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TECHNICAL SPECIFICATION

colour inside

Photovoltaic cells –
Part 2: Electroluminescence imaging of crystalline silicon solar cells

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PHOTOVOLTAIC CELLS –

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The text of this Technical Specification is based on the following documents:

Draft	Report on voting
82/1912/DTS	82/1951/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 63202 series, published under the general title *Photovoltaic cells*, can be found on the IEC website.

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PHOTOVOLTAIC CELLS –

Part 2: Electroluminescence imaging of crystalline silicon solar cells

1 Scope

This part of IEC 63202 specifies methods to detect and examine defects on bare crystalline silicon (c-Si) solar cells by means of electroluminescence (EL) imaging with the cell being placed in forward bias. It firstly provides guidelines for methods to capture electroluminescence images of non-encapsulated c-Si solar cells. In addition, it provides a list of defects which can be detected by EL imaging and provides information on the different possible methods to detect and differentiate such defects. When EL imaging alone cannot provide conclusive information for the presence of a type of defect, suggestions are also made to utilize a combination of other methods.

Finally, this document provides some information on potential effects when using cells with specific EL features in module assembly. Although this document mainly addresses bare c-Si solar cells, it is generally applicable to all wafer solar cell technologies.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 60904-13:2018, *Photovoltaic devices – Part 13: Electroluminescence of photovoltaic modules*

IEC TS 61836:2016, *Solar photovoltaic energy systems – Terms, definitions and symbols*

IEC TS 62446-3, *Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 3: Photovoltaic modules and plants – Outdoor infrared thermography*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836, together with the following, apply.

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
electroluminescence
EL
light emission by radiative recombination of excited charge carriers in a semiconductor device resulting from electrical voltage applied to the semiconductor in forward bias

3.2
open circuit
for a given terminal pair, electric circuit without a continuous path between the two terminals of the pair

Note 1 to entry: A cell exhibits an “open circuit” if defective or damaged so that no current can flow through it when attached to an external circuit at the cell electrical connection points.

Note 2 to entry: A PV cell itself is in open circuit condition if one or all of the cell electrical connection points are not connected to electrical terminations or current is not flowing as defined in IEC TS 61836:2016,3.4.56.

3.3
forward bias
forcing current flow with a power supply where the leads are connected to those of the same polarity (+ and -) on the solar cell

3.4
barrel distortion
geometric distortion of a rectangular raster causing its boundaries to appear convex

3.5
vignetting
reduction of an image's brightness at the periphery compared to the image centre caused by the lense of the imaging system

3.6
dynamic range
DR
ratio between the maximum output signal level and the noise floor

Note 1 to entry: Noise floor is the root mean square noise level in a black image.

3.7
sharpness
S
minimum real dimension from the darkest black to the point which could provide a contrast of 50 % over the brightest white in terms of EL brightness

Unit: mm

Note 1 to entry: The sharpness is used as the index of the resolvable object size.

3.8
gray-scale value
numeral used to define the different levels between the brightest white and the darkest black

Note 1 to entry: EL images will correspond to a weighted average value (mean gray value).

3.9
modulation transfer function
MTF
ratio of contrast of input images over the output image’s contrast

Note 1 to entry: MTF is a function of spatial frequency.

Note 2 to entry: MTF is applied to evaluate the resolution of the images in terms of frequency over the test area.

Note 3 to entry: MTF is also referred to as spatial frequency contrast sensitivity function.

3.10
field of view
FOV
area of a scene that is imaged on the camera sensor

Note 1 to entry: The geometry of a field of view is usually rectangular and corresponds to the camera sensor shape.

3.11
angle of incidence
angle between the normal to the reference surface of the FOV (the cell) and the camera optical axis

3.12
angle of view
maximum angle between any two incident rays from the detector camera to any arbitrary points on the FOV

Unit: dimensionless, usually expressed in degrees

Note 1 to entry: FOV describes the angular extent of a given scene that is imaged by a camera.

4 Imaging

4.1 Apparatus

4.1.1 General

A general description of an EL imaging system and its required apparatus is given in this clause. Figure 1 shows a typical setup for EL imaging. It consists of a camera detector with appropriate lens or filters that senses the EL emission from the device under test, a power supply connected to the DUT which injects current into it for EL emission, a dark chamber that reduces stray light from ambient and a computer that controls all the components. Under normal test conditions, the device under test shall be forward biased in the dark such as to achieve a current flow, similar to the AM1.5G short-circuit current. The resulting radiative recombination causes a light emission of the cell which is captured by the camera detector.

