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Non-destructive testing of crystalline silicon photovoltaic back-contact modules

Dirk Veldman, Ian J. Bennett, Bart Brockholz, Paul C de Jong

ECN Solar Energy, P.O. Box 1, 1755 ZG Petten, The Netherlands

Abstract

One-step module encapsulation and interconnection using conductive back sheet foils and conductive adhesives has advantages including i) fast module assembly, ii) limiting cell handling to a one time pick-and-place, and iii) low temperature (< 160 °C) processing. Drawback of the integrated module production, however, is that interconnected cells can only be inspected after the module has been laminated. Furthermore, because all electrical interconnections are located between the cells and the conductive foil, non-destructive test methods are required for the inspection of photovoltaic (PV) modules produced with this method. In this contribution complimentary non-destructive test methods, including lock-in thermography using a forward bias in the dark (power is dissipated) are compared as methods for testing back-contact modules allowing i) the accurate discrimination of failed and functioning interconnections between cells and the conductive foils, and ii) the detection of delamination of the back side foil. Included in the comparison are electroluminescence, infrared thermography, X-ray scanning, and ultrasonic inspection. Drawbacks and benefits of each test method are summarized and this shows that lock-in thermography is a fast, accurate, and economical non-destructive test method that can be applied for back-contact modules.

Keywords: Photovoltaics, back-contact modules; reliability testing; non-destructive testing; dark lock-in thermography.

1. Introduction

In recent years, one-step module encapsulation and interconnection, or monolithic module assembly using conductive back sheet foil and conductive adhesives has been successfully applied to metallization wrap-through (MWT) [1] and emitter wrap-through (EWT) [2] solar cells, thereby allowing the interconnection of very thin cells with high module efficiencies. Advantages of the combined electrical

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interconnection of the cells to the conductive back sheet foil (using conductive adhesives) and encapsulation include i) very fast module assembly with throughputs of more than one module per minute, ii) limiting the cell handling to a one time pick-and-place, and iii) low temperature (< 160 °C) processing. Drawback of the integrated module production, however, is that the conductive adhesive interconnects of the cells can only be inspected after the module has been laminated. Furthermore, because all electrical interconnections are located between the cells and the conductive foil, visual inspection of the interconnections can only be applied destructively. This articulates the need for non-destructive test methods for the inspection of PV modules produced using the one-step encapsulation and interconnection method.

Commonly used and fast non-destructive test methods for the performance analysis of photovoltaic modules include light-current-voltage measurements (flash-testing), electroluminescence (EL) and infrared (IR) thermography measurements. EL and IR thermography can be used as complementary tools to locate and identify defects in interconnections (dark in an EL and cold in an IR image) or shunts (dark in an EL and hot in an IR image) [3]. However, these methods do not provide enough detailed information to identify whether individual interconnections between cell and conductive foils in back-contact modules are functional or not.

Drawback of using IR thermography for PV module inspection is that heat spreads over the materials, reducing the sensitivity of the technique. As excitation sources (infrared) light sources can be used, or – in case of PV modules – heat can (also) be injected by power dissipation of a current applied by an external power source. An alternative to conventional infrared imaging is lock-in thermography. In this method a pulsed heat source (e.g. a flash light or a pulsed electric current source) is heating the sample under test. The IR camera captures the heat propagation by collecting a series of IR images taken during and after the heat pulse. After that, software is used to convert the image data into a spatial presentation of how the heat waves propagate. The resulting amplitude and phase images reveal much more detail than a standard IR image.

Other methods that have been applied for non-destructive testing of back-contact modules are ultrasonic inspection and X-ray scanning [4].

