Electroluminescence Imaging

34553 Applied Photovoltaics

G. Benatto, N. Riedel, A. Santamaria, S. Thorsteinsson, S. Spataru

2020 August

Abstract: In this exercise, you will perform electroluminescence (EL) on a PV panel for fault diagnostics. We cover several topics from the recently published IEC Technical Specification.

References and links

- Slides from class (Block 4)
- Lecture slides from Course 34552 PV Systems, Lecture 11.

Safety

- Careful with the power supply connection and management: most of the experiment uses high current (~8A DC).
- Careful handling big PV modules. Two people should carry them carefully <u>always</u>.
- If in doubt, ask an instructor.

---

1. Introduction

In this laboratory assignment, you will acquire electroluminescence (EL) images from PV modules with the goal of detecting defects and faults. You will acquire high-resolution and fast integration EL images indoors. For the acquisition of images in high-resolution, we use a modified DSLR Nikon camera, while the fast acquisition EL are acquired using an InGaAs camera. With this exercise, you will be able to evaluate the accuracy of EL imaging technique for fault detection in PV modules.

2. Background

The normal working mechanism of photovoltaic cells is to transform radiation (from the sun) into electrical energy. If we drive current through them, i.e. perform the inverse process, they emit radiation. This phenomenon is called electroluminescence, and is the working mechanism for light emitting diodes (LED). The first demonstration of an EL image from a PV cell for defect detection dates from 2005 [1] and since then, it has become a standard measurement tool for industry and academy. It consists of applying a direct current to the PV module and measuring the photoemission by means of a camera sensitive in the short-wave infrared (SWIR) region. The emitted EL intensity is related to the number of minority carriers in the base layer, thus giving information on intrinsic and extrinsic cell parameters influencing them: minority carrier lifetimes, diffusion length, defects, faults, etc. In this exercise, we will focus in the defect and fault detection capability of this technique.

The emitted radiation from crystalline silicon photovoltaic cells has a peak at approximately 1150 nm, and extends in the wavelength range of 950 to 1300 nm. It cannot be seen with the naked human eye, since it is sensitive to the 390-750 nm range. Digital single-lens reflex (DSLR) photographic cameras are very common in the market and have either charge-coupled device (CCD) or complementary metal–oxide–semiconductor (CMOS) detectors, which are both Si-based detectors. These detectors are optimized for visible light detection, however they can detect further in the IR spectrum including a portion of the crystalline silicon emission, as can be seen in Figure 1. Such conventional camera requires three main changes to be able to perform EL images:

a) The camera includes an IR filter that has to be removed to allow the EL signal to reach the sensor,
b) A visible light filter need to be added to avoid exposure where the detector is most sensitive;
c) The camera has to be able to perform long exposure times, since the small portion of the spectrum requires it to be detected. The exposure has to be in the order of several seconds.

Another option is to use a camera with a detector built with a smaller bandgap semiconductor material, such as InGaAs. This material has greater quantum efficiency in the longer wavelength part of the spectrum when compared to silicon and covers the full emission spectra from c-Si. This allows much faster exposure times and the ability of performing videos with EL signal. Enhanced InGaAs detectors are able to acquire further in the visible than typically InGaAs detectors do, and this is the case of the camera you will also have available in the lab.

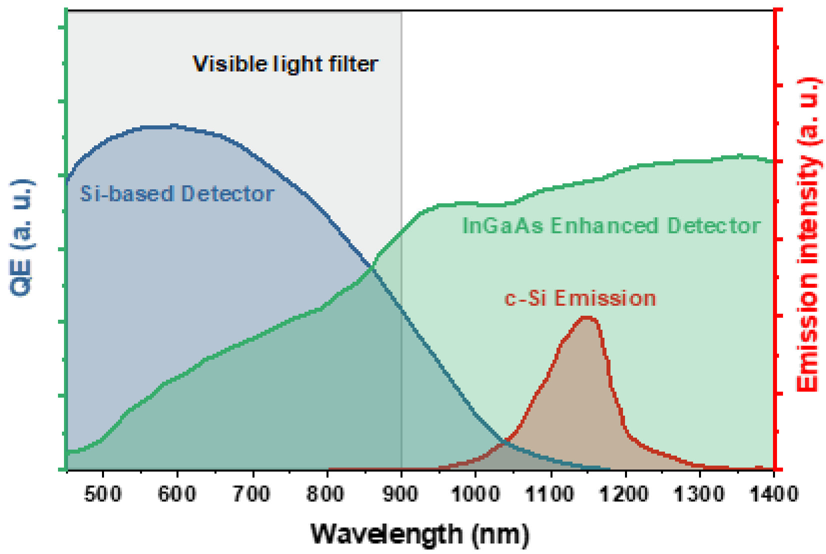

Figure 1 – Camera detectors quantum efficiency and EL emission spectra

3. Equipment and methods

Figure 2 illustrates the EL setup, which consists of a DC power supply unit (PSU), the PV module and a camera. A computer connected to the camera is required for image data acquisition and settings control.