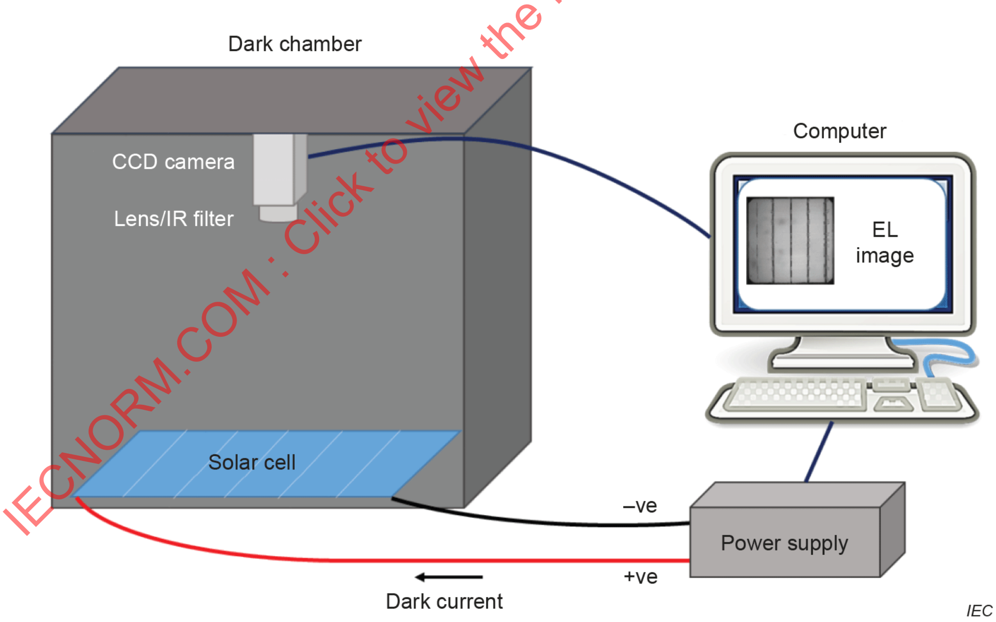


Figure 1 – Typical setup of an electroluminescence imaging system

4.1.2 Electroluminescence imaging camera

4.1.2.1 Camera detector

Detectors are typically light-sensing pixels consisting of charge coupled devices (CCD) or complementary metal oxide semiconductor (CMOS) devices arranged in a focal-plane array. To achieve better signal-to-noise ratio (SNR) by means of reducing device dark current originating from thermally generated charges, they may be cooled, usually with thermoelectric cooling. Semiconductor light absorber materials in the detector shall be sensitive to the EL emission of the device under test. For crystalline silicon the detector shall be sensitive in the wavelength range between 900 nm and 1 100 nm and able to achieve SNR_{50} of 45 or better, determined using the method detailed in IEC TS 60904-13:2018,4.3. An example image with SNR_{50} of 45 is given in Figure 2. Images with SNR_{50} below 45 are not suitable to be qualitatively interpreted. Determined SNR for images obtained shall be reported per Clause 6.

SNR_{50} = 45

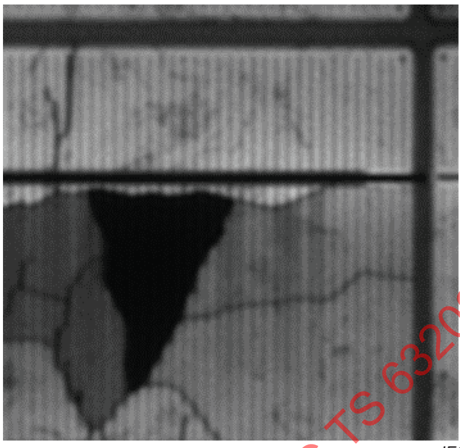


Figure 2 – Image of multi-crystalline silicon solar cell with SNR_{50} value of 45

4.1.2.2 Lens

Lenses shall be free of absorption filters or coatings that remove the infrared near the band-gap of the semiconductor material to be examined. For crystalline silicon this means: wavelengths between 900 nm and 1 100 nm shall not be attenuated by absorption filters or coatings. Optical glass is generally suitable when measuring Si based solar cells. Lenses vary from telephoto to wide-angle in focal length. Choices will depend on the specific application and geometric considerations when capturing the image. Wide-angle lenses that have short focal lengths used in conjunction with the higher resolution cameras capture a larger FOV. The camera may be placed much closer to the solar cell under test, which is useful when space is a consideration. Some wide-angle lens optics, however, may cause undesirable barrel distortion in the images that will require correction by post-processing.

Lenses with longer focal lengths generally have less barrel distortion and can therefore more accurately image a solar cell, in which case the resulting images may not require correction by post processing. Lenses may feature components that correct for the difference between visible and infrared wavelengths, which can facilitate focusing.

