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# PV module defects detection, a study using electroluminescence, infrared thermal imaging and IV curves analysis.

# Detección de defectos en módulos fotovoltaicos, un estudio usando electroluminiscencia, termografía infrarroja y análisis de curvas IV.

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**Technological Innovation:** The combination of the results of different characterization techniques to detect and identify defects in photovoltaic modules.

**Area of Industrial Application:** A shorter characterization time can be achieved using the results of this work. In addition, more information regarding the module characterized can be obtained from the combined results of the different characterization techniques. This can be used in PV power plants to reduce defect detection time.

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## Abstract

After a photovoltaic (PV) module is sold, several defects could appear. A PV system with damaged modules can lead to fast degradation of the system components (e.g. inverter and batteries). Characterization techniques aid in the detection of these defects and in the measurement of the performance of PV systems. Electroluminescence (EL), infrared thermography (IRT) and IV curve tracing were performed on modules of different materials. These techniques are an important tool for PV characterization since they can give a substantial overview on what defects are present in a module or array in a very short time.

This work had the objective of finding the main advantage of each of these characterization techniques and how to use them in the most efficient way depending on the conditions of the investigated PV system. EL images analysis corresponding to aged CdTe PV modules showed a 73 % reduction of the brightness level, corresponding to the effect of the light induced degradation. IRT showed that cells in a sc-Si PV module in outdoor conditions can present a 30 °C increase when part of the module is shaded. In addition, when a forward bias was applied to CdTe PV modules under dark conditions, the temperatures differences were of around 5 °C. At last, the temperature coefficients for the CdTE modules were compared to the ones given in the corresponding datasheet. The voltage temperature coefficient was reduced from -0.24 %/°C to -0.26 %/°C, and the current temperature coefficient was increased from +0.002 %/°C to +0.0054 %/°C. It was concluded that, within the studied techniques, IRT is the fastest and easiest technique to perform, EL was the most accurate when looking for specific defects in a module, and IV curve tracing was the most precise at giving a quantitative result.

**Key Words:** Photovoltaic module, characterization techniques, defect detection.

## Resumen

Algunos defectos pueden surgir posterior a la compra de un módulo fotovoltaico (FV). Un sistema FV con módulos dañados puede resultar en la degradación acelerada de componentes del sistema. Las técnicas de caracterización fungen como valiosas herramientas de evaluación y detección de defectos. En este estudio se llevó a cabo el monitoreo de módulos FV utilizando electroluminiscencia (EL), termografía infrarroja (TIR) y rastreo de curvas IV. Estas técnicas son herramientas útiles para obtener información substancial de manera rápida y sencilla para determinar los defectos presentes en un módulo o generador fotovoltaico. En algunos casos, es posible determinar cómo surgieron estos defectos.

Este estudio tiene como objetivo encontrar las principales ventajas de cada una de las técnicas de caracterización mencionadas, además de establecer el modo más eficiente para utilizarlas dependiendo de las condiciones en las que se encuentre el sistema FV que será analizado. El análisis de las imágenes de EL correspondientes a módulos envejecidos de CdTe mostró una reducción del nivel de brillo del 73 % respecto a módulos nuevos, efecto correspondiente a la degradación inducida por luz solar. La TIR mostró que algunas áreas de un módulo FV de silicio monocristalino (sc-Si) en condiciones al aire libre presentan un incremento de 30 °C cuando parte de éste se encuentra bajo sombra. Igualmente, cuando polarización directa es aplicada a módulos FV de CdTe, las diferencias de temperatura en el módulo fueron de 5 °C. Finalmente, los coeficientes de temperatura de estos módulos se compararon con los correspondientes en la hoja técnica. El coeficiente de temperatura para voltaje se redujo de -0.24 %/°C a -0.26 %/°C, y el de corriente aumentó de +0.002 %/°C a +0.0054 %/°C. Se concluyó que TIR es la técnica más rápida, EL la más exacta para identificar defectos específicos, y el rastreo de curvas IV es el más preciso para obtener datos cuantitativos.