Nomenclature

MWT	Metallization wrap-through
EWT	Emitter wrap-through
PV	Photovoltaic
EL	Electroluminescence
IR	Infrared
DLIT	Dark lock-in thermography

2. Results

2.1. Dark lock-in thermography and electroluminescence

In this contribution dark lock-in thermography (DLIT) is introduced as a method for non-destructively testing back-contact modules. The modules under investigation make use of Sunweb® cells from Solland Solar or cells provided by Q-cells. DLIT is a thermographic method that is routinely used for the detection of so-called pre-breakdown sites in crystalline silicon solar cells [5, 6] while applying a reverse bias, in time frames as short as 10 ms [7]. Here, DLIT is successfully applied for i) the accurate discrimination of failed and functioning interconnections between cells and the conductive foils in back-contact modules (Fig. 1), and ii) the detection of delamination of the back side foil (Fig. 2) by applying a forward bias in the dark (power is dissipated).

Figure 1 shows four images of a single-cell module after 1250 hours of damp heat (85% RH, 85 °C) exposure. The cell-area efficiency of 13.3% and fill factor of 65.5% are 91% of the initial performance, and the shape of the I-V curve (not shown) indicates an increase in series resistance. The EL image (Fig. 1 a) reveals that, upon electrical excitation, the lower part of the module does not provide as much light as the top part of the module. This can be indicative of a higher series resistance in the lower part of the module. The standard (steady state) IR thermography image taken from the rear side of the module reveals that the top side of the module heats up a bit more than the lower part of the module (yellow is warmer than green in the image), however, the origin of that is not directly apparent. The DLIT images in Figures 1 c and d reveal much more information. The amplitude image (Fig. 1 c) reveals that the 4 x 4 interconnections to the emitter contacts of the cell are heating to nearly the same temperatures. The 3 x 5 interconnections to the base contacts, however, reveal seven hot interconnections and two interconnections only marginally heating up. The six interconnections to the lower part of the cell are not visible at all in the amplitude image. In the phase image (Fig. 1 d) features are more clearly visible, for example revealing the pattern of the conductive foil showing a different phase at places where the copper has been etched away. Also, the 16 interconnection to the emitter contacts are more clearly visible, but still the lower six interconnections to the base contacts of the cell are not revealed. Thus DLIT clearly reveals that the increased series resistance (and lower fill factor and power output) is a consequence of a number of failing (missing) interconnections between the conductive foil and the MWT cells. This forces the current to pass through a limited number of interconnections that consequently heat up considerably and will lead to a non-uniform extraction of the light-generated current in the cell.

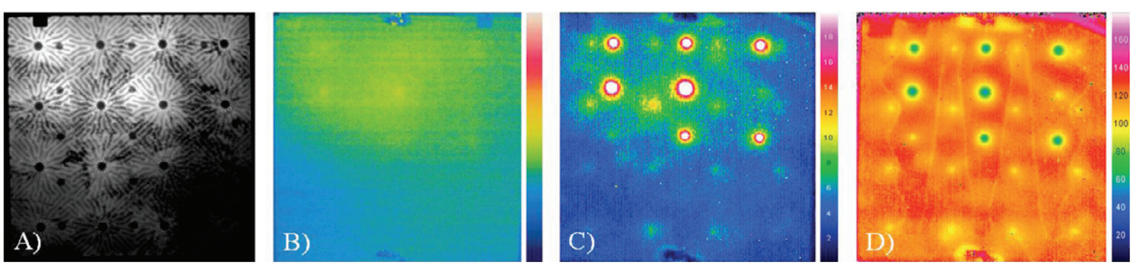

Fig. 1. (a) electroluminescence, (b) infrared thermography, and (c, d) dark lock-in thermography images of a single-cell conductive foil-based back-contact module. The images in b-d that were recorded from the rear side are flipped horizontally for direct comparison to the image in a that was recorded from the sunny side of the module. The color scales ranges are 24-32 °C (b), 0-20 mK (c) and 0-180° (d).

In Fig. 2 another comparison is made between an EL (Fig. 2 a) and a DLIT image of the same section of a large module. In Fig. 2 B the circles in the top left cell mark functional interconnections between cell emitter contacts and the conductive foil. All of these 16 interconnections are visible and hence functional, in contrast to the interconnections to the base contacts. The arrow in the top right cell indicates the single functional base interconnect of that cell. When comparing that to the EL image, the center of that cell is also brighter than the rest of the cell, but it is not apparent from the EL image alone what is causing that effect. The solid and dashed circles in the bottom right cell of the DLIT image indicate functional and non-functional base interconnects, respectively. The arrow in the bottom left cell points to an area where the conductive sheet delaminates from the PV module: air between the copper foil and the rest of the module causes thermal isolation, affecting the way the backsheet is heated, which can be observed using DLIT.