NOTE Lenses typically have adjustable aperture with their size generally referred to by a *f*-number. Ignoring differences in light transmission efficiency, a lens set to a greater *f*-number has less light gathering area and projects less electroluminescence signal to the image sensor. Depth of field increases with increasing *f*-number. Image sharpness is related to *f*-number through two different optical effects; aberration, due to imperfect lens design, and diffraction, which is due to the wave nature of light. Many wide-angle lenses will show significant vignetting at the edges when using a smaller *f*-number.

4.1.2.3 Filters

Filters on the camera lens may be used to help cut light of extraneous wavelengths from being detected. Long-pass filters above 850 nm may be used when imaging near band-edge EL from silicon.

4.1.3 Dark room imaging studio or environment

While not mandated, a darkened environment is favoured for high quality images. Precautions should be taken to eliminate stray light entering the imaging studio, such as with use of hard walls, curtains, baffles, and sealing of any gaps with material that are of light absorbing nature (black). If a filter is used on the camera, then LED lighting may be used that emits light only in the spectrum that is cut by the filter. If stray light is present, an image subtraction procedure, as discussed in 4.1.5.2, will be necessary. Stray light should be avoided in the dark room.

Laboratory measurements, for consistency, are recommended to be performed at solar cell temperature between 23 °C and 27 °C. Temperature shall be measured using instrumentation with an accuracy of ± 1 °C and repeatability of ± 0,5 °C. Only images taken at temperature ranges of the same span are to be used for quantitative comparison with the purpose of identifying solar cell degradation or cell-to-cell differences (see also 4.2.2.5). As current injection increases the cell temperature, it is recommended that the cell temperature is stabilized by passing current until the temperature reaches equilibrium before capturing EL images. Furthermore, temperature may also affect the sensitivity and signal-to-noise ratio of the detector. Therefore, once the temperature of the solar cell under test has been stabilized, images captured in sequence can be used to identify if the camera detector temperature has been also stabilized. When the camera exposure and thus the current injection time is short enough to avoid cell heating, it may not be necessary to thermally stabilize the sample by current injection. An estimate of temperature increase of the cell can be calculated from the total power applied and the silicon heat capacity of the cells' volume.

4.1.4 Power supply

An electric DC power supply capable of applying current equal to the short-circuit current (I_{SC}) under standard test condition (STC) of the solar cell under test is necessary.

It is recommended to measure voltage and current using instrumentation with an accuracy of ± 2 % of the open-circuit voltage and short-circuit current or better. Cabling from the cell leads shall be of sufficient gauge to maintain less than 2 % voltage drop over the leads, or alternatively, a four wire configuration can be used to separately supply current and measure voltage at the terminals of the cell under test.

4.1.5 Image processing and displaying software

4.1.5.1 Assignment of image colours

Lowest EL signal should be represented by black and the highest EL signal in the image should be represented by white; however, the image data of the active cell area shall not exist in the upper extreme to avoid detector saturation except where unavoidable (see 4.2.2.4). If false colour scaling is used, the false colour scale should be chosen so that each level is assigned a unique colour thereby avoiding misinterpretation of the image features.

4.1.5.2 Software capabilities

Software should produce histograms in counts versus EL signal level bin to quantitatively interpret the images for features that are observed.

Basic software features that may be helpful for post-processing of images while applying this document include:

- Level range adjustment: Non-linear contrast optimisation (for example gamma correction) should be avoided. Linear contrast optimisation such as rescale to maximum and minimum value is acceptable.
- Cropping the image to the region of interest (see 4.2.2.2).
- Determination of EL signal level at any given point on the image.
- Frame subtraction: Uniform subtraction of noise signal including from dark current or stray light, such as by subtracting the signal when the cell is unpowered. An in-depth example of how background subtraction is performed is given in IEC TS 60904-13:2018, 4.1.5.2 software capabilities.
- Dead pixel removal.
- Single time effects removal.

– Barrel distortion.
– Vignetting.
– Parallelism correction (typically to reshape images that are taken with a non-orthogonal angle of incidence).

4.2 Procedure

4.2.1 Camera settings and positioning

4.2.1.1 Angle of incidence

Angle of incidence of the camera relative to cell surface to be imaged is preferably normal (0°), but should be less than 50°. Emissivity adjustment for angle is required if it is greater than 50°.

The principle light facing side of the cell is imaged. However, it may be advantageous to image bifacial cells from the opposite side as well.

4.2.1.2 Sharpness determination

Sharpness is dependent on the pixel dimension, the linear distance on the cell sampled by a pixel, and it includes the effects of image blurriness. It is recommended to obtain images with a sharpness of less than 0,5 mm to identify defects, but the smaller solar cell objects such as solar cell fingers, or localised defects may require lower sharpness to be clearly imaged.

