Metrol. Meas. Syst., Vol. 30 (2023) No. 3, pp. 381–401
DOI: 10.24425/mms.2023.146426

METROLOGY AND MEASUREMENT SYSTEMS

Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

IMAGING METHODS OF DETECTING DEFECTS IN PHOTOVOLTAIC SOLAR CELLS AND MODULES: A SURVEY

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Abstract

In pursuit of increased efficiency and longer operating times of photovoltaic systems, one may encounter numerous difficulties in the form of defects that occur in both individual solar cells and whole modules. The causes of the occurrence range from structural defects to damage during assembly or, finally, wear and tear of the material due to operation. This article provides an overview of modern imaging methods used to detect various types of defects found in photovoltaic cells and panels. The first part reviews typical defects. The second part of the paper reviews imaging methods with examples of the authors' own test results. The article concludes with recommendations and tables that provide a kind of comprehensive guide to the methods described, depending on the type of defects detected, the range of applicability, etc. The authors also shared their speculations on current trends and the possible path for further development and research in the field of solar cell defect analysis using imaging.

Keywords: solar cells, defects, photovoltaic cell characterization, defect imaging, electroluminescence, photoluminescence.

1. Introduction

It is well-known that one of the key factors affecting the efficiency and durability of photovoltaic installations is the occurrence of various types of defects and damage during their operation. The reasons for their occurrence can range from material defects that reveal themselves over time, defects that occur during production, to various defects that occurred accidentally during the use of the panels or that result from the natural processes of degradation and wear of the materials used. The occurrence of defects is the main reason for the degradation of the performance of a photovoltaic system. While various types of mechanical defects in the panels can result from, for example, accidental damage during transport or installation, or during the exploitation of the system due to environmental incidents such as storms or hail, other types of defects that become

Article history: received April 13, 2023; revised May 23, 2023; accepted May 31, 2023; available online September 20, 2023.

apparent during the use of PV panels may result from defects present in the PV cells themselves. These primarily include various types of inhomogeneities and microcracks. Therefore, it is important to effectively eliminate such defects in solar cells yet at an early stage of the production of the panels. Some of the defects can be detected using optical inspection. However, the outcome of such inspection often depends on the operator's perception, experience, and personal judgment, and can only be effective for a limited type of typical macrodefects, *e.g.*, cell fractures. In recent years, due to the rapid development of the solar energy market, there has been a growing demand for fast and reliable methods to detect various types of defects that could be applied during the subsequent manufacturing stages of PV panels. These include various selection tests based on random quality control between stages and in-line inspection. Some of the modern inspection methods include vision systems and defect imaging, the end result of which is an image that is subject to further analysis. Decisions are often made using automatic detection systems that apply artificial intelligence [1–3]. These include, among others, infrared imaging methods [4], electroluminescence imaging [5], or photoluminescence imaging [6]. Each of these methods has its own advantages, as well as limitations, *e.g.* regarding the scope of application, type of defects detected, speed of operation, invasiveness, *etc.* This article provides a brief overview of typical defects that can occur in photovoltaic cells, along with a discussion of selected methods for their imaging.

2. Types of defects in photovoltaic cells and modules

The defects that occur in photovoltaic panels can be divided into those that occur directly in the photovoltaic cells and those related to the design of the PV panels themselves. In this section, the typical types of defects that can be found in both are characterised in terms of the causes, scale, and type of consequences they cause.

2.1. Defects in photovoltaic cells

2.1.1. Hotspots

The hotspot in itself is a local anomaly in the temperature distribution on a working solar cell, characterised by a significantly higher temperature value than the rest of its surface. It may be triggered by local shading of a given surface, causing a consequential increase in local resistance that leads to overheating. Such shading may find its causes in, *e.g.*, nearby trees or any towering infrastructure, overdue snow, or not cleaned dirt. Other causes may also be structural damage such as microcracks or incorrectly designed construction in which solar cells with different I–V characteristics are merged in a serial connection. It is one of the most dangerous defects that can lead to the complete destruction of the solar cell in a very short period of time [7, 8].

2.1.2. Solar cell breakages and microcraks

Breakages and microcraks are defects consisting of breaking the structural continuity of the solar cell. Most of them, first of all, are not harmful with time, and further exploitation may significantly affect solar cell efficiency. Breakages may appear in every part of the life cycle of solar cells, from the production line, during transportation, and finally in installation [8, 9]. An example of breakages visible with the naked eye appearing in solar cells is presented in Fig. 1.