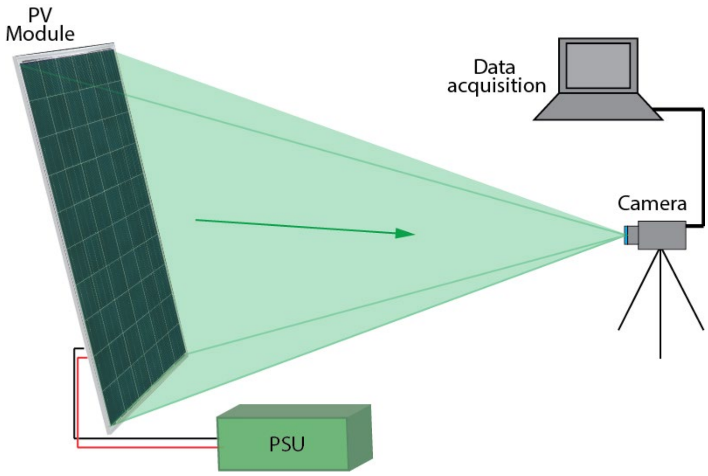

Figure 2 - EL experimental setup. The green shade represents the EL signal.

You will use the same PSU you have used in the IRT exercise. The cameras are a Nikon DSLR modified camera (Bright Spot Automation) and an OWL640 VIS-SWIR (Raptor Photonics) with a fixed 25 mm lens. The picture of the cited cameras and specifications of the Raptor camera can be seen below in Figure 3 and Table 1, respectively.

Figure 3 – DSLR Si-based (left) and InGaAs-based (right) cameras

Table 1 - Raptor OWL 640 VIS-SWIR Specifications

FPA Specification	
Sensor	SCD
Sensor Type	InGaAs PIN-Photodiode
Active Pixel	640 x 512
Pixel Pitch	15µm x 15µm
Active Area	9.6mm x 7.68mm
Spectral response	0.4µm to 1.7µm
Readout Noise (RMS)	LG: 174 electrons (typical), HG: 36 electrons (typical)
Quantum Efficiency	>80% @ 1.55µm
Full Well Capacity	Low Gain: 650Ke-, High Gain: 10Ke-
Pixel Operability	>99.5%
Camera Specification	
Digital Output Format	14 bit Camera Link (Base Configuration)
Exposure time	10µs to 26.8
Shutter mode	Global shutter
Frame Rate	Up to 120Hz
Optical Interface	C mount or M42
Dynamic Range	Low Gain: 71dB, High Gain: 49dB
Trigger interface	Trigger IN and OUT - TTL compatible
Power supply	12V DC ±0.5V
TE Cooling	Active
Image Correction	3 point NUC (Offset, Gain & Dark Current) + Pixel Correction
Functions controlled by serial communication	Exposure, Intelligent AGC, Non Uniformity Correction, Gamma, Pk/Av, TEC, ROI
Camera Power Consumption	<3.5W with TEC OFF, NUC ON
Operating Case Temperature	-20˚C to +55˚C
Storage Temperature	-30˚C to +60˚C
Dimensions & Weight	90.93mm x 50.00mm x 50.00mm | 282g

3.1. EL image interpretation.

The interpretation of EL images can be very straight forward, since many controlled faults have already been performed in laboratories and associated with EL images. Currently this assessment needs to be made by a person, since the research in automatic detection of cracks, differentiating crystallographic defects for example, is still ongoing [2], [3]. The most common defects and faults identifiable using EL imaging are related in the report "*IEA-PVPS - Review of Failures of Photovoltaic Modules*" in Table 5.4.1, pages 42-46. They were also shown in the intro lecture slides.