**Palabras clave:** Fotovoltáico, técnicas de caracterización, detección de defectos.

## Introduction

Performance of PV modules can be lower than the rated performance [1]. This is a problem for both the consumer and manufacturer. The consumer will obtain less energy than guaranteed, while replacing underperforming modules constitutes costs for the manufacturer. This project is focused on field testing. The underperformance of PV modules can be caused by defects. This research focuses on characterization techniques needed to detect and monitor these defects, and how to combine them efficiently to obtain better results. This will allow to study the reliability of PV systems as well. Before explaining these characterization techniques, a general introduction to PV systems will be given. A PV system is composed by a group of elements that have the objective of generating power to supply energy to a load using solar energy. The main components of a grid connected PV system are PV modules, inverters, charge controller, maximum power point tracker and cables. Standalone PV systems (not connected to the electricity grid) will require batteries to store the produced energy when it is not being consumed [2]. The electricity produced by the PV system will be transported through the different connections into a load. The component with the shortest lifetime are the batteries (around 5-8 years), followed by the inverter, with a life time of around 15 years. Modules have a typical lifetime of at least 25 years. During this time, the guaranteed efficiency of the PV modules is reduced gradually, until reaching a maximum decrease of 20 % compared to the initial efficiency. Several types of defects can reduce the performance of a PV module, such as intrinsic defects in the materials, or defects created during the installation due to wrong handling. In addition, some of the defects can damage the rest of the modules [3] [4]. The identification of defects in PV modules during the production process helps to select out malfunctioning PV cells or modules before going to customers. PV module characterization using electroluminescence (EL), infrared thermography (IRT), and IV curve tracing has been applied by producers at different stages of the production process of the PV modules. The purpose of using these characterization techniques is to verify that the performance of the cell/module is within an acceptable range guaranteed by the manufacturer. These methods contribute importantly to find defects that are not visible to the naked eye. The combination of EL, IRT, and IV curve tracing leads to shorter testing time compared to always using only one of the characterization tools mentioned, and conclusive results. Modules of PV systems can get damaged at different stages after they are sold to the consumer. This report will show the advantages of each technique and how to utilize them properly. In addition, the relations found between the characterization techniques will be presented.

In summary, IV tracing can reveal the performance level of a PV module or array. EL and IRT will be useful to identify the potential defects in a PV module. Identification of the specific defect/s that are diminishing the performance of the PV system can give the required information to the manufacturer in order to improve specific characteristics or components of the modules during the production process.

## Materials and Equipment

Modules used during the experiments were single and poly crystalline silicon, and thin film (CdTe and CIGS), with a nominal power ranging from 30 W to 327 W.

For the EL imaging experiments a Nikon D700 camera was used. In this section, a brief description of this camera and the modifications made will be presented. This camera has a CMOS sensor.

The camera will have a different sensitivity level depending on the bandgap of the material analyzed. For example, c-Si emits photons of 1100 nm, and CdTe of 780nm. This means that this camera is more sensitive to CdTe than to c-Si. The total pixels amount is of 12.87 million. The infrared filter of this camera was replaced by an 830 nm long-pass filter, this was performed to be able to detect the photons being emitted by the modules.

The technical specifications of the camera used for IRT are as follows: The camera used was a ThermaCAM S65HS FLIR, with an accuracy of ± 2 °C, an electronic zoom of 2x, 4x and 8x, interpolating, and the digital enhancement was through an adaptive digital noise reduction. At last, the detector type was a focal plane array, with 320 x 240 pixels [5].

An IV curve consists of a graph showing all the possible operation points of a PV device. An IV tracer is required to obtain this curve. This device uses the variable electric load method for the range of 0 V up to the value of the $V_{oc}$. The result, in this specific case, is a graph formed by 256 data points. Temperature of the module, irradiance, $I_{sc}$, and $V_{oc}$ were registered as function of time. The temperature of the module was measured with a T-type thermocouple. Table 1 lists the equipment used to obtain all the data used to calculate the IV curves. The data was gathered by the software provided by the IV tracer producer, and then processed using Matlab.