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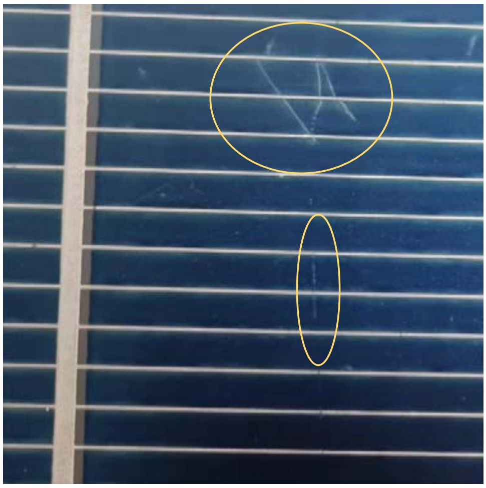

Fig. 1. A hotspot appearing on the conductive path at the top of the photovoltaic cell.

2.1.3. Other types of defects in solar cells

Other types of defects commonly found in solar cells include inhomogeneities in the dopant distribution in the junction region of the silicon wafer, defects in the antireflection layer or gaps in the front electrode paths. The presence of defects of this type is most often caused by a defective manufacturing process, *i.e.* during doping, application of the anti-reflective layer, surface soiling, or a defective screen-printing process. It is important that such defects can be detected at an early stage, before the defective cells are assembled into modules in PV panels.

2.2. Defects in photovoltaic modules

2.2.1. Delamination

Delamination consists in the loss of cohesion of individual component layers of a solar panel, which can lead to a notable loss of efficiency. It applies to both glass, front and back active area, and also encapsulation. Delamination is easily detectable not only with specialized imaging methods but also during visual inspection. It can appear during production, *e.g.* as a result of a too long/short burnout process, in conservation/storage, but also during transportation or installation and finally during exploitation itself. The appearance of delamination ends up in a lack of separation from external conditions, which can lead to the penetration with water or pollution, resulting in contact corrosion, short circuits of wires, or changes in the cell surface absorption coefficient due to the presence of moisture. An exemplary image of the delamination in a solar panel is presented in Fig. 2.

2.2.2. Backsheet flaws

A defect that appears as a consequence of exposure of the module to weather conditions or mechanical stress [10]. The type of failure is mainly dependent on the quality of the materials used to produce the backsheet [11, 12]. An example of such a flaw might be the delamination of the backsheet encapsulation, which can be caused by the attrition of the outer layer due to exposure to weather conditions and which might be a result of mechanical damage caused during

Fig. 2. Delamination of the photovoltaic panel on its surface.

production or installation processes. It may also be an effect of increased ductility on the basis of ultraviolet radiation and high temperature. Every failure appearing around the backsheet is critical for the safety of the module mostly because, in addition to protection of any electronic components inside it, it is also responsible for secure work when high voltages appear.

2.2.3. Potential-induced degradation (PID)

This defect consists in a flow of leakage currents through the cell induced by the potential difference arising at the two sides of the photovoltaic module. This phenomenon is the stronger, the larger the module on which it occurs. Initially unnoticeable, over time it contributes to a significant decrease in the efficiency of individual cells in the module drastically reducing its efficiency [8, 13–15].

2.2.4. Junction box failures

A defect involving loosening or breaking the attachment between the box and the rear wall of the panel. It can be identified mainly during operation and its occurrence is conditioned by the presence of manufacturing/assembly defects or the use of low-quality materials in manufacturing. The occurrence of this defect can result in the ingress of moisture leading to corrosion. Furthermore, a defect that involves poorly constructed or improperly protected wiring that is part of the connection system (which is particularly dangerous) can cause short circuits that cause the panel or its parts to ignite [8, 16].

2.2.5. EVA discolouration

The discoloration of the *ethylene-vinyl acetate* (EVA) foil is one of the most common defects found in PV panels (Fig. 3). Its causes can be wrong manufacturing process (poorly conducted encapsulation process, improper cleaning of the surface of the tempered glass on which the film is be applied) or the properties of the material from which the film was made (improperly selected manufacturing parameters) [8]. Depending on the degree of severity, discoloration of the EVA

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film can have a different impact (negligible or significant) on cell performance. The reason for this is the change in the absorption coefficient of the surface, which is a direct effect of the presence of discoloration, which can occur over the entire surface of the cell.

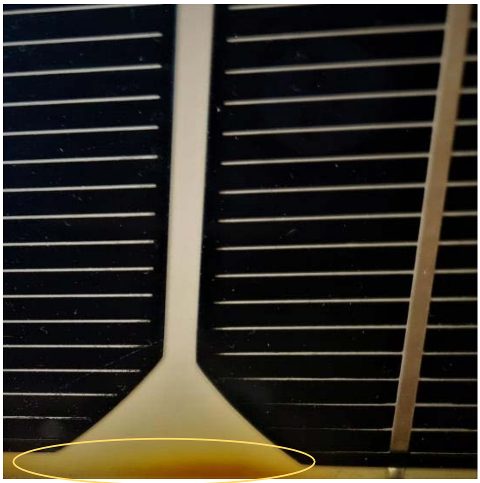

Fig. 3. Yellowing of the EVA film on the photovoltaic panel.