A method for determining image sharpness is defined in IEC TS 60904-13:2018, 4.2.3.

4.2.2 Camera setting

4.2.2.1 General practice

For routine measurements, the image intensity for the camera at each forward bias current level may be optimized by adjusting the total exposure time, aperture (gain, *f*-number), or by gain adjustment after a survey of cells of the type to be examined is made, and then kept consistent. If changes need to be made to achieve the desired image intensity, exposure time shall be adjusted and the change recorded. See 4.2.2.4 for guidelines regarding image intensity.

4.2.2.2 Recommended camera settings (focus, gain, *f*-number)

A first, rough focus may be performed by viewing in the visible light regime, but fine focus shall be optimized to the wavelength of the EL signal to be imaged. This can be simplified by using IR-corrected lenses. In this case the focus setting is the same for the EL and visible images. Focus shall be sufficient to resolve the features according to the desired level of sharpness defined in 4.2.1.2. An algorithm is given in IEC TS 60904-13:2018, that may be used for computing the optimum lens focus position

Other recommended settings are as follows:

– Gain setting shall be set to obtain optimum pixel depth resolution of cell to be imaged.
– *f*-number shall not be changed between images to be compared. If an adjustable *f*-number is available, choose the lowest *f*-number by default when imaging samples that are centred in front of the camera and the optical axis passes through the centre of the cell. A different *f*-number may be selected and fixed if it is deemed to produce optimized results, such as to decrease vignetting, increase sharpness, and increase the depth of field for imaging with an oblique view of the cell face.

4.2.2.3 Field of view

It is recommended to have optimized field of view, at least larger than the cell including its perimeter which is not producing luminescence. A non-luminescent portion of the FOV, outside of the cell, is suitable so that the cell perimeter is clearly identified. Typically, a ratio 80 %/20 % of the luminescent/non-luminescent FOV is adequate.

4.2.2.4 Image intensity

The exposure shall be optimized (increased) to achieve maximum signal to noise ratio, but limited such that pixels in the image are not saturated (see also 4.1.5.1 for assignment of image colours). Single time effects and random noise are not counted in the analysis of pixel saturation.

4.2.2.5 Comparisons of cells

Various cell types and degradation processes may show differing EL behaviour under different measurement conditions. For easy comparison of a degraded cell to a non-degraded cell, image the degraded cell at the original condition and optionally, with settings re-optimized for the degraded condition. Only the exposure time may be used for the readjustment when comparing non-degraded and degraded cells in this way. The current shall not be changed. The device temperature of the solar cell shall be controlled as close as possible in the initial and degraded state of the solar cell in accordance with the requirements described in 4.1.3. Furthermore, the camera temperature can influence the sensitivity and signal-to-noise ratio of the detector. Therefore, the detector shall also operate at the same temperature, when comparing electroluminescence images. Effort shall be also made so the electrical contacting of the solar cell under test is the same in the initial and degraded state.

If frame subtraction is necessary, apply the procedure described in IEC TS 60904-13:2018,4.1.5.2.

When visual comparison is desired for cells imaged with different exposure times, the intensities of the pixel may be scaled in post-processing by inversely scaling the pixel intensities by the exposure time. The brightest image intensity in such comparisons shall be set according to 4.1.5.1 and 4.2.2.4.

4.2.3 Imaging

4.2.3.1 Electrical connection

Connect cell stage to the (+) and (-) electrical leads from the DC power supply to the sample, matching the (+) lead of the power supply with the (+) of the sample. The distribution of the probes shall match the busbar pattern so that even current output distribution is obtained. It is recommended that multiple current probes are connected to each busbar of the solar cell to ensure an even distribution of current flow. For busbar-free, or rear contact solar cells, a suitable conducting system is recommended so that current flow is evenly distributed.

4.2.3.2 Biasing and imaging

For additional information retrieval, mainly a separation of series resistance defects and defects caused by variations in charge carrier lifetime, it is recommended that imaging is taken at two bias currents sequentially; one corresponding at high current injection and one at low current injection. Since the short-circuit current may vary for cells of the same type, the applied bias currents shall meet the accuracy requirements previously (4.1.4) defined, i.e. it shall meet the set point to ±2 %. For reasons of comparability it is recommended to sample EL images at the following current injection level set points:

- High current injection: I_{SC}.
- Low current injection: 0,1 × I_{SC}.

Exposure time may be optimized according to 4.2.2.4, for each bias current applied. See 5.2 for interpretation of the images obtained at each of the bias current levels.

