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Non-destructive techniques for quality control of photovoltaic modules: Electroluminescence imaging and infrared thermography

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ABSTRACT
Non-destructive methods for measuring photovoltaic modules are discussed in this paper, with the aim of comparing different quality-assurance methods for different module technologies (e.g. crystalline and thin-film technologies: a-Si, CdTe, CIS). For a complete quality control of PV modules, a combination of fast and non-destructive methods was investigated. In particular, camera-based measurements, such as electroluminescence (EL) and infrared (IR) technologies, offer excellent possibilities for determining production failures or defects in solar modules, which cannot be detected by means of standard power measurements. These methods are applied effectively in quality control and development support, and EL is already an important characterization tool in industry and research. Most short circuits reduce the voltage in their surrounding area and appear dark in EL images. However, as this failure is not always critical and apparent, short circuits are only precisely identifiable in combination with IR measurements. Therefore, to quickly detect at high resolution the most common defects in a PV module, a combination of EL and IR measurements is advisable.

Introduction

Infrared (IR) and electroluminescence (EL) imaging are both non-destructive measurement techniques. These types of optical measurement provide fast, real-time and (in the case of EL imaging) high-resolution images with a two-dimensional distribution of the characteristic features of PV modules.

These methods have been introduced and used by several groups for determining a few physical parameters of solar cells, e.g. EL for measuring local effective diffusion length l_{eff} [1], carrier collection length l_c [2], local junction voltage [3] and series resistance [4,5]. The work presented in this paper, however, focuses on quality control and characterization using EL and IR imaging with conventional cameras; as an example, imaging is carried out before and after ageing. In addition, some rules for measuring with cameras are included in the presentation of this work.

> "The high resolution of EL images allows some defects to be determined more precisely than with IR images."

EL has proved to be a useful tool for investigating electrical inhomogeneities caused by intrinsic defects (e.g. grain boundaries, dislocations, shunts or other process failures) and extrinsic defects (e.g. cell cracks, TCO corrosion or interrupted contacts). IR measurements, on the other hand, allow the thermal behaviour of cells in a module and a number of defects (e.g. short circuits in solar cells, shunts, inactive cell parts, moisture, defective bypass diodes) to be determined.

Theory

IR thermography

IR measurements can be taken by using an external current or by applying light. During measurements in the dark, no light is applied to the module but an external current (less than or equal to the short-circuit current I_{sc}) is supplied in the forward direction [6]. In order to avoid thermal damage to thin-film modules it must be ensured that the I_{sc} of the modules is not exceeded. During illuminated measurements, a current is generated by incident light (e.g. the sun), which can cause different emitted heat radiation.

For a more precise defect detection, illuminated thermography imaging is performed and comparisons are made for modules operated under different conditions, such as short circuit, open circuit and maximum power point (MPP). Several defects can be distinguished by varying the electrical load corresponding to certain states of the current–voltage characteristics.

Heating can be identified using an appropriate IR camera, and compared to electroluminescence measurements. In this work, thermography imaging was performed by means of a portable, uncooled IR camera, with the IR detector having a wavelength between 8 and 14µm.

Electroluminescence (EL)

EL measurements take advantage of the radiative interband recombination of excited charge carriers in solar cells. For EL investigations the module is operated as a light-emitting diode and the emitted radiation due to recombination effects is detected with a sensitive Si-CCD camera. The wavelength window of the Si-CCD camera is 300 to 1000nm.

The solar cells are supplied with a defined external excitation current (less than or equal to I_{sc}) while the camera takes an image of the emitted photons. Damaged areas of a solar module appear dark or are less shiny than areas without defects. Electroluminescence imaging can be used to detect a number of defects in crystalline and thin-film solar cells [7]. The high resolution of EL images allows some defects to be determined more precisely than with IR images.

Experiments

Different module technologies, such as crystalline (single and multicrystalline) and thin-film (CIS, a-Si, CdTe), were analyzed by electroluminescence and IR thermography under external bias and illumination. Additional characterization tools used were common characterization measurements (e.g. *I-V* measurements) and new improved evaluation processes.