**Table 1.** Equipment details.

| Equipment | Type | Brand | Accuracy |
|---|---|---|---|
| **IV curve tracer** | MP-160 | EKO | +/- 0.5% |
| **Pyranometer** | MS-802 | EKO | +-0.2% |
| **Thermocouple** | Type T | Roessel | +/- 1.0$^{0}$C |
| **Data logger** | DT85 | DataTaker | +/- 0.1% |

## Experimental Methods

This section will present a short description of the experimental setups with focus on the conditions under which the experiments were executed.

Figure 1 shows the schematic representation of the experimental setup used during the EL imaging for the indoor conditions. The blue horizontal line represents the PV module. The yellow lines represent the tripod used to hold the camera. A tent was placed on top of the tripod to block other light sources, and to obtain sharper images. Figure 2 shows schematically the electrical circuit used to induce a forward bias into the module to analyze. The electrical circuit consists of a power source and a PV module. The positive end of the power source is connected to the positive end of the module, and vice versa.

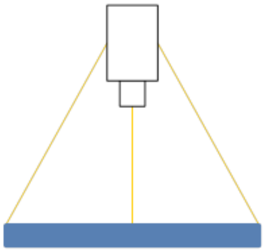

**Figure 1**. EL imaging experiment setup, tripod placement.

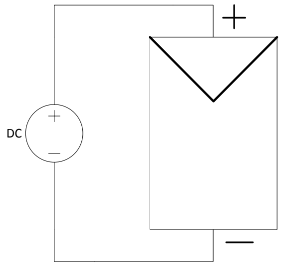

**Figure 2.** EL imaging experiment setup, electrical simplified circuit.

For the IRT experiments, the same configuration was used. The only difference was that to help avoiding the detection of the camera reflection from the camera itself, the orientation of the camera relative to the module had to be between 5° and 60° as seen in figure 3 [6].

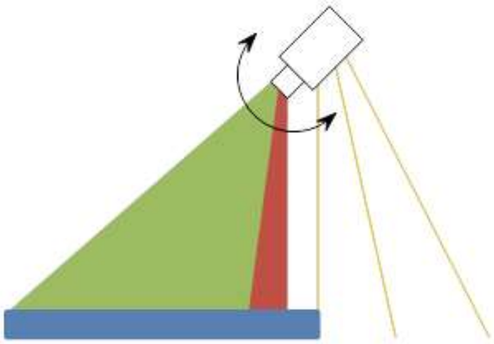

**Figure 3.** IRT camera placement, the red area corresponds to a forbidden angle range.

In the case of the IV curve tracing, the modules were connected by “channels”, formed by two modules connected in parallel which were directly connected to the measurement system. This is shown in figure

4. This configuration was chosen prior to the start of this project.

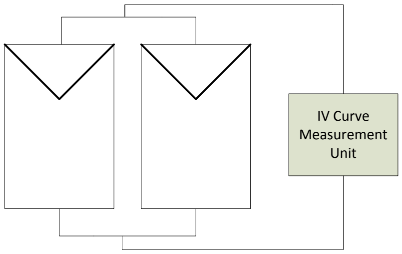

**Figure 4**. Schematic representation of IV curve tracing electrical circuit.

## Results

The results obtained with each of the three characterization techniques, EL, IRT, and IV curve tracing, were used to determine which defects are present in the modules used. Results for each characterization technique are presented. EL, IRT and IV tracing were performed under outdoor conditions. At last, the relationship between the results obtained with the different techniques will be presented and described.

This EL image was chosen as it shows a wide variety of defects that are present. Normal crystalline silicon modules do not have as many defects as this module. Figure 5 shows the location of the defects found.