It is often preferable in a production line to apply higher current injection to reduce exposure time and save testing time. In this case, it is not recommended to exceed the mean I_{SC} by more than 25 %. Typically in a production line, all cells of the same type would be measured with the same bias current applied to them. For the purpose of determining solar cell degradation, EL images shall be taken with identical current supplied to the cells for all images used to examine the degradation (see also 4.2.2.5). If higher current than I_{SC} has been applied, its value has to be explicitly stated in the report in accordance with Clause 6.

4.2.4 Image correction

After image acquisition, images are corrected to achieve, characterize, and optimize desired image quality. Image corrections are essential if images will be analysed quantitatively. These image corrections are:

- frame subtraction, and
- vignetting correction.

More information on how frame subtraction is performed is given in IEC TS 60904-13:2018, 4.1.5.2.

Procedures for vignetting calibration and correction are given in IEC TS 60904-13.2018.

5 Evaluation of EL images

5.1 Principles of electroluminescence

EL is the phenomenon of light emission of a semiconductor device in response to current injection [1][1]. The light emission is attributed to radiative recombination of free carriers that occurs predominantly in the bandgap region. The presence of localized defects affects the intensity of EL signal recorded per area, hence electroluminescence can provide a wealth of information for the solar cells under test and their defect topology [2], [3]. More information on the principles of electroluminescence are given in IEC TS 60904-13:2018,5.1.

5.2 Image interpretation

5.2.1 Series resistance

Areas where current flow is limited by series resistance will show a reduced EL signal because of the lack of supply of injected carriers at those regions. Conversely, for a given net current supplied to the device, areas of reduced series resistance will have higher numbers of injected carriers flow there and generate a higher EL signal. Generally, the EL signal will vary with the voltage potential across the cell, V. Assuming other parameters such as minority carrier lifetime are not changing across the solar cell, the voltage ΔV between two points (x_1 and x_2) associated with series resistance in an EL image is related to the EL intensities $K(x_1)$ and $K(x_2)$ as:

$$\Delta V(x_1, x_2) = V(x_1) - V(x_2) = kT/e \times (\ln(K(x_1)) - \ln(K(x_2)))$$

where

k is the Boltzmann constant,

T is the temperature in Kelvins, and

e is the elementary charge.

The EL intensities $K(x)$ are proportional to:

[1] Numbers in square brackets refer to the Bibliography.

$$K(x) \sim \exp[\, V(x) / (kT/e) \,]$$

Defects related to series resistance reveal at high bias currents (such as I_{SC}), whereas they cause a low contrast at low bias current (such as 0,1 × I_{SC}). Comparing contrast of defects at high and low injection EL images thus helps to separate series resistance related defects from defects caused by minority carrier lifetime.

5.2.2 Minority carrier lifetime and diffusion length

EL emission intensity is closely related to the effective diffusion length, as the function of diffusivity and minority carrier lifetime. When the ambient temperature is controlled, diffusivity can be assumed constant and EL emission scales with minority carrier lifetime. Typically effects related to minority carrier lifetime are visible in EL images recorded under forward bias conditions.

Solar cell areas with higher minority carrier lifetime as well as longer diffusion lengths will appear brighter, while areas with lower minority carrier lifetime and shorter diffusion lengths will appear darker. Minority carrier lifetime defects usually remain noticeable at both high and low current injection.

5.2.3 Shunt resistance

Shunts through the p-n junction of a cell provide alternate recombination paths to the near-band edge recombination responsible for EL signal and thus reduce its intensity. High currents applied to the device (such as I_{SC}) may saturate leakage paths associated with shunts, thus the cells may appear bright except at the shunt locations that appear dark. When reduced current is applied to the device (such as 0,1 × I_{SC}) then unsaturated shunt paths may reduce overall minority carrier density and overall cell EL intensity.

Shunts or areas of non-luminescent recombination especially around solar cell edges will be localized at higher bias currents, whereas the whole cell will appear darker at lower bias current.

Generally the visibility of ohmic shunts in EL imaging depends on the series resistance that connects the shunt with the rest of the cell. EL imaging is not a suitable method for quantitative spatially resolved analysis of shunts; thermographic methods under reverse bias conditions are required for this task.

5.2.4 Assignment of root cause

While defects such as cracks are visible in EL images with an easily recognizable signature pattern, it is not always possible to assign a specific physical phenomenon using EL images taken at a unique forward bias current and temperature. Signals taken at two bias currents and combined with infrared thermography (IEC TS 62446-3), photoluminescence, or laser-beam induced current methods can be used to further identify various root causes of EL signal variation across cell surfaces.

5.2.5 Qualitative image interpretation

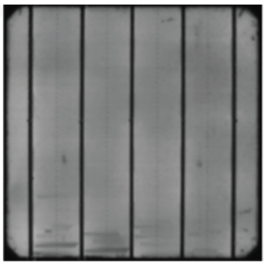
5.2.5.1 General

The following descriptions present individual features, recognizable by EL imaging. They describe the physical mechanisms leading to these features and provide some recommendation on the impact of identified features on the electrical stability of a PV-module made of such solar cells.