EL and IR measurements of a single crystalline module

In the EL image of the single crystalline (sc-Si) module shown in Fig. 1, the defects appear as dark areas. Some cracks and dark cells of lower electrical activity are visible. The illuminated IR image of the sc-Si module in Fig. 2, under short-circuit current conditions, shows some hot cells. The darker cells in Fig. 1, where a bad cell quality was assumed, caused higher cell temperatures.

When the sc-Si module is operated at MPP (Fig. 3), some cells have lower temperatures than when under I_{sc} conditions; this is caused by different I_{sc} levels of the cells. Cell measurements before integrating the cells in the sc-Si module confirmed that the hottest cells are mainly those with high series resistances and/or low short-circuit currents.

It turned out that dark thermography measurements were not suitable for crystalline modules (Fig. 4). In the dark thermography image of crystalline modules, only fractured cells could be identified as very hot cells with an inactive part. Other defects could not be identified very clearly using this method.

EL measurements of a multicrystalline (mc-Si) module before and after mechanical load

The EL imaging and the current–voltage measurements of a mc-Si module were carried out before and after a mechanical load analysis for loads of 1500Pa, 2400Pa, 4500Pa, 5400Pa, 6500Pa and 9000Pa. The module broke when subjected to a pressure of 9000Pa. The imaging and measurement results before and after the application of mechanical loads of 2400Pa and 6500Pa are shown in Figs. 5–7 and Table 1.

Besides some darker areas, caused by grain boundaries, in the EL image of Fig. 5, there are also some significant defects (e.g. cracks and finger failures) visible. After a load of 2400Pa (Fig. 6), the number of cracks (visible as darker cell areas) increased. After four mechanical load tests (Fig. 7), the number of cracks and broken cells increased further.

The results of the current–voltage measurements indicate a degradation of power of 7% as seen in Fig. 8. This power loss is mainly caused by the reduction of U_{mp} and I_{mp}, which is dependent on the number of cracks, the consequently reduced available cell area and the increased series resistances.

Vertical and horizontal 'line scans' over the EL images of the mc-Si module, before and after applying the load tests, help to identify a defect increase per row or column. By averaging all EL pixel colours along an axis, average line scans can be calculated over the whole module. A decrease of EL radiation density with distance from the bus bars, especially in the projection along the long axis (x-direction, 9 cells), is evident in Figs. 5–7.

Fig. 9 shows a vertical line scan over the short axis (y-direction, 6 cells). It is

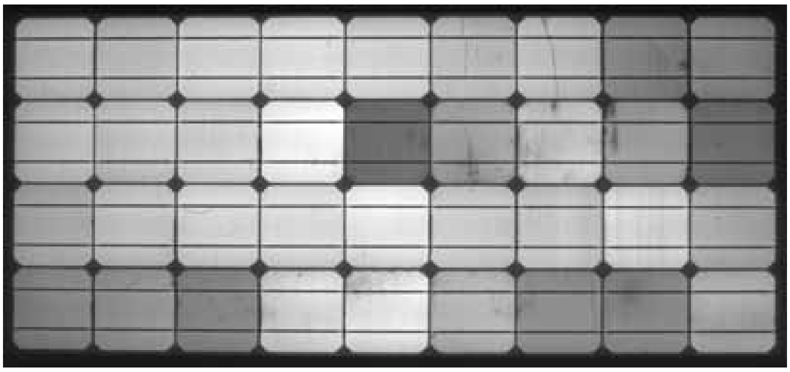

Figure 1. EL image of the sc-Si module.