2.2.6. Snail trails

Snail trails are defects involving corrosion of the front electrodes in the PV panel. They occurs during the early stage of its operation and can be observed with the onset of EVA film degradation or malfunction of the encapsulation process (usually 3–12 months after the start of operation) [8]. This defect is easily noticed by visual inspection as a cell discoloration. Very often snail trails are accompanied by (micro)cracks.

2.2.7. Frame breakages

The frame, as the element that unites the entire link and is the outer part of it, is the most vulnerable to weathering. Its damage can result from both mechanical stress to which it is subjected during the installation process and during an explosion, when it accumulates large amounts of snow on itself in winter [17, 18]. Its components can also be defective, especially silicone fittings, whose leaks can lead to moisture entering the device, which can cause corrosion and short circuits.

2.2.8. Front glass breakages

Front glass breakages are defects involving structural breaks in the glass that covers the photovoltaic module, as shown in Fig. 4. As a result of damage to the glass, external contaminants and moisture, which are highly damaging factors for the operation of the system, can enter the cell. Damage to the glass also contributes to exposing the cell to the destructive effects of temperature and UV radiation, against which the glass was supposed to be a barrier, and its absence can result in significant overheating of the panel in exposed areas and the occurrence of further damage in the form, for example, of hot spots. Cracks can form at all stages of cell operation, from cell manufacture and transport to its installation at the final site [8, 16].

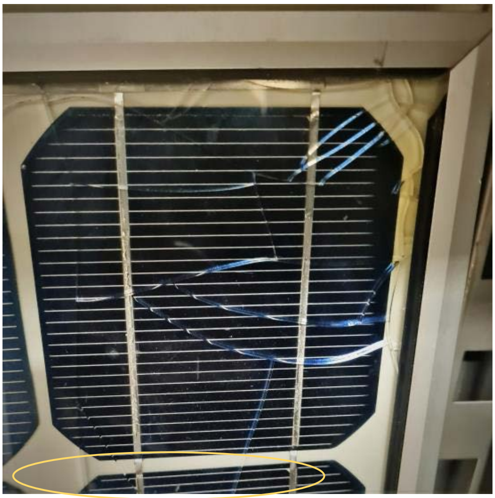

Fig. 4. Front glass breakages as a result of stress.

2.2.9. Damaged busbars or disconnected contacts

Damaged busbars are defects in the connection between cells that are part of a larger module, resulting in partial or complete exclusion of individual cells from the circuit (Fig. 5) [19]. They can occur during the manufacturing, transportation, or assembly of the entire structure. Disconnected/damaged cells stop generating current and begin to heat up severely, which can result in structural fire and damage/destruction of the working parts of the module. Disconnection of one of the modules during the operation of the structure results in activation of the bypass diode, which protects our cell in the event of such a situation, but in the case of prolonged procedure, it can completely destroy the entire series.

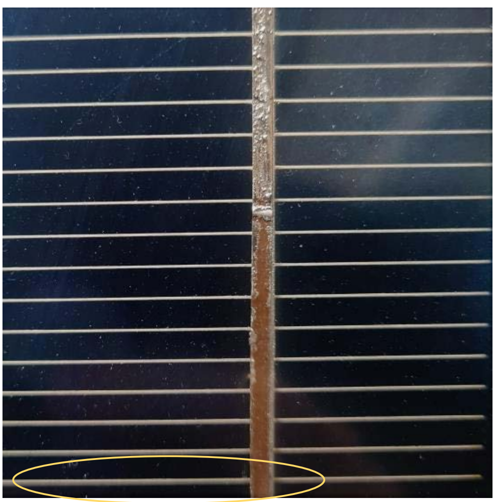

Fig. 5. Busbar degradation.

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2.2.10. By-pass diode failures

By-pass diode failures are defects consisting in intense overheating of the by-pass diode. It is a consequence of the use of a diode that is not in agreement with the circuit parameters in the production stage or an incorrect assembly, causing the part of the cell to become constantly darkened. As a result of overheating, the diode will affect the cell, which can cause hot spots or damage the junction box [8, 20, 21]. It should be noted that, despite the design of the bypass diode to serve as a safeguard in the photovoltaic module system, it is not designed for continuous operation and its regular operation significantly reduces the life of the panel.