5.2.5.2 Missing, broken grid finger lines

Missing or broken grid fingers (confirmable by visual inspection) can influence the efficiency of the cell. Such defects in Figure 3 typically increase the series resistance of the solar cell locally, which lowers EL intensity in the respective position. The contrast of the EL intensity due to variations in series resistance will be low at low bias current, but increased contrast will be seen at higher bias current. Examples of solar cells with missing or broken finger lines are displayed in Figure 3a), b), c), and d).

The severity of broken finger defects depends on their frequency of occurrence and the size they extend. A common origin of such finger interruptions are clogged print screens, such defects are usually stable. Although singular defects are less likely to cause a noticeable efficiency reduction, multiple finger defects that extend over a large area of the solar cell can reduce solar cell efficiency. For broken fingers of other origin, grid finger adhesion may continue to degrade over time, which may reduce the cell performance. As such defects may or may not be stable, it is advisable to further investigate their thermomechanical stability by means of accelerated service life testing before using defective solar cells in PV-module assembly.



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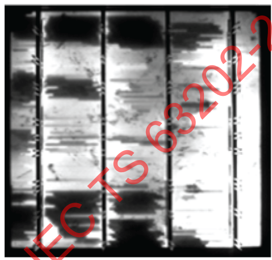
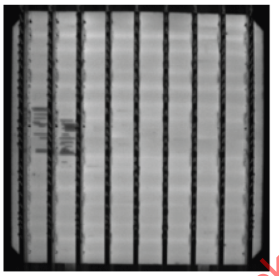
a) Minor



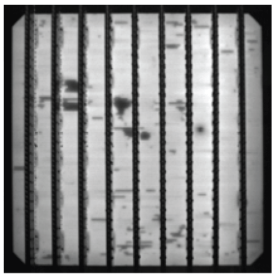
IEC

b) Localized



IEC

c) Moderate



IEC

d) Severe

Figure 3 – EL images of PV solar cell with broken fingers

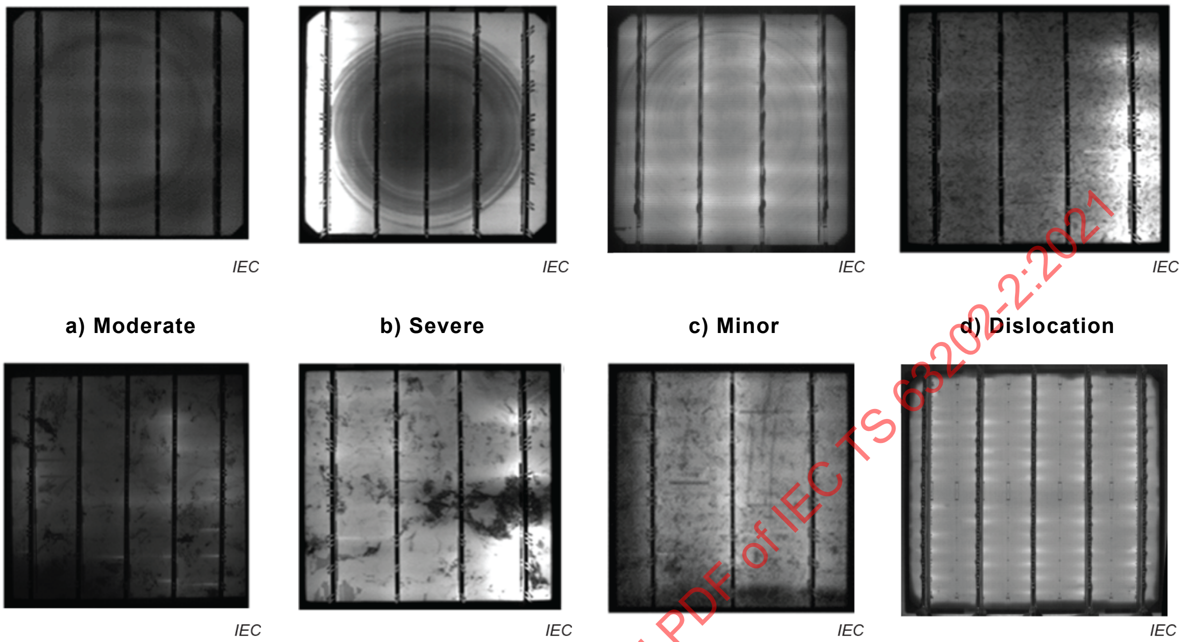
5.2.5.3 Reduced carrier lifetime

Elevated defect and impurity concentrations can exist over particular grains or regions of the wafer.