Cracks in a solar cell can be generally classified into three categories depending on their severity [4]:

i. Mode A cracks (micro-cracks) are solar cell cracks that does not generate inactive cell areas;

ii. Mode B cracks are defined as cell areas that exhibit an increase in the resistance across the crack. They can appear darker at high current EL images (100% I_{SC}) but are confirmed if they appear darker at low current EL images (10% I_{SC});

iii. Mode C cracks are defined as cell areas that show a complete electrical separation from the active cell area, which appear completely dark, both in the high (100% I_{SC}) and low current (10% I_{SC}) EL image.

3.2. Image processing

There are several cases for EL imaging where a background (BG) image must be subtracted from the EL image. This happens when stray light is present in the environment and this can happen even in a controlled lab environment. Remember we are dealing with long exposures or very sensitive cameras. Typically the BG subtraction is required in EL performed outdoors (even during the evening) or when the EL signal is low (i.e. very damaged cells or EL with 10% I_{SC}). Many other image processing steps can be required just to make the use of the EL image practical for the report and interpretation, such as, cropping, enhancing contrast, converting 14bits images into 8bits, rough quantitative analysis, among others.

To perform such image processing, you should install the software ImageJ (flash drive). Follow the guidelines shown in the intro lecture slides.

Task 1 – Indoors EL of c-Si PV modules

The test samples for this task are:

1. 36 multicrystalline silicon 156 mm x 156 mm cells PV module organized in a 6x6 matrix (**squared PV module**).
2. **Your working module**.

The procedure below refers to the 156 mm cells module, where the correspondent steps will be followed afterwards with your own module.

<u>High Resolution DSLR Si-based camera:</u> After positioning the camera DSLR and connecting the DUT to the PSU, adjust the focus roughly in the video mode, the ISO (100) and the exposure time (30 seconds). Settle the PSU to I_{SC} (8.4 A) and voltage to a value few volts higher than V_{OC}, so it can overcome the internal module resistance and allow current flow into the module. Use these settings during the focus adjustment to the best possible (if you see the finger interconnections it is good!).

Three images should be acquired to be used in the results presentation:

a) EL image with 100% I_{SC}
b) EL image with 10% I_{SC}
c) BG image

The BG image is an image with the identical scene of the EL, with PSU off.

Repeat the same process with your working module.

<u>VIS-SWIR or InGaAs-based camera:</u> Using now the Raptor Photonics camera and your working module, repeat the same image acquisition process you just did for the DSLR. This time you must take note of the exposure time in which you acquire the 100% and the 10% I_{SC} images. Make sure to acquire the BG with the same exposure time as the 10% I_{SC} image.

<u>ELID analysis and comparison of IV curves and EL images:</u> In Figure 4, you can see the IV curves taken before and after a mechanical stress was applied in the squared 36 cells PV module. The cracked curve shows a power loss of 4.6% in comparison to the intact one.

a) Perform the ELID threshold analysis and estimate the power loss based in the EL image taken from the squared PV module. Was you know the power loss for this module from the IV curve, adjust the ELID to match it.

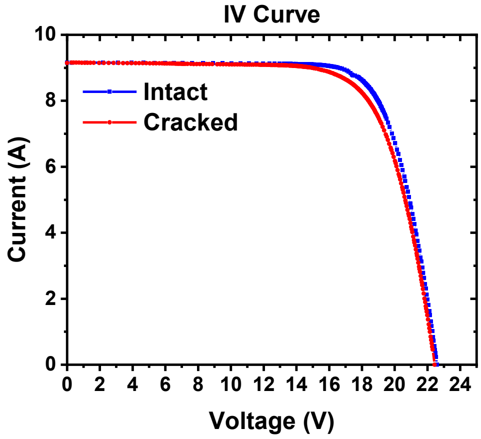

Figure 4 – IV curves of the intact and cracked squared PV panel.

b) Perform the ELID threshold analysis and estimate the power loss based in the EL image taken from your working module. Do it before verifying how the IV curve compared with the manufacturer specifications.

Task 2 – Indoors EL of Thin-film PV modules

Acquiring EL images from thin-film PV can be very different from c-Si PV. In this task, you will acquire an EL image from a CdTe module. Based on Figure 5, which camera should we choose?