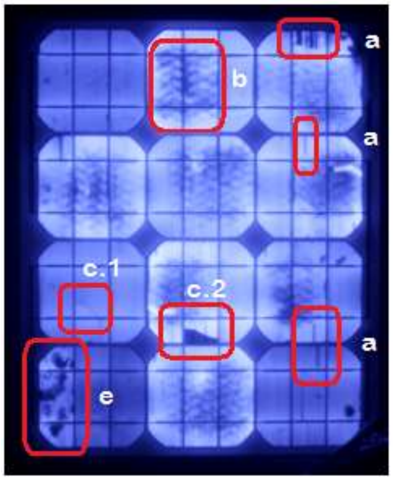

**Figure 5**. EL image of 12 cells sc-Si module @ 23.4V / 2.01A. a) Broken fingers, b) Furnace belt burn c) Crack: Partial (c.1) and full interruption (c.2) d) Unequal cell quality (seen as cells with different brightness levels) e) Delamination.

The following defects were found in this module:

- Broken fingers: Manufacture error.
- Furnace belt burn: Manufacture error. Darkening of damaged area related to low charge carrier concentration.
- Crack: Partial (c.1) and full interruption (c.2): A full interruption will decrease the total current output of a solar cell in the same percentage as the damaged area.
- Unequal cell quality (seen as cells with different brightness levels). Several elements can influence the brightness difference. Doping quality and Shockley-Read-Hall recombination rate are examples of influential factors.
- Delamination: This defect is caused by a reduction in the adhesion strength between layers inside a PV module. A proper encapsulation process, material usage, and handling, can prevent this defect.

In addition, a CdTe module was tested under various current levels to compare the difference in brightness intensity of different images. This comparison will help determine which current level is required to be able to obtain images with enough brightness [7]. At the beginning of the experiment low currents forward biased to the module (~0.05 A), and hardly any emission was observed. A current of at least 0.99 A (50 % of the $I_{sc)}$ was required to obtain images with enough light intensity to allow more defects to appear.

Figure 6 shows the module at a current of 0.5 A (~25 % $I_{sc}$), and it can be observed that the current level is not high enough to show all the defects in the module, leaving dark areas causing uncertainty on the resultant analysis. Moreover, three shunt resistances are circled in red in order to give the reader a better picture of how a shunt resistance is represented in this material.

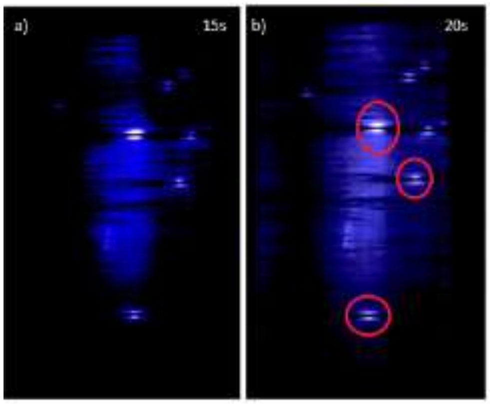

**Figure 6**. EL image of CdTe Module, under 60.6 V, exposure time of 10 and 20 s, from left to right. Red circles indicate low shunts.

There is a significant efficiency drop registered in CdTe module caused by low shunt resistances [8]. A normal value for a low shunt resistance is in the range of 1-10 Ω [8]. The low shunt resistances found in this work were not measured given that the analysis was made on a module level and it was not possible to measure the resistance of the shunt paths on a cell level. In addition, it can be seen in figure 7 that as the exposure time of the photograph increases, the overall brightness also increases. However, in order to obtain a more punctual location of the shunt path, it is better to apply a higher current.