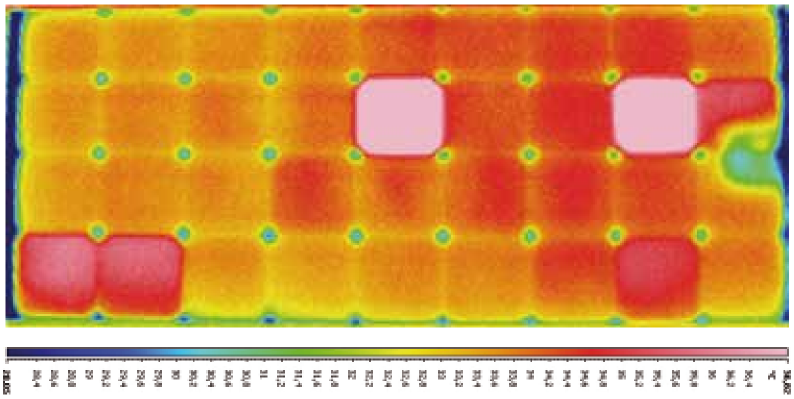

Figure 2. IR image of the I_{sc}-operated sc-Si module.

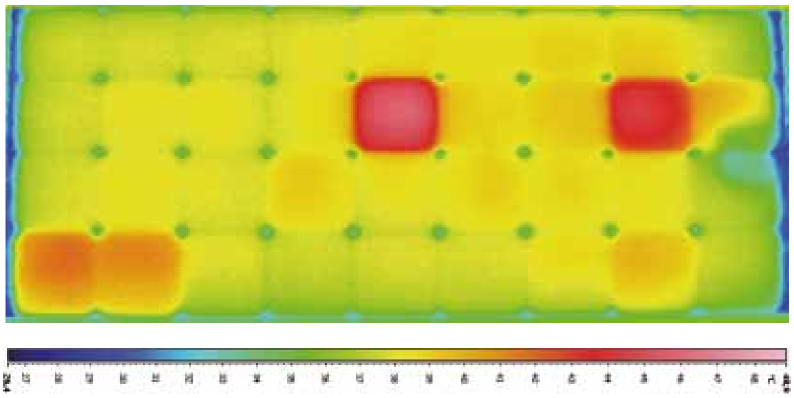

Figure 3. IR image of the MPP-operated sc-Si module.

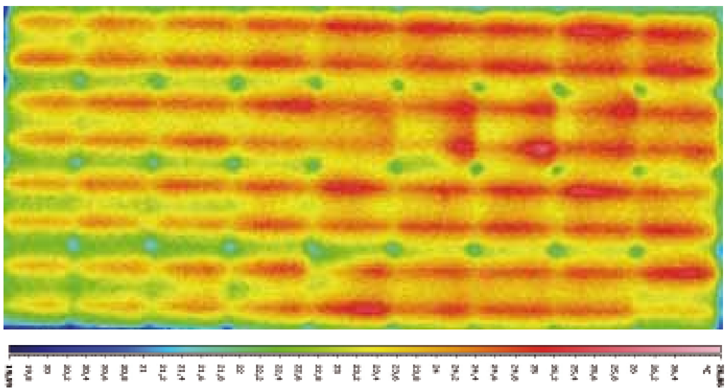

Figure 4. Dark IR image of the sc-Si module.

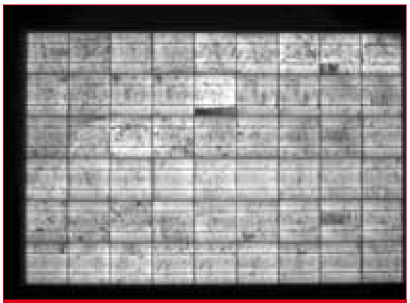

Figure 5. EL image – mc-Si module before the mechanical load test.

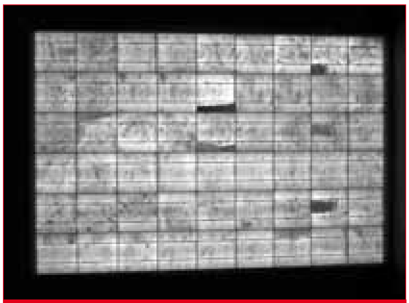

Figure 6. EL image – mc-Si module after the 2400Pa load test.