3. Methods of detection

Modern methods used to detect different types of defects in photovoltaic cells and panels are based primarily on imaging methods. Unlike typical current-voltage tests, which help determine the efficiency of converting solar energy into electricity, imaging methods help visualise and locate the cause of cell (or PV panel) degradation. The imaging methods used can be divided into those in which (i) an image of defects is formed by excitation of the cell with electric current or illumination (*e.g.*, UV) and next the image of the PV cell (panel) under test is acquired with an external CCD or CMOS camera, and those in which (ii) an image is created based on the signal induced or emitted from the cell as a result of local excitation with a focused beam of light, electrons, or ions.

The methods most commonly used today in industrial practise include type (i) imaging methods such as *electroluminescence* (ELI), *photoluminescence* (PLI), *infrared imaging* (IRI), or *ultraviolet imaging* (UVI). Such methods can be applied in-line at particular stages of the PV panel production process or in a working PV plant. Other methods of type (ii), such as lock-in thermography, electron- or light-beam-induced current and time-of-flight secondary-ion mass spectrometry, are specialised methods typically applied to solar cells to identify the cause of defects, only in laboratory conditions. The section provides below an overview of the above-mentioned methods and discusses their advantages and limitations.

3.1. Electroluminescence imaging (ELI)

ELI is an imaging method to record images of radiation emitted from a photovoltaic cell that is powered in the forward direction [22]. The range of cell radiation measured, depending on the detector used, is 300–1250 nm [23–26]. The recommended exposure time ranges from 120 s [25] to 300 s [24] or 400 s [27]. This method allows characterization of individual photovoltaic modules/cells, as well as whole panels [8, 23, 28, 29]. To ensure high-quality measurements, it is recommended to isolate the cell under test from external light sources [23, 24, 26]. Cooled CCD cameras [22–25, 29–31], CMOS detectors, and InGaAs detectors [23, 24] are used for measurements. The allowable current can be less than or equal to the I_{SC} (short circuit current) of the cell under test [24, 30]. An exemplary measurement system of EL imaging is shown in Fig. 6.

The following defects can be tested with ELI:
- discoloration of EVA film [22],
- interconnection failures [24, 25, 30, 32, 33],
- delamination [32, 34],
- hotspots [35],
- busbar corrosion [24],

– PID [30, 33, 36],
– snail trails [33],
– bypass diode failure [33],
– crystal dislocations [8],
– glass/cell cracks [22–25, 27, 30, 32, 33, 35–39].

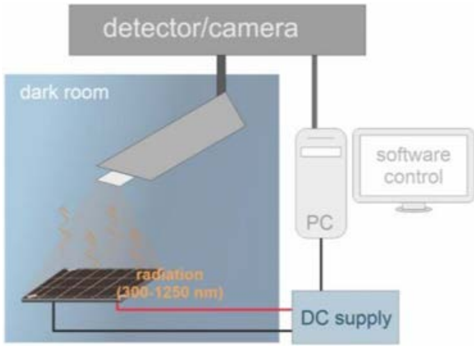

Fig. 6. Sample measurement system of the EL imaging (the DC supply, as well as the camera, can be controlled by dedicated software).

3.2. Photoluminescence imaging (PLI)

PLI is a noncontact imaging method based on optical excitation of the panel under test and reading the radiation emitted by it (Fig. 7). Due to its non-contact nature, it can be used at any stage from production to the operation of cells/panels [24, 26].

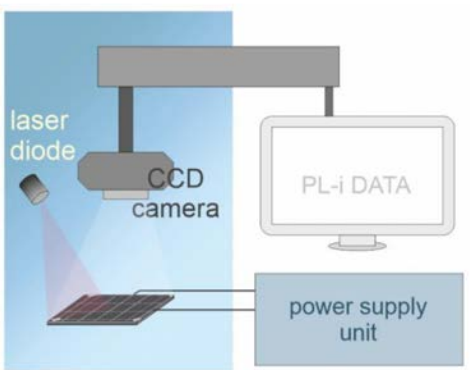

Fig. 7. Illustrative measurement system of the PL imaging.

At first, InGaAs detectors along with strong monochromatic lasers were used for measurements [25], however, over time, cooled CCD Si cameras along with illumination by LEDs in the 808-850 nm range became popular [23, 25, 31, 33, 40]. Depending on the chosen detector, the exposure time varies, from 1 s for InGaAs detectors [23, 40] to significantly longer for CCD Si cameras. The type of detector determines the application range of the method (production/exploitation). It is common to use edge filters to cut off unwanted light, lowpass below 800 nm and highpass in

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the range above 970/1000 nm [23, 33, 40]. The PLI method allows testing of single photovoltaic cells and solar modules [40].

Using PLI, it is possible to visualise such defects as:
– glass/cell cracks [23, 25, 33, 38, 40, 41]
– hotspots [25],
– PID [33],
– snail trails [33],
– interconnection failures [33],
– bypass diode failure [33],
– EVA film discoloration [33].