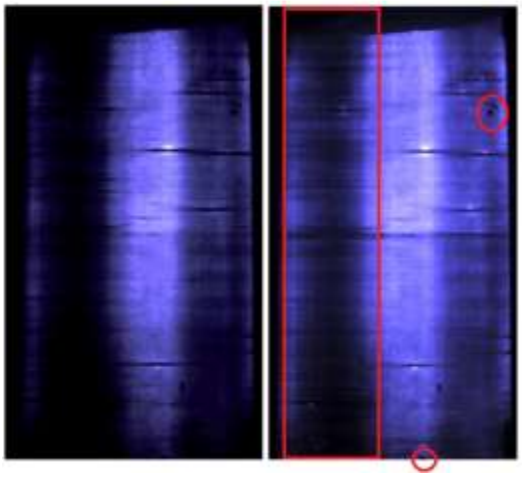

**Figure 7**. El image of CdTe module, under 90V, 97V / 2A, from left to right. Exposure time of 30 s. The red rectangle indicates a low charge carrier concentration area. The red circles indicate a low local charge carrier concentration.

In figure 7, a darker area can be seen in the module indicated by a red rectangle. The difference of brightness throughout the module can be caused by inhomogeneous cell quality. This inhomogeneous cell quality can be caused by the different methods for doping the materials or how the P- and N-type materials are put together [9]. For example, sputtering deposition, vapor transport deposition or closed space sublimation, are used for the deposition of semiconductor or metallic materials. These methods cause differences in the distribution of the charge carrier concentration that can lead to the different brightness distributions observed in the different PV modules analyzed. It could also be related to the amount of current flowing on each section related to how the cells are interconnected.

Figure 7 shows the image taken when using an exposure time of 30 seconds. There are some defects in this image that cannot be seen in the previous image at lower current. Darks spots, circled in red, or a defined darker area in respect to the rest of the module can be seen. These darker spot are caused by a local low charge carrier concentration.

Next, IRT was performed in CdTe PV modules to have a list of defects present in a thin film type PV module. In comparison with crystalline silicon technologies, thin film PV modules are better to be analyzed using dark thermography rather than outdoor conditions. This distinction is caused by how the temperature difference in c-Si and CdTe PV modules is observed. In a c-Si module, normally the temperature increase will take place in a complete cell, group of cells, or even the whole string. But in the case of CdTe, the temperature differences are punctual, like in the case of shunt resistances. These small heat sources are hard to identify because heat dissipates from the PV active material to the rest of the module materials. Before starting the discussion of the images, it is important to note that the hot circle-like shape in the center of the module is the reflection of the lens of the camera (circled in green in figure 8). This can be avoided tilting the camera at least 5 and maximum 60 in reference to the module being analyzed, as presented in figure 3. Shunt paths will represent a heat source when doing dark thermography [10]. As more current is flowing through the shunt, more electrical energy is dissipated and a higher temperature is detected by the camera. This can be seen in figure 8 (circled in black). It can be noted that the temperature differences over the CdTe module presented in this section are smaller than in the sc-Si modules.

If the forward bias is maintained, hot spots will be clearer as the module temperature will continue to rise until the module temperature is in equilibrium with its environment. Equilibrium will depend on the environmental conditions, heat conduction coefficients of the module materials, and convective coefficients of the module with the surrounding air. For crystalline silicon and thin film materials, when the forward bias is stopped, heat starts to distribute. This makes more difficult to detect the defect location and shape.

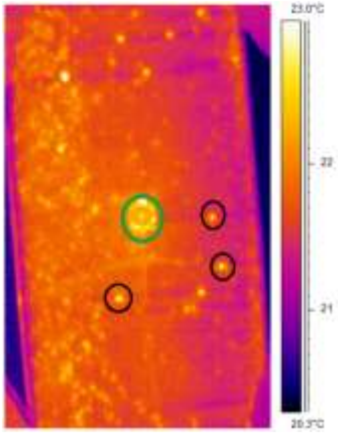

**Figure 8**. IRT of CdTe at ~2 A, after 5 minutes. The green circle indicated the reflection of the camera caused by misplacement. The black circles indicate shunt resistances.