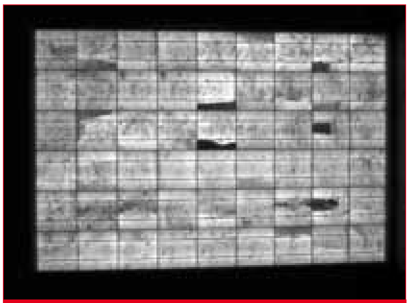

Figure 7. EL image – mc-Si module after the 6500Pa load test.

	U_{oc} [V]	I_{sc} [A]	U_{mp} [V]	I_{mp} [A]	P_{max} [W]	FF [%]
Before load test	33.43	8.54	26.71	7.93	211.68	74
After 2400Pa load test	33.38	8.55	26.51	7.79	206.61	72
After 6500Pa load test	33.34	8.54	26.14	7.23	196.18	69

U_{oc} = open-circuit voltage; I_{sc} = short-circuit current; U_{mp} = voltage at P_{max}; I_{mp} = current at P_{max}; P_{max} = maximum power point; FF = fill factor

Table 1. Current–voltage measurements before and after mechanical load tests.

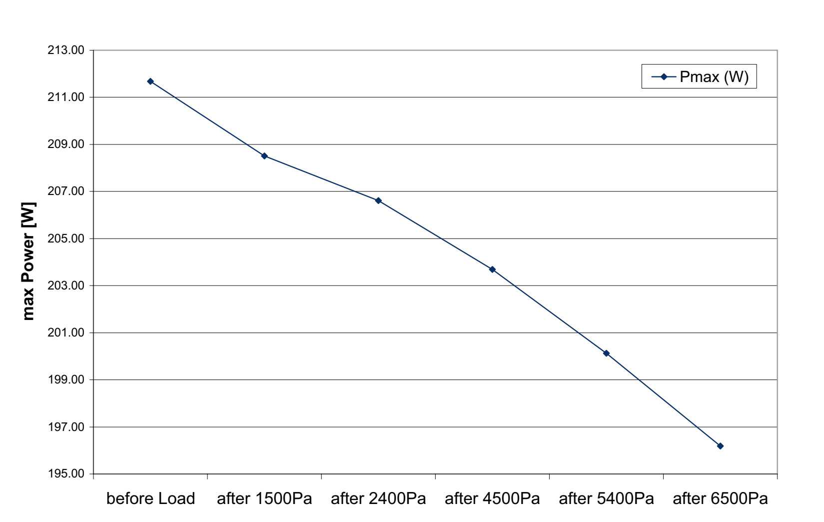

Figure 8. Power degradation.

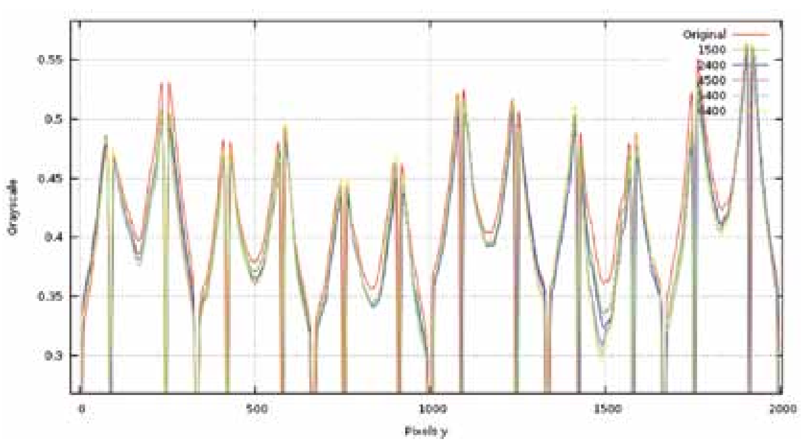

Figure 9. Vertical 'line scan': averaging of all pixel intensities along the module long axis. The busbars and borders of the six cells are visible, together with the developing effect of the load tests.

remarkable that the upper three cell rows (on the left of the figure) have relatively more damaged cell areas than the lower three cell rows (on the right), while an inhomogeneous current distribution between the two bus bars of a cell row is also observed. The individual asymmetries were, however, hardly affected by the load tests.