3.3. Infrared imaging (IRI)

Infrared imaging is based on recording radiation emitted by the module under study in the near and mid-infrared. This emission can be induced by both an external power source connected to the cell and a light incident on its surface [25]. It is possible to test throughout the current range when an external source is connected, from a short-circuit, through an open circuit, or to the maximum power point [25]. Therefore, the IRI method can be used both under laboratory conditions, isolated from external radiation, and "in the field" with external lighting present [24, 25, 33]. In the case of operation outside the laboratory, suitable weather conditions are necessary, minimum illumination of 700 W/m^2 on a cloudless day [8, 33]. The detectors used have wavelength ranges from 3.6 to 15 µm and exposure times from 60 to 600 s [8, 22, 25, 35, 36]. An illustrative measurement setup of the IR imaging with a sample image is shown in Fig. 8.

a) b)

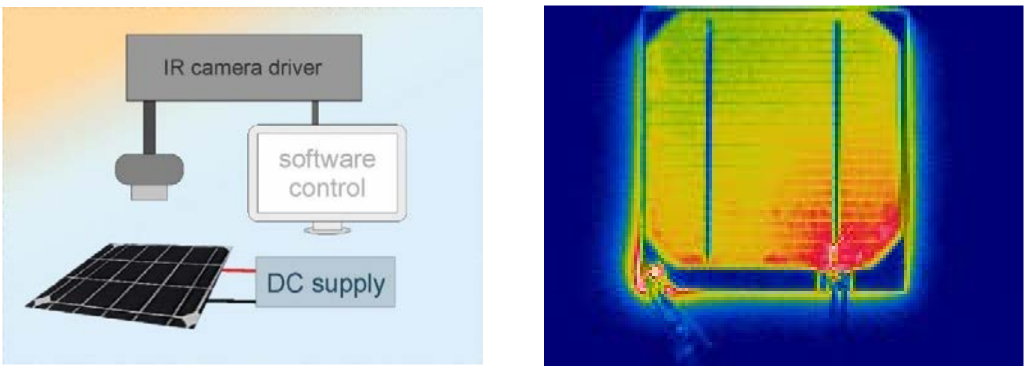

Fig. 8. Illustrative measurement system of the IR imaging (a) and IR image of an exemplary PV module (b).

IRI allows to detect of such defects as:
– hot spots [22, 25, 35, 42],
– glass/cell cracks [8, 24, 33, 36, 38, 42],
– EVA film discoloration of [42],
– bypass diode failure [8, 33, 42],
– busbar corrosion [42],
– delamination [8, 24, 42],
– inactive part of panel/cell [8, 24, 25, 33],
– PID [8, 33, 36].

3.4. Ultraviolet imaging (UVI)

Ultraviolet imaging is a method based on the detection of radiation from a PV cell in the UV wavelength range. It is a fluorescence method, so it requires prior excitation of the material. For this purpose, monochromatic lasers or LEDs in the 315-380 nm range are used [8, 22]. To ensure the highest quality of the readout signal, low- and high-pass filters are used [8, 22]. This method allows for the test cells and whole PV modules in the laboratory and in the field. However, it is recommended to perform measurements in an environment isolated from external light radiation (and in the case of modules without the presence of a protective glass that does not transmit UV radiation) [8, 28, 43]. The optimum time to perform "in the field" measurements is approximately 45 minutes after sunset [44]. The idea of the measurement setup for UVI measurement is presented in Fig. 9.

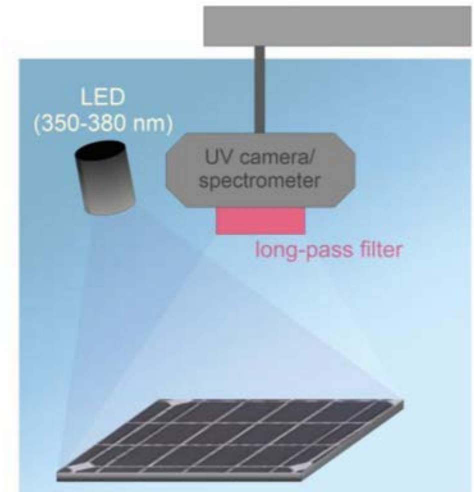

Fig. 9. Illustrative measurement system scheme of UV imaging.

Using UVI, it is possible to investigate:
– EVA film discoloration [8, 22, 33],
– glass/cell cracks [8, 22, 32, 33, 43–45],
– delamination [32, 44],
– hotspots [43, 44],
– interconnection failures [8, 43],
– snail trails [33].

3.5. Lock-In Thermography (LIT)

Lock-In Thermography is a non-contact method involving optical or electrical excitation (depending on the type of method used) of the solar cell under test and studying the response at designated wavelengths for the defects sought (Fig. 10). The amplitude image thus created makes it possible to identify the location and type of defect. Excitation can be carried out in two ways, using a light beam, in which case we speak of ILIT [22, 23] or using an external current source – DLIT [22, 23].

