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TECHNICAL SPECIFICATION

colour
inside

Photovoltaic devices –
Part 13: Electroluminescence of photovoltaic modules

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FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 60904-13, which is a technical specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
82/1292/DTS	82/1424/RVDTS

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60904 series, published under the general title *Photovoltaic devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

PHOTOVOLTAIC DEVICES –

Part 13: Electroluminescence of photovoltaic modules

1 Scope

This part of IEC 60904 specifies methods to:

a) capture electroluminescence images of photovoltaic modules,
b) process images to obtain metrics about the images taken in quantitative terms, and
c) provide guidance to qualitatively interpret the images for features in the image that are observed.

This document is applicable to PV modules measured with a power supply that places the cells in the modules in forward bias.

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

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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

3.1
electroluminescence
EL
emission of optical radiation resulting from the application of electrical energy

3.2
open circuit
electrical circuit that has a break, or “open”, somewhere in the conductive path

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

Note 2 to entry: A PV module itself is in open circuit condition if one or both of the module electrical connection points are not connected to anything or current is not flowing as defined in IEC TS 61836:2016, 3.4.57.

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 sample

3.4
barrel distortion
distortion in the image whereby rectangular features in an image appear expanded, as in a curved barrel wall

3.5
vignetting
reduction of an image's brightness at the periphery compared to the image center

4 Imaging

4.1 Apparatus

4.1.1 Electroluminescence imaging camera

4.1.1.1 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. They may be cooled, usually with thermoelectric cooling, to achieve better signal-to-noise ratio by means of reducing device dark current originating from thermally generated charges. Semiconductor light absorber materials in the detector shall be sensitive to the EL emission of the device under test. Example semiconductor light absorber materials and their useful wavelengths of detection for PV module characterization are given in Table 1. The spectral response for some semiconductor detectors is given in Figure 1. The typical emission spectrum for Si, ZnO/CdS/Cu(In,Ga)Se_2 (CIGS) and CdS/CdTe heterostructure solar cells are given in Figure 2. The signal strength obtained during EL measurements will be proportional to the product of the spectral response and the emission. For a given EL signal from a sample, a greater spectral response at the wavelength of interest will typically permit a shorter exposure time. Spectral response of Si detectors to Si cell PV module EL emission is relatively low. Commercial Si detectors frequently offer the best resolution, but spectral response of silicon detectors is typically compromised as a result.

Table 1 – Detectors and their applicable wavelengths

Detector	Sensitive wavelengths µm
Ge	0,8 to 1,7
InGaAs	0,7 to 2,6
Si	0,3 to 1,1
InAs	1,0 to 3,8

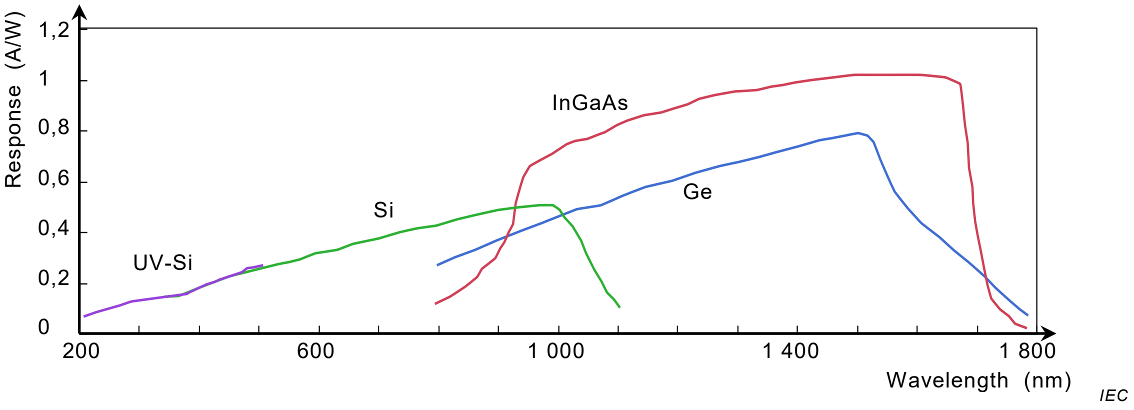
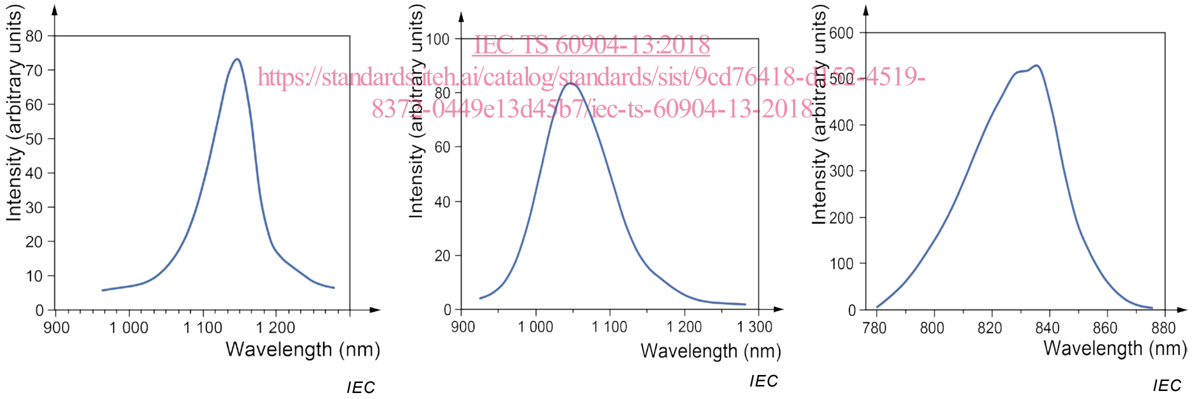