Characterization of an a-Si module before and after ageing processes

An a-Si module was characterized before and after it was exposed to some ageing tests – preconditioning, light soaking and application of a reverse current. EL and IR imaging, as well as performance measurements, was carried out and the results compared.

In the EL image of the a-Si module before ageing (Fig. 10), there are no significant

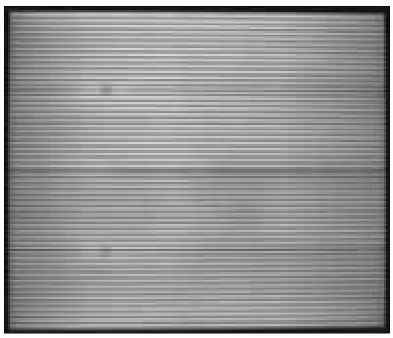

Figure 10. EL image – a-Si module before ageing.

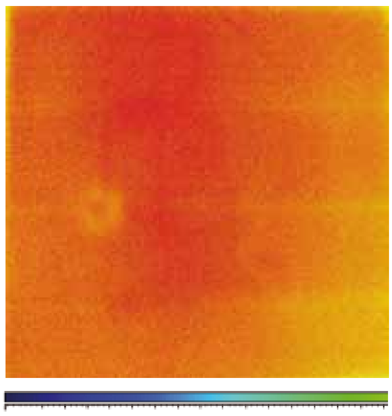

Figure 11. Dark IR image – a-Si module before ageing.

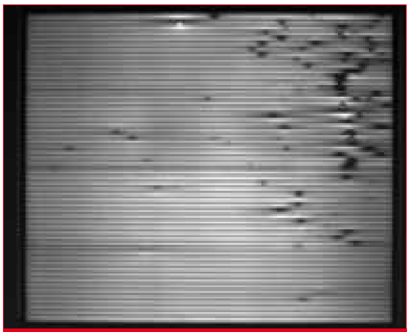

Figure 12. EL image – a-Si module after ageing.

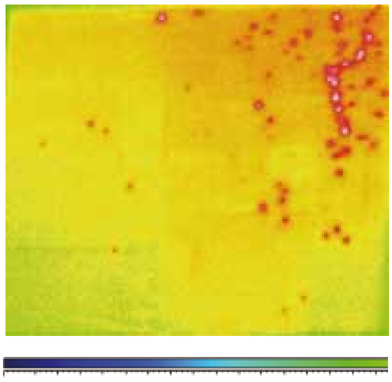

Figure 13. Dark IR image – a-Si module after ageing.

defects visible, apart from some darker areas. Likewise, there are hardly any defects identifiable in the IR image of the same module (Fig. 11): only the metallic junction box was visible as a cooler area in the image.

The EL image of the a-Si module after ageing (Fig. 12) mainly shows punctual shunts inside a cell or between the metal layers of two adjacent cells. In the EL image the punctual shunts in the cell area appear as black points; bright points appear in between two cells, where the current flows through the shunt to the Si-layer of the next cell. The bright points are caused by increased recombination of electron-hole pairs and/or increased thermal radiation in the surroundings of the shunt area [8]. The dark thermography image of the a-Si module (Fig. 13) shows almost the same defects as the EL image, but it is not always possible to identify their exact locations.

The EL image detected with the Si-CCD camera generally shows an intensity distribution (grey-scale image) of the luminescence radiation. A further evaluation process is the generation of a frequency distribution, specifically a histogram of the available grey values in the EL image. The increase in defects before and after electrical or mechanical loading of modules can be more accurately determined using this evaluation.

A comparison of the frequency distributions of the available grey values before and after ageing tests (Figs. 14 and 15) shows a shifting of the intensity distribution and a rise in the dark/defect areas (circled in Fig. 15). This evaluation process is very helpful in the case of modules for which no increase in defects is clearly observable.