Concentric circles in p-type cell are not recommended for module assembly. Such patterns indicate the presence of high oxygen content, which may result in accelerated light-induced degradation in these areas causing non-uniform degradation patterns in the cell. They may impact the long term stability of cell's and module's efficiency, and therefore further reliability study is recommended. Examples of silicon solar cells exhibiting concentric circles are shown in Figure 4a), b) and c).

In multi-crystalline silicon wafers, especially in metallurgical ones, regions of high dislocation density are often present. Their formations originate from the thermal history during the cooling after growth of multi-crystalline silicon ingot, usually capturing significant impurities. Such defects affect the minority carrier lifetime and cause areas of a solar cell to appear darker. Elevated defect and impurity concentrations are generally stable over time. Their influence is captured in the initial efficiency of the cell and do not cause any issues with performance stability or degradation. Examples of such defects in silicon wafer solar cells are shown in Figure 4 d), e), f), g) and h).

Reduced carrier lifetime defects will typically remain noticeable at both high and low current injection, EL imaging alone may not always provide accurate information for the origin of these defects. Thus, it is a good practice to employ carrier lifetime measurements to assess the magnitude of carrier lifetime reduction and IV measurement to assess their impact on solar cell efficiency.



a) Moderate **b) Severe** **c) Minor** **d) Dislocation**

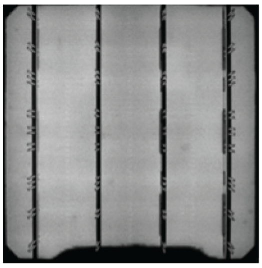
e) Dark wafer **f) Dislocation cluster** **g) Dark edge in multi-crystalline silicon solar cells** **h) Dark edge in monocrystalline cell**

Figure 4 – EL images of PV cell with different grades of concentric circles in mono-crystalline silicon

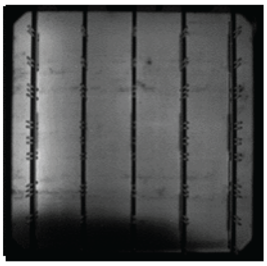
5.2.5.4 Local shunt defects

Localised p-n junction shunting is often attributed to manufacturing defects. Such defects may further degrade or develop into hot-spots, and they are generally undesirable during solar cell operation. The defects lower the shunt resistance and provide an alternative path for charge carriers for the light-generated current. Such a diversion reduces the amount of current flowing through the junction. As a result shunted areas appear black in colour in EL imaging. Shunts or areas of non-luminescent recombination will be localized with higher bias currents, whereas whole cells will appear darker with lower bias current. Other origins for dark areas in EL imaging which are not shunted areas are e.g. series resistance related defects (see 5.2.5.2), or locally reduced bulk carrier lifetimes (see 5.2.5.3). Figure 5 a) and b) shows examples of shunting defects in silicon wafer solar cells.

It is not recommended to use shunted cells in the assembly of a PV-module. However, EL imaging alone may not always reveal accurate information for the presence of localized shunt defects, and therefore it is recommended to utilize other techniques such as infra-red thermography and IV measurement to identify their presence.



a) Moderate



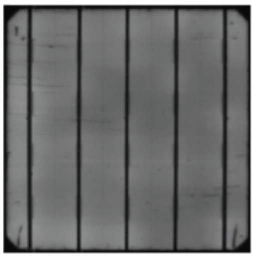
b) Severe

Figure 5 – EL images of PV cell with local shunting

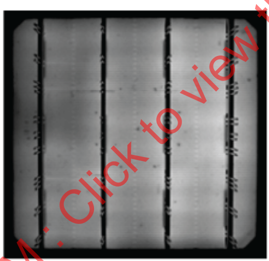
5.2.5.5 Wafer or cell processing contamination and abrasion marks

Localized areas of low EL signal may be attributed to wafer/cell processing such as contamination, abrasion marks and grazes by handling equipment. Such defects are often systematic in cell production, resulting in higher localized series resistance or lower minority carrier lifetime, causing lower EL intensity under high current bias. Examples of such defects are shown in Figure 6 and Figure 7 for mono-crystalline and multi-crystalline silicon solar cells respectively

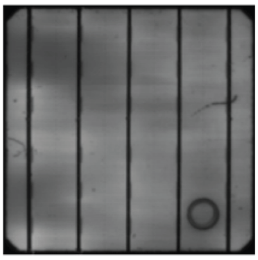
Many defect types which are caused by production steps are generally stable over time and their influence is captured in the initial efficiency, however there is a large variety of defects and some of them might as well cause further degradation. Therefore, it is generally a good industry practice to verify the electrical stability of these defects by means of accelerated service life testing before using such cells in PV-module assembly.