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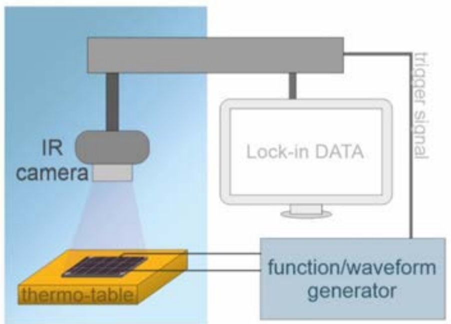


Fig. 10. Illustrative measurement system scheme of DLIT imaging.

Measurements use software designed to analyse and cut off frequencies other than designated, an infrared-sensitive camera, and, depending on the method, LEDs that optically excite the cell [22, 23, 25], infrared-sensitive cameras in the range of 2–5 µm range, InSb detectors or bolometers [8, 22, 23, 26] are used in the research (Fig. 10). The commonly used exposure time is 100 s [8, 22]. Both crystalline, thin-film, and organic cells can be measured using the LIT method [46].

LIT allows to examine:
– EVA film discoloration [22],
– glass/cell cracks [8, 23, 38, 41],
– hotspots [25],
– inappropriate shunts [8, 26, 41],
– busbar and contact corrosion [26],
– delamination [8],
– damage to the bonding strip in panels [8],
– grain boundaries [47]
– dislocations within the cell structure [47].

3.6. Electron-beam-induced current (EBIC)

Electron-beam-induced current is a method that involves imaging the surface of a solar cell while it is scanned with an electron beam, causing the generation of electron-hole pairs. The electron beam-generated current is then measured and an image in the form of a bitmap is created. On the basis of the resulting bitmaps, one is able to track potential defects/nonuniformities, which are observed in the image as shadowed areas. The measurements use a beam with a power of 20–35 keV and the current in a range of several pA [34, 48–52].

Using the EBIC method, defects such as those mentioned below can be characterized:
– cell microcracks [53],
– recombination centres [47, 48, 50, 52],
– PID [34, 50],
– inappropriate shunts [34, 47, 49, 50],
– grain boundaries [48–50],
– dislocations within the cell structure [48, 50–52].

The advantages of this method are possible high resolution and that it allows testing of polycrystalline, monocrystalline, and thin-film solar cells [34, 48, 49, 52].

The disadvantages are that EBIC implementation requires a vacuum and can only be used in the laboratory; it is usually as used as an attachment to a scanning electron microscope. Thus, it has no application in either the manufacturing process or in the field.

3.7. Light-beam-induced-current (LBIC)

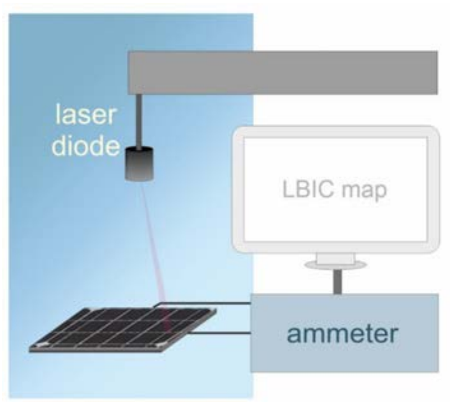
Light-beam-induced-current is non-destructive imaging technique that involves step-by-step scanning of the surface of the solar cell under test with a focused light beam. Under the influence of incident light, the photocurrent is generated locally and then a bitmap is created [40]. Tests using it are best carried out at room temperature [48], isolating the system from external sources of radiation [54, 55].

The wavelengths of excitation light are in the range of 400-1200 nm [29], [36, 40, 48, 54–59]. It allows the examination of monocrystalline and polycrystalline cells, perovskites, or silicon heterojunctions [55], [56, 58, 59]. To ensure the highest possible precision of the created bitmaps, a step of 0.1–25 µm is used [29, 40, 59].

The following defects and inhomogeneities can be measured using the LBIC method:
- recombination centres [40],
- interconnection failures [40],
- grain boundaries [58],
- inappropriate shunts [58],
- cell cracks [54, 57],
- PID [57],
- EVA film discoloration of [54].