Since not all defects have an influence on the power output of cells or modules, performance measurements were taken in addition to the EL and IR measurements. These measurements show a relation between the increase in defects within a cell or module and the measured power losses. The results of the current–voltage measurements before and after ageing are shown in Table 2. After ageing of an a-Si module (Fig. 12), there was a degradation in power of approximately 30%; this power loss was mainly caused by the reduction of the short-circuit current due to the reduced cell area.

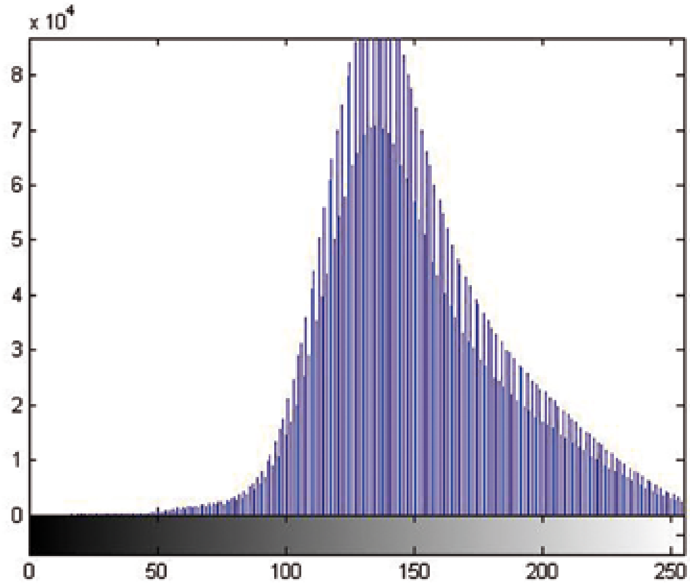

Figure 14. Frequency distribution of grey values before ageing.

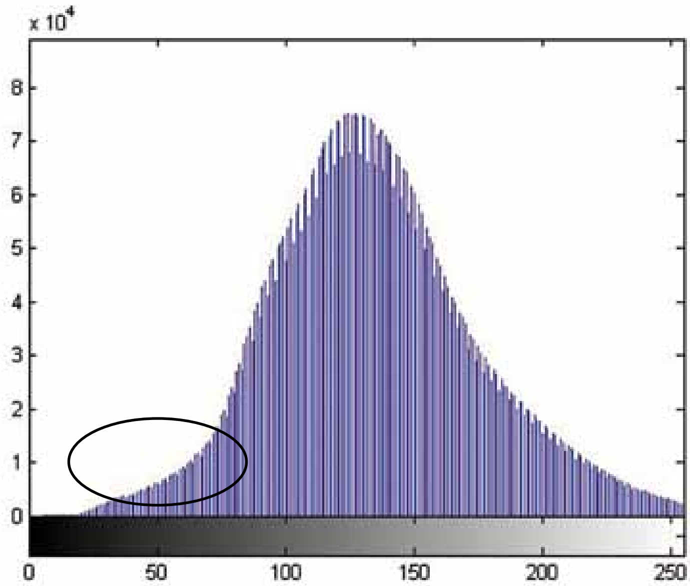

Figure 15. Frequency distribution of grey values after ageing.

	U_{oc} [V]	I_{sc} [A]	U_{mp} [V]	I_{mp} [A]	P_{max} [W]
Before ageing	23.59	7.07	16.97	5.73	97.23
After ageing	22.98	5.19	16.60	4.13	68.52

Table 2. Current–voltage measurement results.

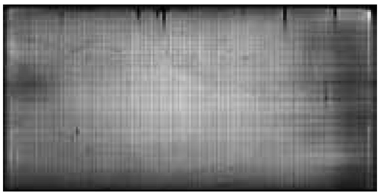

Figure 16. EL image – CdTe module (injected current = 1A).

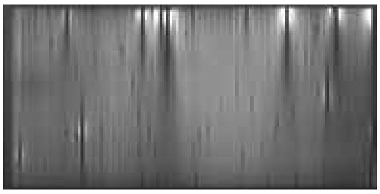

Figure 17. EL image – CdTe module (injected current = 0.1A).