Next, the results obtained from the IV curve measurement analysis will be presented. In figure 9, it can be seen how the $V_{oc}$ level is reduced as temperature rises. As discussed before, the pyranometer is not always reading the same irradiance as the irradiance that is in reality falling onto the module. This causes the $I_{sc}$ values to be inaccurate in relation to the irradiance level.

Irradiance will only play an important role in the $V_{oc}$ measurement at very low irradiances, e.g. lower than 100W/m$^2$.

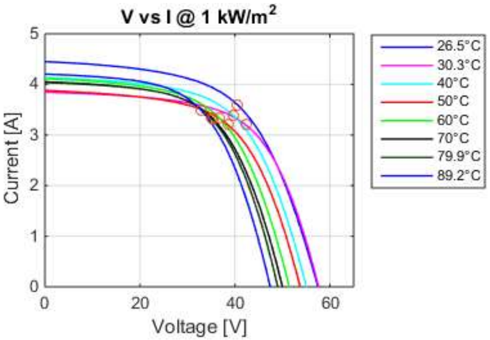

**Figure 9**. IV curves at 1kW/m$^2$.

Temperature influence on the $V_{oc}$ was quantified and compared to the specification of the modules as given by the manufacturer.

Figure 10 and figure 11 show the measured temperature coefficients of the PV modules, and the coefficients that were in the datasheet. These graphs shows that even though the modules have degraded, the measured coefficient (red line) has a similar value to the one in the datasheet (green line).

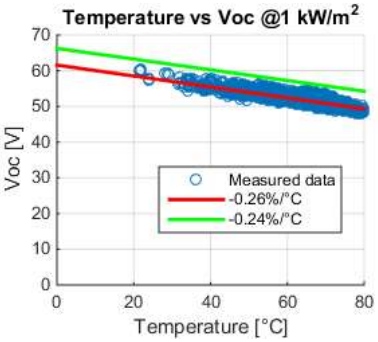

**Figure 10**. Temperature influence on Voc. Datasheet value (green line), and data measured (red line).

If the change in performance is calculated using the new temperature coefficients, an increase in of 0.4 % of the MPP was obtained. This calculation used the $V_{oc}$ and $I_{sc}$ of the datasheet and a temperature of 60 °C, which was a normal operation temperature of the modules. Even though the new temperature coefficients represent a higher MPP level for temperatures higher than 25 °C, the real performance will be lower because the as it can be seen in figure 11, the $V_{oc}$ has been reduced by ~5 V.

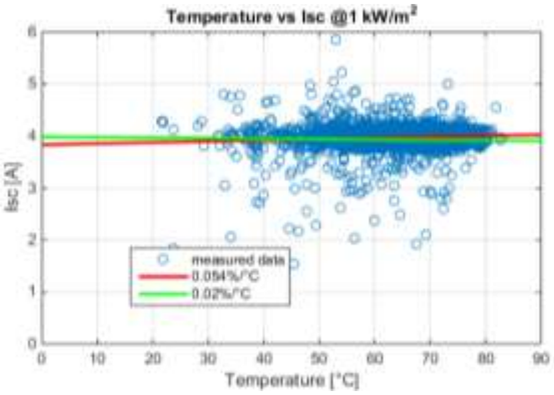

**Figure 11**. Temperature influence on Isc. Datasheet value (green line), and measured data (red line).

Several relations were found between the results of the different characterization techniques. For an overview of whether a defect can be detected in EL or IRT, see table 2. This table also demonstrates that EL can detect a broader amount of defects compared to IRT.