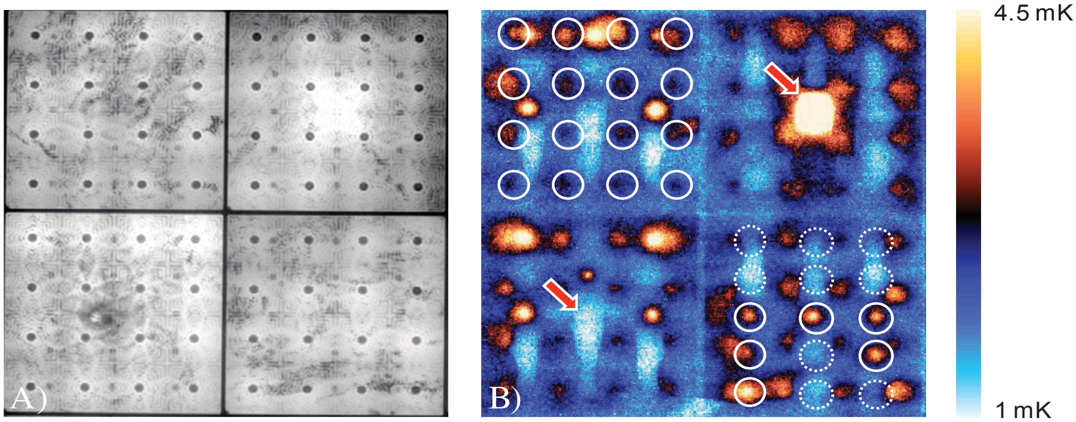

Fig. 2. a) electroluminescence and b) lock-in thermography (amplitude) image of cells in a module aged for 2000 hours of damp heat exposure (close-up of the module in Fig. 3).

Both EL and DLIT are methods that allow fast inspection for large-size PV modules. The images in Fig. 3 of a 1 x 1.5 meter back contact module were recorded within one minute time. And the inspection time can easily be reduced, if desired. Electroluminescence reveals more information on cell breakage and can be used to discriminate between increased series resistance and reduced parallel resistance, both of which may lead to a hotter area in an IR image. The EL image in Fig. 3 a reveals a cell that is clearly broken (a small corner section of a cells is completely dark). Furthermore, the image provides additional evidence that the variations in the IR images are due to variation in series resistance, because all of the relatively hot areas in the IR (and DLIT) images correspond to brighter regions in the EL image. If the hot spots would have been a result of a reduced parallel resistance (shunting), they would have lead to dark regions in the EL image.

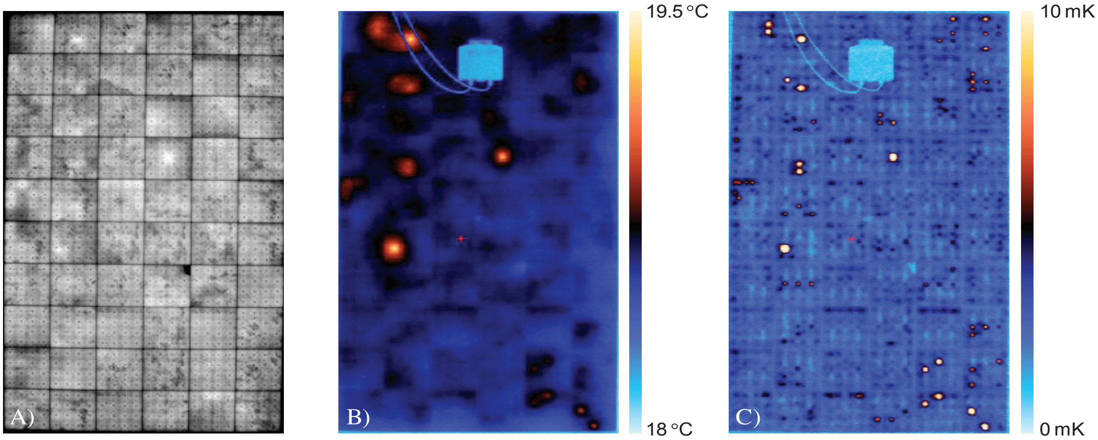

Fig. 3. a) electroluminescence, b) infrared, and c) lock-in thermography (amplitude) image of a 60-cells MWT back-contact module aged by damp heat (85% RH/85 °C) exposure for 2000 h.