An example of an LBIC bitmap with a setup scheme is presented in Fig. 11.

a)



b)

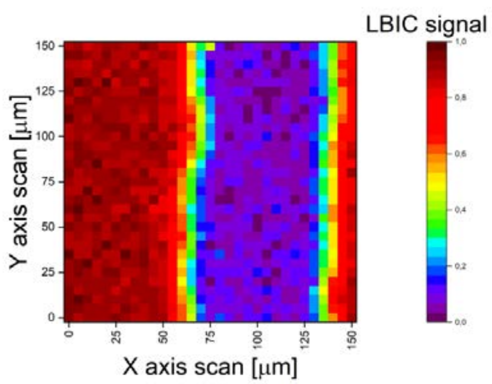


Fig. 11. Illustrative measurement system scheme of LBIC (a) and an LBIC bitmap image with 30 steps of solar cell with visible part of metallization which covers partially the cell surface (area with lower LBIC signal level) (b).

3.8. Time-of-flight secondary ion mass spectrometry (ToF-SIMS)

Time-of-flight secondary ion mass spectrometry is an invasive imaging method using a pulsed ion beam that removes the top molecular layer from the surface under study and then accelerates them and determines their mass based on their recorded transit time to the detector. ToF-SIMS

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imaging can be performed in three modes: surface imaging, surface spectroscopy, and depth profiling [60–63]. Monocrystalline and polycrystalline cells, as well as perovskites, can be studied using the ToF-SIMS method [60, 61].

4. Recommendations

When considering the choice of the best imaging method, there are several aspects to consider. Among the basic ones is the answer to the question of whether the study will concern PV cells or a working PV plant. Next, it is important to focus on the expected results. When looking for hot spots, it will be more advantageous to choose electroluminescence or photoluminescence imaging, infrared imaging, or for superficial assessment, visual inspection.

Looking for cell cracks on the macro scale, we can also use visual inspection; but moving to the micro-scale, we should choose ELI, PLI, IRI, UVI, lock-in thermography, or beam-induced current imaging. If one wants to investigate the discoloration of an EVA film, we should use EL, PL, IR, UV, LIT, or LBIC imaging in addition to superficial visual inspection. When we suspect shunt diode damage, the best way to confirm our suspicions would be to use PL, EL, or IR imaging methods. The presence of contact corrosion is best confirmed with EL or LIT imaging. If the encapsulation coatings are delaminated, the cell should be tested with IR or UV imaging. With a drastic decrease in current-voltage parameters and the PID hypothesis in the module under test, the cell is worth checking with EL, PL, IR imaging and LBIC. It is also possible to check with EBIC or ToF SIMS, which can confirm such assumptions. Broken contacts are best seen in images obtained with ELI, IRI, UVI, PLI, and LIT methods. The hot spot is most easily identified by analysing the image obtained with the ELI, PLI, or UVI methods. An image indicating the grain boundary can be obtained by examining the PV cell with LIT, LBIC, EBIC, or ToF-SIMS methods. Any dislocations in the material are best imaged with LBIC, EBIC, ToF-SIMS, and possibly LiT methods. We can detect the presence of short circuits using EL, PL, IR, UV, or LIT imaging and LBIC. A summary of the overview of the methods presented in article is provided in the Table 1.

It is also worth looking at the application specifications of each method, the circumstances under which they can be used, and the types of PV cells/panels for which they are applied. Electroluminescence imaging can therefore be used both on the production line and in the laboratory or in the field. With its help, we can examine both individual cells and entire panels made of polycrystalline, monocrystalline, or amorphous silicon.

In the case of lock-in thermography, this method can be used only in the laboratory, although it can be used to test both the PV cells as well as panels. Its performance is outstanding for analysing poly/monocrystalline and amorphous silicon. It is also suitable for testing thin-film and organic PV cells.

The need for much more sophisticated equipment means that the ToF-SIMS method can be used only in the laboratory. The nature of the measurement itself also limits it to scanning only single PV cells made of monocrystalline or polycrystalline silicon.

With the LBIC method at our disposal, we can perform measurements on polycrystalline and monocrystalline cells, but also on perovskites and heterojunctions, limiting it to scanning single solar cells only in the laboratory.

The same is true of the EBIC method; the precision it provides us, however, requires sacrifices and limiting ourselves to testing in the lab on single cells. We can examine those made of polycrystalline or monocrystalline silicon and perovskites. A detailed survey by cell type under study, its construction, and area of application is shown in Table 2.

Table 1. Overview of the imaging methods used for detection of various defects in photovoltaic cells and panels (VI – visual inspection, ELI – electroluminescence imaging, PLI – photoluminescence imaging, IRI – infrared imaging, LiT – lock-in thermography, EBIC – electron-beam-induced-current, LBIC – light-beam-induced-current, TOF-SIMS – Time-of-flight secondary ion mass spectrometry)