**Table 2.** Defects detection \ in EL and IR.

| Defect | EL | IRT |
|---|---|---|
| **Broken fingers** | ✓ | X |
| **Low Shunt resistances** | ✓ | ✓ |
| **Crystal grain boundaries** | ✓ | X |
| **Micro-cracks** | ✓ | X |
| **Burn marks** | ✓ | X |
| **Potential induced degradation** | ✓ | ✓ |
| **Delamination** | ✓ | ✓ |
| **Cell mismatch** | ✓ | ✓ |
| **Black core** | ✓ | X |

## EL/IRT comparison

Figure 12 shows an EL and IRT image of the same CdTe module. It can be seen clearly that the brighter areas in the EL image of the module are corresponding to the hotter areas in the IRT image, and the darker correspond to cooler areas. The brighter/hotter area in the right side of the module corresponds to an area that was shaded during operation. When it was installed, the top module had this section shaded by a plate of the roof. As this area was not exposed to light during the operation of the modules, it did not suffer from LID. Therefore, the PV active materials in this area were not degraded as compared to the rest of the module.

Figure 13 presents an EL and IRT image taken from the same cell which has several broken fingers. These broken fingers are indicated by red rectangles in the LE image, but it is impossible to identify them in the IRT image. This demonstrates how EL images are more precise to identify defects than IRT images. This is the same case for all the defects that are only identifiable by EL, and not by IRT.

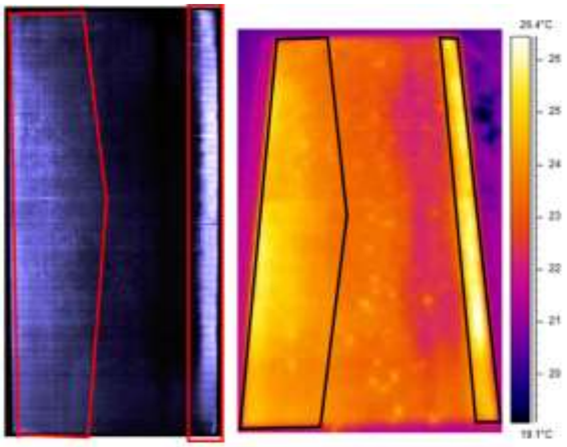

**Figure 12.** EL (left) and IRT (right) on module 3.1. In the EL image, there are two brighter areas and one black spot indicated. These correspond to hotter areas/spots in the IR image.

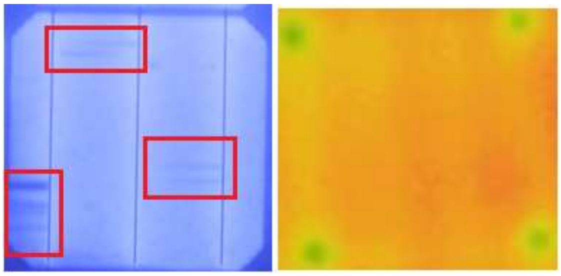

**Figure 13**. EL (left) and IRT (right) image taken from the same sc-SI solar cell. Broken fingers identified in EL but not in IRT.

## Discussion and Conclusions

A. What are the main advantages of EL, IRT and IV tracing as PV characterization techniques?

1. EL is the most efficient way to detect the widest variety of different defects present in a PV module. From typical defects that do not influence the behavior, like burn marks, to shunt resistances that directly reduce the performance of the module, can be observed using EL. All the defects found in the PV modules analyzed were: broken fingers, low shunt resistances, crystal grain boundaries, micro-cracks, burn marks, delamination, cell mismatch, black core, error in production line and light induced degradation (LID). In addition, the light emission was observed to have an angle dependence. It was observed that there is less light transmission towards the camera for smaller angles.

2. Between the characterization techniques utilized, IRT was the quickest way to locate defects since it is the simplest. This is because the module doesn't have to be dismounted or disconnected, IRT measurements can be done while the module is working. In addition, no image processing needs to be done on the image obtained from the camera. The main disadvantage of IRT is that it cannot always show the nature of the defect being observed, or what the cause of it is. Heat diffuses and if the heat production is not high enough compared to the rest of the module, it will not be possible to identify the defect. IRT is suited for both indoor and outdoor conditions.