Figure 1 – Various semiconductor detector materials and their absolute spectral response [1][1]

Relevant parameters in choosing detectors include number of pixels, noise, quantum efficiency at the wavelength of interest, and dynamic range. This document contains provisions for various image resolutions. Choice of camera to obtain images that meet the sharpness classes given subsequently in 4.2.3 is made with respect to its imaging sensor and lens, with consideration to working distance (WD) and field of view (FOV). Theoretically, camera sensor resolution translates one-to-one with the image resolution. The resolution of an image in one of the dimensions (length or width) of an orthogonal array of pixels is the number of pixels in the image in that dimension.



(a) (b) (c)

Figure 2 – Electroluminescence emission spectra for (a) Si, (b) ZnO/CdS/Cu(In,Ga)Se_2 (CIGS) [2], and (c) CdS/CdTe [3]

Sensor resolution = Image resolution = FOV/smallest image feature

For example, if it is desired to image features of 2,5 mm onto a pixel and the length of the module to be imaged (corresponding to the FOV) is 1 600 mm, the sensor resolution (in pixels) required in this dimension is 640. This example implies the camera being in focus and neglects image sharpness considerations (see 4.2.3).

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

The camera response function (CRF) relates the actual quantity of light impinging on each element of the sensor array to the pixel values that the camera outputs. When the same object is captured at different exposure times but with an otherwise identical camera setup, a non-linear CRF causes the resulting image intensity distribution to exhibit nonlinearity, even after application of a correction for exposure time. Therefore, when analyzing image intensities, either the linearity of the CRF needs to be assured (basic methods are commonly found in the camera literature), or a correction for non-linearity needs to be performed using image processing. Scientific grade Si or InGaAs-based sensors are often linear or have a correction for non-linearity embedded. Neglecting non-linearity will cause erroneous results when applying procedures for image correction that are given in Annex A or any quantitative analysis.

To obtain maximum image resolution and electroluminescence signal, the optical axis of the camera is placed perpendicularly and as close as possible to the module face to image the solar cell or module area. Images captured at the highest resolution may require a longer exposure time and time to transfer from the camera and process. Binning features may exist to combine pixels for lower resolution and shorter image processing times. Gain feature may exist to amplify the signal of the EL image.

4.1.1.2 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. Optical glass is generally suitable, however Ge lenses will be necessary for measuring EL from the very low band gap materials (under 0,6 eV). Lenses vary from telephoto to wide-angle in focal length. Choice 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 subject, which is useful when space is constrained. Some wide-angle lens optics however 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 module, whereby the resulting images may require little or no correction by post processing. Lenses may feature components that correct for the difference between visible and infrared wavelengths, which can aid in focusing.

Lenses typically have an aperture with the size 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 result in significant vignetting at the edges of the image when using a smaller *f*-number.

4.1.1.3 Filters

Filters on the camera lens may be used to help cut light of extraneous wavelengths from being detected. 850 nm to 950 nm long-pass filters may be used when imaging near band-edge EL from modules with silicon cells.

4.1.2 Dark room imaging studio or environment

A darkened environment is favored 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. For non-laboratory measurements, minimize extraneous light when possible. For example, perform measurements at night. If stray light is present, an image subtraction procedure will be required, as discussed in 4.1.5.2.

Fixed mounting of the camera and a mount for the module(s) to be imaged are required so that the camera and the module positions are absolutely stable.