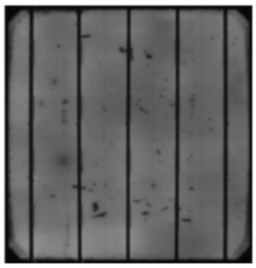
a) Scratches



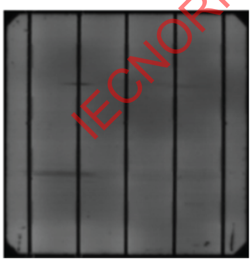
b) Suction disk mark



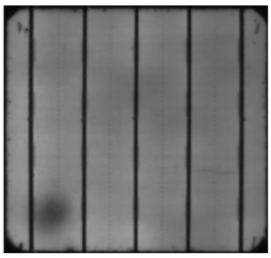
c) Suction pen mark



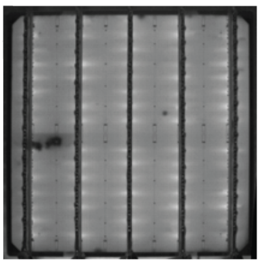
d) Handling frame spot



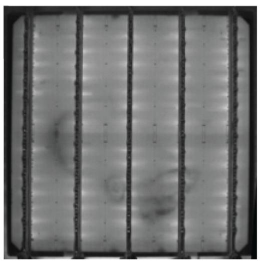
e) Belt mark



f) Dark spot

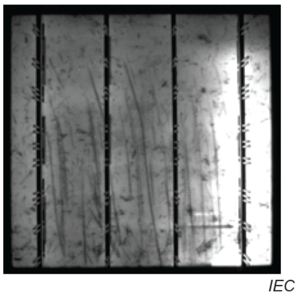


g) Contamination



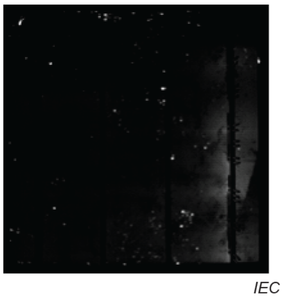
h) Contamination

Figure 6 – EL images of PV mono-crystalline silicon solar cells

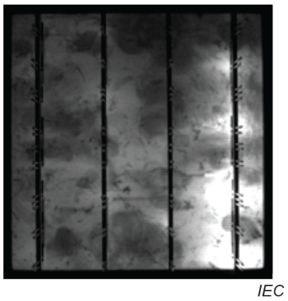


a) Scratches

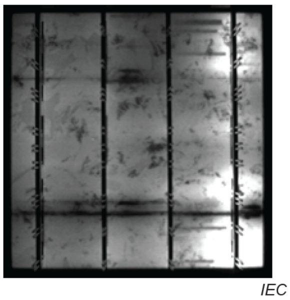
b) Reverse etching



c) Severe contamination



d) Handling frame spot



e) Belt or water mark

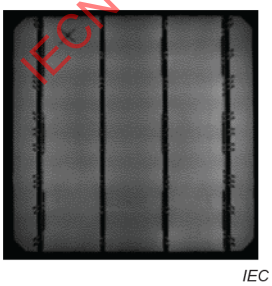
f) Poor rear passivation

Figure 7 – EL images of PV multi-crystalline silicon solar cells

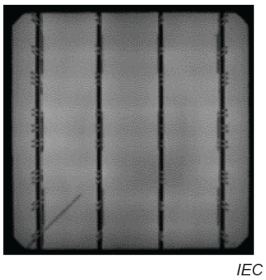
5.2.5.6 Cell cracking

Cell cracks are susceptible to further degradation if cracks expand due to different external forces such as thermal stress. Cracks may expand and eventually isolate electrically parts of the cells, which is undesirable for solar cell performance. Generally, the severity is lesser for single cracks than multiple cracks. In addition, edge cracks located at the perimeter of a solar cell border, as shown in Figure 8c), are more concerning as they are more likely to electrically isolate active parts of the solar cell, if they propagate further.

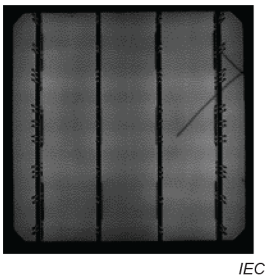
It is not advisable to assemble PV-modules made of cracked solar cells, as small cracks may develop into large area cracks during lamination or post-lamination phases. Hence such solar cells are better avoided in PV-module assembly. It is worth noting that cracks seen in pre-lamination phase should be distinguished from cracks that occur in lamination and post-lamination phases which may not necessarily expand or affect the electrical stability of PV-modules.



a) Cross-crack



b) 45° crack



c) Edge crack

Figure 8 – EL images of PV cell