	Hot-spots	PV cell cracks	EVA discoloration	By-pass diode failure	Busbar corrosion	Delamination	PID	Inter-connection failures or inactive cell areas	Snail trails	Grain boundaries	Dislocations	Inappropriate shunts
VI	+	+	+	−	+	+	−	−	+	−	−	−
ELI	+	+	+	+	+	−	+	+	+	−	−	+
PLI	+	+	+	+	−	−	+	+	+	−	−	+
IRI	+	+	+	+	+	+	+	+	−	−	−	+
UVI	+	+	+	−	−	+	−	+	+	−	−	+
LiT	−	+	+	−	+	−	−	+	−	+	+	+
EBIC	−	−	−	−	−	−	+	−	−	+	+	−
LBIC	−	+	+	−	−	−	+	−	−	+	+	+
TF-SIMS	−	−	−	−	−	−	+	−	−	+	+	−
References	[8, 22, 24, 26]	[22–25, 27, 28, 30, 32, 33, 35, 36, 38, 39, 41, 54, 57]	[8, 24, 26, 42]	[33, 42]	[26, 33, 41]	[22, 24, 32, 34]	[30, 33, 36, 57]	[24–26, 28, 30, 32, 33, 54]	[22, 33]	[47, 58]	[47, 48]	[58]

Table 2. A detailed comparison table of defect detection imaging methods in PV cells and panels. (Examined structures: P – in production process, F – in field, L – the lab examination; Solar cell type: poly. – polycrystal, mono. – monocrystal, amorph. – amorphic, perov. – perovskite, thin – thin-film cells/panels, org. – organic)

Characterization method	**VI**	**ELI**	**PLI**	**IRI**	**UVI**	**LiT**	**EBIC**	**LBIC**	**ToF-SIMS**
Solar cell type	All	poly., mono., amorph.	poly., mono.	poly., mono.	poly., mono.	poly., mono., amorph., org., thin	poly., mono., perov.	poly., mono., perov.	poly., mono., perov.
Examined structures	cell, panel	cell, panel	cell, panel	cell, panel	cell, panel	cell, panel	cell	cell	cell
Area of using	P, F, L	P, F, L	P, F, L	P, F, L	P, F, L	L	L	L	L
References	[8, 22, 24, 26]	[22–25, 27, 28, 30, 32, 33, 35, 36, 38, 39, 41, 54, 57]	[23, 25, 33, 38, 40, 41]	[22, 25, 35, 42]	[22, 28, 32, 33, 43, 44, 64]	[22, 23, 26, 38, 41]	[34, 48, 65]	[40, 48, 54, 56, 57, 65]	[34, 61]

When considering which of the methods presented is the easiest and cheapest to use in the field, the authors recommend infrared imaging or electroluminescence. Relatively inexpensive portable cameras are sufficient for basic thermal imaging tests, but at the same time allowing detection of defective panels. The advantage is also that such testing can be performed during the day with the panels illuminated by natural sunlight. In the case of the electroluminescence

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method, kits are now available that enable field testing, such as those based on the use of modified cameras.

Analysing Table 2, it can be seen that El, PL, IR and UV imaging methods are much more versatile, but at the same time they give more general information about defects. In the case of investigation of more complex defects appearing in PV cells while seeking possible explanations for their occurrence, the usage of LiT, EBIC, LBIC, or ToF-SIMS is recommended.

5. Future challenges

Many of the aforementioned defects, *i.e.* cell microcracks, snail tracks, or hot spots, have been present since the photovoltaic installations appeared. Due to that, in that field, there is a need of improving the methods instead of searching for the causes of photovoltaic panel malfunction. However, constant development of photovoltaic technology and increase in complexity of photovoltaic systems are also connected with relative new defects, such as the PID mentioned. Such a fault is strictly connected with the connection of many panels and still needs further research and improving the methods of detection, as undetected in systems, can cause significant further damage. Such a phenomenon needs to be described and analysed in a more complex way. Although efforts to increase the efficiency of photovoltaic modules are constantly underway, this would likely involve the appearance of new types of defects.

Also, not to be neglected is the need from industry, which has striven, is striving, and will strive to optimize the production process of solar cells that will resist the numerous defects that may affect them.

6. Conclusions

The vast variety of existing defects in both single solar cells or whole modules and many possibilities to detect them depending on currently existing needs may be overwhelming at first. The goal of this review is to gather and organize most recent trends and goals in research on photovoltaic defect detection and the study of imaging techniques, presenting them in a pleasing and legible way. Thanks to that, the reader may support his current studies by implementing other complementary methods to extend his knowledge and understanding of the problems he is facing. The authors also propose their point of view, based on knowledge gathered during the development of this article, on most possible ways in which further research will be conducted. Lastly, being faced with the most recent state-of-the-art may help to identify the most recent trends in the field of detecting defects in solar cells and find fields in which he may contribute to further advance the knowledge and understanding of problems we are facing.

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Metrol. Meas. Syst., Vol. 30 (2023), No. 3, pp. 381–401
DOI: 10.24425/mms.2023.146426

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