Laboratory measurements, for consistency in achieving qualitative or quantitative comparisons, should be performed with the module maintained between 20 °C to 30 °C. Temperature should be obtained with a temperature sensor accurate to within 1 °C placed on the module rear (the side not being imaged) and installed in a manner that does not interfere with the imaging. It may however be necessary to obtain EL images with the module at temperatures outside of the prescribed range to evaluate the effect of temperature or when it is not possible to maintain the module temperature within the prescribed range. For such measurements, the module temperature shall be noted and indicated as being performed "outside of the standard testing condition" (See Clause 6). The final temperature, measured within 15 s of the end of the image capture, shall be recorded for module temperature reporting requirements.

For highly accurate work, the module temperature may be stabilized by passing current until the temperature reaches equilibrium. The comparison of two images taken in sequence may be performed to see if both the module temperature and the camera detector (also affected by temperature) is stable by employing image histograms defined in Clause 5.3.8 and Formula C.1. The module may be considered stabilized if the absolute difference of the image intensity histogram of sequentially captured images is below 0,02 in each bin, where for this analysis, each bin width is 5 % of the EL intensity range captured from the module area (not including the background, area with no cells, or defective pixels).

For repeated measurements on a single module type under condition where the room temperature is maintained within a range of 5 °C, the module stabilization time may be determined by passing current until the temperature reaches equilibrium. EL imaging shall commence after thermal stabilization, and the module temperature shall be recorded. The waiting time required for the module to thermally stabilize shall be validated on at least one module of the same type, after which stabilization may be based on waiting time (and not direct temperature measurement) for future measurements of the module type. Images with the module temperature outside of the range of 20 °C and 30 °C shall be noted as being performed "outside of the standard testing condition."

NOTE 1 EL images obtained at different temperatures, including within the range of 20 °C and 30 °C, lead to different visibility of defects, such as those due to shunting and partially disconnected regions of broken cells because of thermal coefficient of expansion mismatches.

NOTE 2 Due to factors including module positioning and poor connections in the cell (e.g. cracks), grid fingers and interconnects, some EL signal may change, even when measurements are repeated at the same temperature.

4.1.3 Power supply

An electric DC power supply capable of applying I_{SC} of the module or a series string of cells or modules to be imaged is required. The power supply shall be able to provide sufficient voltage to achieve I_{SC}. Depending on the module technology, the required voltage may be approximately equal to the open circuit voltage V_{OC} of the module, but it may be significantly higher for some PV modules, such as those based on thin-film technology.

Measuring voltage during application of DC current through the module for EL imaging gives additional information about the condition of the module including the existence of shunt resistance reduction (lower voltage is measured), series resistance (higher voltage is measured), and correct connection to the module, but its measurement is optional. For accurate voltage measurement reporting, cabling from the module leads shall be of sufficient gauge to maintain less than 2 % voltage drop over the leads, or alternatively, a four-wire configuration shall be used to separately supply current and measure voltage at the connectors of the module(s) under test.

4.1.4 Computer interface with camera and power supply for image capture

Computer control of the power supply and camera so that pre-programmed currents can be quickly applied and coordinated with image capture are optional equipment that will provide speed and improve accuracy of the imaging of module EL. Further if the image and its capture settings are programmatically transferred into a file on the computer, it can aid in automatically recording image parameters for reporting requirements described in Clause 6.

4.1.5 Image processing and displaying software

4.1.5.1 Assignment of image colours

The image is transferred electronically from the camera to a computer for saving and maintaining in raw image format for subsequent display and image post-processing. Computer software should load EL image files, assign colours or a grey scale to each signal level measured within the PV module and any regions of interest. In the case of a colour image, a legend to indicate the meaning of the colours or levels shall be provided. Lowest EL signal shall 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 4.2.2.3). The colours in the scale between these extremes are not defined herein, but there should be no possibility of misinterpretation by re-use of similar colours to represent multiple signal levels or by the highlighting of areas where there are in fact no features; i.e., the number of colors should be minimized.

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 will be helpful, depending on the nature of the original image, for post-processing of images in the application of this document include:

- Level range adjustment
- Cropping the image to the region of interest
- 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 module is unpowered. An example of results from this procedure is given and explained in Figure 3. This may be performed with image processing software or in signal processing software, including with pulses of forward bias current applied cyclically.
- Dead pixel removal
- Single time effects removal
- Dark current variations (variation in CCD sensitivity and offset)
- Barrel distortion
- Vignetting

Fundamentals of image processing may be found in published literature. [4] [5]

When programming for operations on images involving matrix calculations (e.g., signal-to-noise ratio calculations, vignetting corrections), cast the data to double-precision floating point variables to prevent numerical errors. For saving images after performing calculations, image files may be reconverted to their original bit depth.