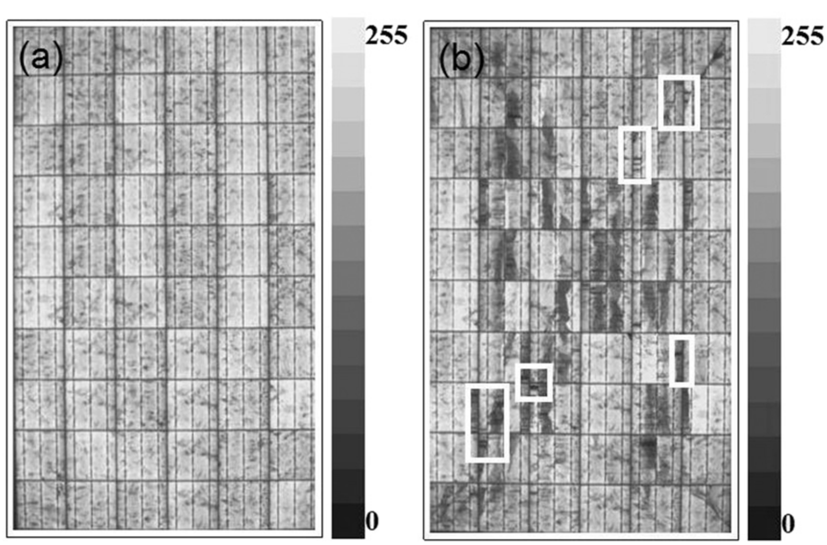

Fig. 1. Electroluminescence images of a silicon wafer based PV module (a) before and (b) after a uniform 2400 Pa load mechanical load test. Many dark areas are present in the EL image of the module after mechanical loading.