2.2. X-ray and ultrasonic inspection

Two-dimensional X-ray scanning and ultrasonic inspection are accurate non-destructive test methods for the detection of alignment and delamination, respectively. This is revealed in Fig. 4. The 2D X-ray image (Fig. 4 A) of a single-cell module clearly reveals (from the back to the front side of the PV module): i) the locations in the conductive back sheet foil where the copper has been etched away, ii) the electrically conductive adhesive (see the close-up image), iii) the (circular) pattern of the silver metallization on the rear side of the cell, and iv) the 8 straight metallization lines surrounding each laser-drilled hole on the front side of the cell. Thus X-ray scanning can be used to inspect alignment between the back sheet foil, the electrically conductive adhesive and the back contact cells. Drawback of this method is that equipment for large-size modules is not readily available and that equipment is relatively expensive (in comparison to EL and DLIT), for example because during inspection the product must be located in a lead cabinet to protect the environment from damaging X-rays.

Ultrasonic inspection, a method using sound waves to non-destructively detect defects is a method that can be used to very sensitively detect air inclusions in PV modules. Fig. 4 B gives an example of such a measurement, where air inclusions hidden between the back contact cells and the conductive back sheet foil are readily detected. Drawback of such measurements is that water needs to be used as a medium between the transducer/receiver and the product under inspection. This requires the use of a large water tank. In addition to that, the method is time consuming: the image taken in Fig. 4 B was recorded in 30 minutes time.

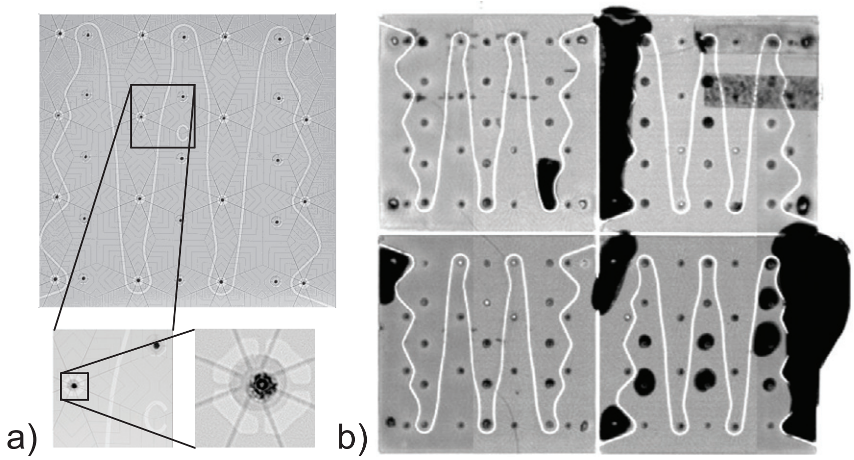

Fig. 4. a) X-ray and b) ultrasonic scans of back-contact modules using conductive foil.

3. Conclusions

A number of methods have been used for the non-destructive testing of back-contact PV modules. (2D) X-ray scanning and ultrasonic inspection are accurate tools to visualize (alignment of) interconnections and delamination, respectively. The major drawbacks of these methods is that X-ray inspection is relative expensive and that ultrasonic inspection is time consuming.

Dark lock-in thermography (DLIT) at forward bias, on the other hand, is a fast, accurate and economical tool to detect interconnection functionality. DLIT can be used for full-size modules and even allows for detection of delamination in PV modules. Electroluminescence (EL) imaging is complementary to DLIT.

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