3. IV tracing is the most efficient method to obtain quantitative data related to the module performance. Various parameters can be obtained from an IV curve (Isc, Voc, FF, and MPP). These, combined with temperature and irradiance measurements, are direct methods to quantify the deviation of the measured performance versus the rated. Even though this method is precise to quantify the performance level of the module analyzed, it is not always possible to determine which defect is causing the poor performance of the module, or the origin of the defect.

B. Can the same setup and equipment be used for indoor and outdoor conditions?

The required equipment to conduct indoor measurements for the three techniques is very similar to the equipment required for outdoor conditions. In the case of EL, the tent will always be required under daylight conditions. During night time if the light from the surroundings is not dominant in the resultant image, it will allow the EL to be performed without the tent. Light filtering and image processing are the two factors that need to be improved in EL measurements. Doing the EL imaging at night is not possible in every location because of practical reasons (e.g. obtaining a permit to access the site on late hours). During night time, there are some conditions that will allow the EL to be performed without the tent. This happens if the light from the surroundings is not dominant in the resultant image. In the case of IRT, no dismounting or disconnection of the modules is required for outdoor conditions. In addition, the tent will not be used at all, radiation is desired to be falling into the module. At last, no artificial power source is required for outdoor conditions. For IV-curve tracing, only the sun simulator will not be used.

C. How are the results of these techniques related? Which is the most efficient way to combine their use?

When characterizing a PV system, EL, IRT, and IV curve tracing measurements can take from a couple of minutes up to an hour depending on how these techniques are used. In order to use these three techniques together when characterizing a module or system, the following suggestions can reduce the characterization time. Different scenarios and how to apply the characterization techniques are presented here:

1. The performance of the system is being monitored:

1.1 The modules are monitored individually: The first step if a low performance is detected is to locate the modules that suffer from lower performance. EL can be used on these specific modules to determine what the origin is or if the modules have to be replaced. If the defects present on the modules do not contribute significantly to the lowering of the module performance, it can be assumed that the performance decrease is a connection or electronics issue. IRT could be used to check the connections and look for sections of the connections that appear hotter than expected.

1.2 The modules are not being monitored individually: If the system is being monitored without individually monitoring the modules, and a low performance level is observed, the IRT imaging can be used to find defective cells or modules. This leads to locating damaged modules. Afterwards, EL imaging can be done to determine precisely which defects are present and the causes for the reduced performance.

In both cases, if low performance is being measured and no defect can be seen with EL and IR, IV curve tracing can be performed in order to confirm that the modules have good quality. If this is the case, then it can be assumed that the reduction of the performance is not related to the PV modules and testing the rest of the components of the PV system is required.

2. The system is not monitored: In this case a regular IRT imaging can be done in order to check for malfunctioning components in the system. Even though solar panels are not expected to fail after installation, a quick check can be done right after the installation is finished, this will rule out any damages caused during transportation and installation. IRT imaging can be done once or twice per year as a preventive measurement as well. In addition, a power meter can be used to measure performance. If more information is desired IV tracing and EL can be useful. Characterizing PV systems will avoid operation with damaged components, further degrading them, or the rest of the system.

After presenting the general conclusions, specific conclusions are presented:

- A reduction of 6 % and 7 % of the $V_{oc}$ and FF respectively, represent a reduction of 75 % of the brightness level measured in an EL measurement.

-Areas of a PV module that suffered from LID will appear darker in an EL image and hotter in an IRT image.
- Shunt resistances appear as bright spots in EL and hotspots in IRT. Each bright spot will correspond to a hotspot when analyzing one module with these two techniques.
- No direct relation was found between the performance of a PV module and its brightness level measured with EL. All the modules had a brightness level of around 10, and compared to its initial brightness of around 40, the small differences between the modules are not significant.
- EL, IRT and IV curve tracing measurements complement each other. Not using one of them would result in a reduction of the accuracy of the study, the time spent on identifying defects, and therefore, the results.

These specific results relating the characterization techniques can help future research giving guidelines on how to use time efficiently.

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