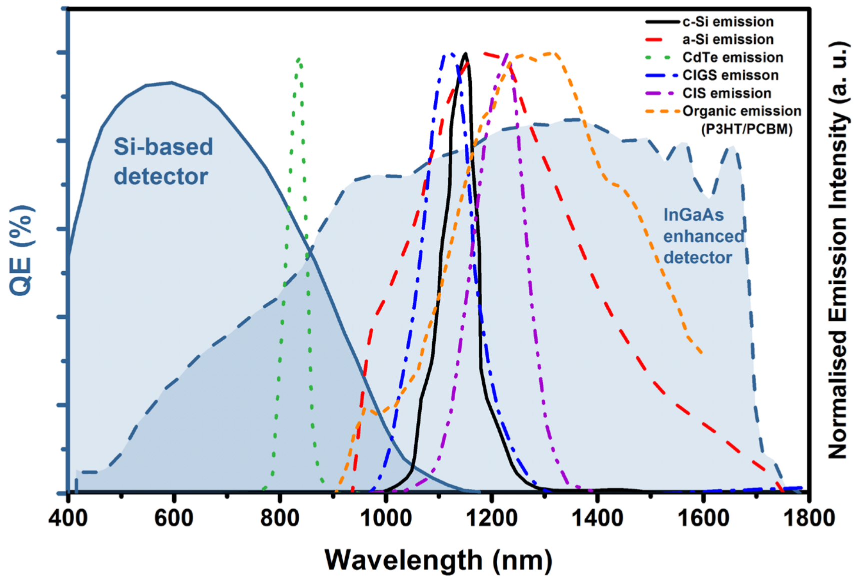

Figure 5 – Camera detector quantum efficiency and EL emission spectra of different PV technologies. Sources: [5]–[8]

After positioning the CdTe module, configuring the camera and PSU, you should acquire:

1. EL image with 100% I_{SC}
2. BG image

4. Results Presentation

The slides containing this exercise results should include:

- Short theory about EL imaging. } 1 slide
- The EL processed images acquired from the squared PV module and your working module.
- ELID of the squared PV module and your working module.
- The EL processed image of the CdTe module EL.

} 3/4 slides

During the presentation, discuss about:

- The comparison of DSLR and InGaAs camera's image quality and experimental details.
- Detailed interpretation of EL images of your working module. Answer to these questions:
  - What is wrong with the DUT?
  - What can be defects/faults from the manufacturing process and what are faults* originated by degradation or handling?
  - What do you think it happened with you working module?
- ELID of the squared PV module and your working module. Answer to these questions:
  - What is the estimated power loss of the squared module compared with the IV curve shown above?
  - What is the estimated power loss of your working module?
- Interpretation of CdTe module EL. Answer to these questions:
  - Is there something wrong with the module?
  - Which experimental details were different from the c-Si PV modules EL imaging procedure?

*If you wish to identify the cells in the PV panel, call the columns as letters (A, B, C…) and rows and numbers (1, 2, 3…) just as in an Excel Sheet. Ex. "Cell C3 presents A, B and C mode cracks".

References mentioned in the text:

[1] T. Fuyuki, H. Kondo, T. Yamazaki, Y. Takahashi, and Y. Uraoka, "Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescence," *Appl. Phys. Lett.*, vol. 86, no. 26, pp. 1–3, 2005.

[2] S. Spataru, P. Hacke, and D. Sera, "Automatic Detection of Inactive Solar Cell Cracks in Electroluminescence Images," *44rd IEEE Photovolt. Spec. Conf.*, 2017.

[3] S. Spataru, P. Hacke, D. Sera, S. Glick, T. Kerekes, and R. Teodorescu, "Quantifying solar cell cracks in photovoltaic modules by electroluminescence imaging," *2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015*, 2015.

[4] S. Kajari-Schröder, I. Kunze, and M. Köntges, "Criticality of cracks in PV modules," *Energy Procedia*, vol. 27, pp. 658–663, 2012.

[5] A. Andersson, "IEA PVPS Task 13 : ST 3 . 3 IR and EL in the Field."

[6] U. Hoyer *et al.*, "Electroluminescence imaging of organic photovoltaic modules," *Appl. Phys. Lett.*, vol. 97, no. 23, pp. 1–4, 2010.

[7] P. G. T. Weber, A. Albert, M. Roericht, S. Krauter, "Electroluminescence Investigation on Thin Film Modules," *26th Eur. Photovolt. Sol. Energy Conf. Exhib.*, pp. 2584–2588, 2011.

[8] R. Photonics, "Raptor Owl Swir 640 - VIS-SWIR technology." .