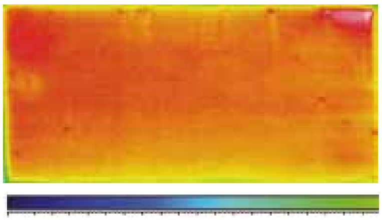

Figure 18. Dark IR image – CdTe module.

Injection current-dependent EL measurements of a CdTe module

To determine the influence of defects (e.g. shunts), the EL behaviour of modules when different current densities are applied was investigated. When a low current density is applied, the conductivity of shunts is very high: the stronger the shunts, the lower the EL intensity in this area. Strong shunts can supress the EL intensity of a whole cell. When higher current densities are applied, the increase in conductivity of the p-n junction is relatively greater compared to the shunt conductivity, and shunts are less influential on the EL intensity distribution [9].

The EL images of a CdTe module, taken after applying different forward bias voltages, were compared. Fig. 16 shows the EL image of the CdTe module with an injected current of 1A (I_{sc} of the module); Fig. 17 shows the EL image with an injected current of 0.1A. A comparison of the two EL images shows very clearly that effective shunts are visible as punctual defects and thus better detectable when high currents are injected. On the other hand, the EL intensity of the area around effective shunts is considerably increased when low currents are injected.

Most of the identified defects (mainly shunts) in the EL image of the CdTe module in Fig. 16 are also visible in the dark thermography image in Fig. 18. The hot spots identified in Fig. 18 can be attributed to areas with a low shunt resistance, where the current flows through the defect and creates a heat source.

Comparison of EL and IR images of a CIS module

Fig. 19 shows the EL image of a CIS module: punctual areas of reduced EL intensity are caused by shunts. Since shunts are easier to locate at high current densities, the current applied was the I_{sc} of the module. An illuminated thermography image (Fig. 20) of the CIS module operated under short-circuit conditions reveals some hot spots, but they are not as clear as in the dark thermography image (Fig. 21). With regard to thin-film technology, it transpired that dark thermography measurements generally supplied more detailed images than illuminated thermography measurements.

Conclusions

It has been shown that EL is clearly an appropriate method for detecting micro-cracks, interrupted contacts or a number of process failures (e.g. shunts or defects in the antireflection layer). However, it was not possible to determine the influence of these defects on the cell/module power output. The IR measurements taken proved that, on the one hand, not all identified defects lead to an increase in temperature. On the other hand, cells/

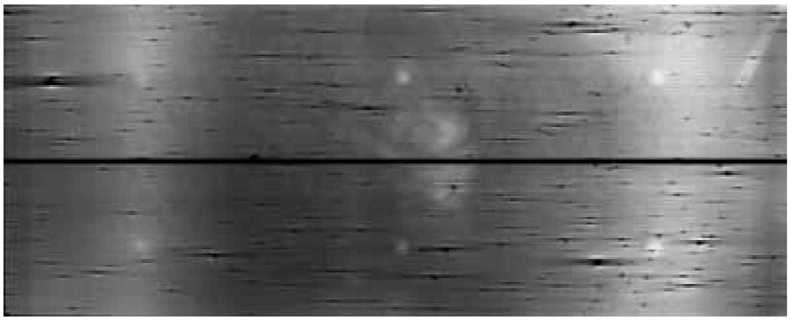

Figure 19. EL image – CIS module.

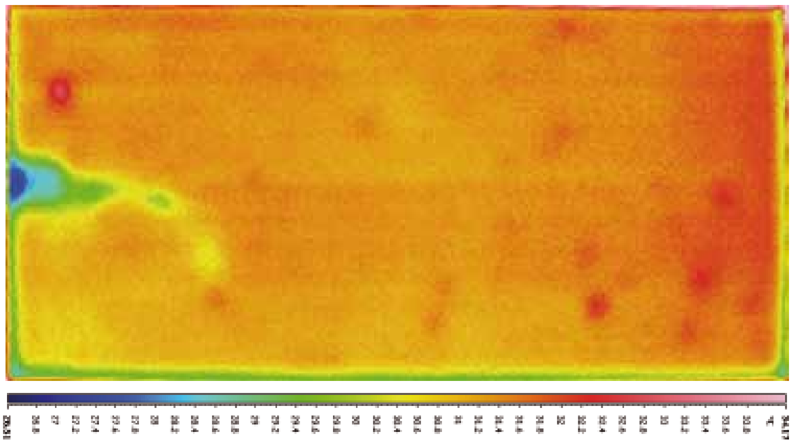

Figure 20. IR image – I_{sc}-operated CIS module.

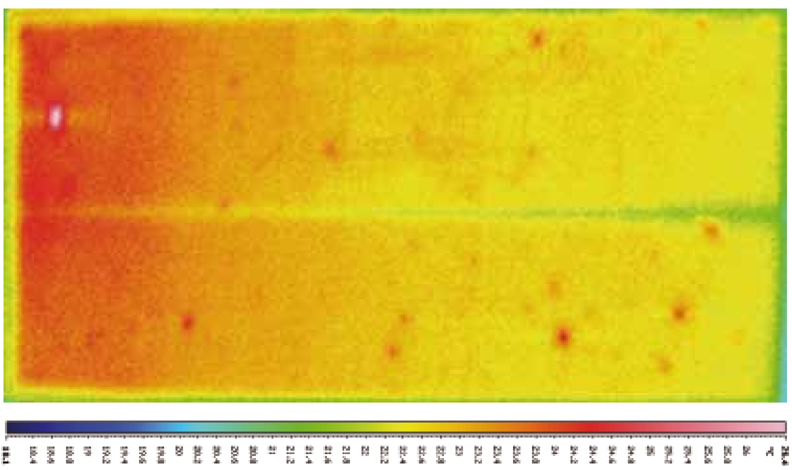

Figure 21. Dark IR image – CIS module.

modules with unremarkable EL images sometimes supply IR images with hot areas, which are caused by high power losses. Therefore, a combination of EL and IR techniques is necessary in order to identify as many defects as possible [8]. Short-circuit measurements of each cell in a module also give information about the cell's condition. In most cases the cell that produces the largest decrease in short-circuit current is also the hottest one (identified by IR measurements).

In the case of sun-illuminated thermography, varying the electrical load helps to distinguish several defects. If the voltage is increased from zero to that at MPP, some hot spots disappear because of the different I_{sc} of the cells. The hot spots, which vanish if the voltage is increased towards U_{oc}, are caused by areas of increased series resistance [10].

It was easier to distinguish defects in crystalline modules than in thin-film modules. In the thermography images of thin-film modules the exact location of the defects could not always be identified and the large number of small spots made this determination difficult.

As regards IR thermography measurements, it turned out that illuminated thermography is more suited to crystalline modules, whereas dark thermography is a better tool for thin-film modules [11]. Compared to dark thermography images of crystalline modules, illuminated thermography images offer more detail and a better defect resolution; for thin-film modules the opposite is true.

"Compared to dark thermography images of crystalline modules, illuminated thermography images offer more detail and a better defect resolution; for thin-film modules the opposite is true."

A vitally important loss mechanism, mainly applicable to thin-film modules, is the loss due to localized shunts in the module. A typical thin-film module consists of a number of elongated cells connected in series and separated from each other by scribe lines. Shunt paths can be caused by imperfections in the scribing procedure, develop during the film growth process (e.g. penetration of the junction depletion layer) or occur when layers are too thin or not properly deposited. The existence of localized shunts, specifically hot spots, could also be proved in this case by means of EL and IR thermography measurements. Finally, it could be proved that the effectiveness of defects (e.g. very strong shunts) is identifiable by means of current-dependent EL measurements.

It was also noticed that the radiation of thin-film modules under forward bias was weaker than that of crystalline modules. It is therefore very important that, when taking EL measurements of thin-film modules, there is no reflection of any other light source on the module: the measurement room must be kept in complete darkness.

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