IMPLEMENTATION OF A FRIENDLY DAYLIGHT ELECTROLUMINESCENCE SYSTEM FOR THE INSPECTION OF SOLAR PV PANELS

O. Martínez[1], M. Guada[1], A. Moretón[1], S. Rodríguez-Conde[1], M.A. González[1], J. Jiménez[1], J. Pérez[2], M. Martínez[3], J.A. Florez[3], H. Silva[3], A. Velasco[3], L. Pérez[3], V. Parra[3]
[1]GdS-Optronlab Group, Dpto. Física de la Materia Condensada, Univ. de Valladolid
Edifico LUCIA, Paseo de Belén 19, 47011 Valladolid, Spain (oscar@fmc.uva.es)
[2]Dpto. Ingeniería Eléctrica, Escuela de Ingenieros Industriales, Univ. de Valladolid
Francisco Mendizábal 1, 47014 Valladolid, Spain
[3]Enertis Solar, SL.
Av. Bruselas 31, 1st floor, 28108 Alcobendas, Madrid, Spain (vicente.parra@enertis.es)

ABSTRACT: Electroluminescence (EL) is nowadays a well-recognized tool for the inspection of solar cells and panels, particularly interesting for the inspection of large plants. Routinely, when the modules are mounted at the PV site, EL measurements are carried out during nighttime and collected with Si CCDs (including conventional - modified - cameras), with good spatial resolutions and relatively low prices. However, daylight EL systems with InGaAs CCDs are promising tools for EL inspection, due to the possibility to analyse the solar panels during the day, which will be beneficial regarding the cost, practicability and module risk mitigation associated to the testing service. Also, in order to reduce production losses, the measurements should be conducted in a fast and reliable way. In this paper, we present a friendly daylight EL system using a cost-effective InGaAs CCD and appropriate filter setup. Good-quality images at high irradiations (above 1000 W/m^2) can be obtained in less than 20 s. Additionally, high-quality photoluminescence (PL) imaging can be registered by this friendly, cost-effective system.
Keywords: Electroluminescence, defects, Silicon, testing, daylight, on-site testing

1 INTRODUCTION

Electroluminescence imaging (ELi) is a well-known tool for the inspection of solar cells from the pioneer publication by Fuyuki and coworkers in 2005 [1]. The generalized use of Si CCDs, with resolutions of the order of 1 MPx or higher and relatively low cost, has allowed the use of ELi as a basic inspection tool for the control of the quality of modules and PV solar plants. The evolution of this technique in the last years has made of it one of the most prominent tools for the inspection of Si solar plants [2].

However, Si CCDs require strict dark conditions to perform the EL measurements, since any ambient light, with visible components, will be in competition with the small EL signal arising from Si solar cells. For this reason, EL measurements with Si CCDs were limited to be performed in a dark laboratory space (indoor EL), although, recently, outdoor EL become common using the Enertis' PV Mobile Lab tools or also by measuring during the night [3, 4].

The appearance in the last years of new CCDs with large efficiencies in the near IR has paved the way to performing EL measurements during the sunrise and nightfall, and has opened the door to perform daylight EL by using adequate filters and procedures [5].

The main objective of our work is to develop a cost-effective, optimized daylight friendly system, allowing EL images to be obtained with good resolution and optimized acquisition times.

2 ELECTROLUMINESCENCE

2.1 Basis

ELi is a relatively very easy characterization technique, requiring only to forward biassing the cell or the module and a CCD to collect the luminescence emitted by the recombination of the electron and holes (e-h) injected into the p-n junction of the solar cell.

ELi is usually based on Si-detector cameras, due to their resolutions and relatively low cost. The main drawback of Si CCDs for ELi inspection of Silicon solar cells is the inappropriate QE at the spectral range of the Silicon near band edge (NBE) emission, centered at ~1100 nm, Fig. 1. The QE of Si CCDs is high in the range 400 – 850 nm, but is very low beyond 1000 nm. However, in spite of the low QE of the CCD detector, it is possible to capture the luminescence emitted by the Si solar cells (alternatively one can use light excitation for Photoluminescence imaging, PLi). In a dark ambient, good EL images can be obtained with very short acquisition times, of the order of a few milliseconds. This makes ELi a very useful technique for identifiying defects related to faults of electrical connections and/or defects related to the Si material itself, in PV modules or plants, e.g., defects such as microcracks, those related to potential induced degradation (PID), etc., can be easily observed [6, 7].

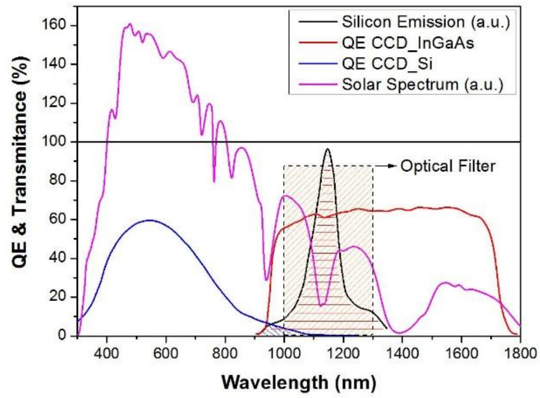

Figure 1: QE of Si and InGaAs CCDs, compared to the NBE emission of Silicon.

A dark condition is mandatory when using Si CCDs, in order to avoid any ambient light. This presents some drawbacks, such as the need to dismantle the panels in the case of measurements in a lab or in a mobile van (which forces EL to be a control tool for only a small portion of a PV plant) or the difficulties and inconveniences of performing the necessary electrical contacts during night; in particular, the manipulation of electrical interconnections by night becomes more complicated that by day, and also the measurements at night require large costs in workforce, security levels, etc.

2.2 Daylight EL

The appearance of IR CCDs such as InGaAs CCDs, with optimal QEs in the near IR region, open the possibility to perform EL measurements at not so strictly dark conditions. For instance, the NBE of Si at ~1100 nm lies on the maximum QE spectral range of InGaAs CCDs, as illustrated in Fig. 1. It is also beneficial the fact that the InGaAs CCD is blind to most of the visible spectrum. In spite of this, large amounts of IR ambient light will still arrive to the CCD, and compete with the comparatively low EL Si signal. For this reason, daylight EL is not straightforward, and the large parasitic ambient light that covers the EL signal must be rejected and filtered. This is especially critical for large background irradiation levels. For instance, at moderate irradiation levels of 700 W/m^2, signal to noise ratios (SNR) of 0.006 were recorded. Another critical point to consider is the significant fluctuation in the levels of the background light (Fig 2). Such large fluctuations in relatively short times make difficult the task to separate the EL signal and background from each other.

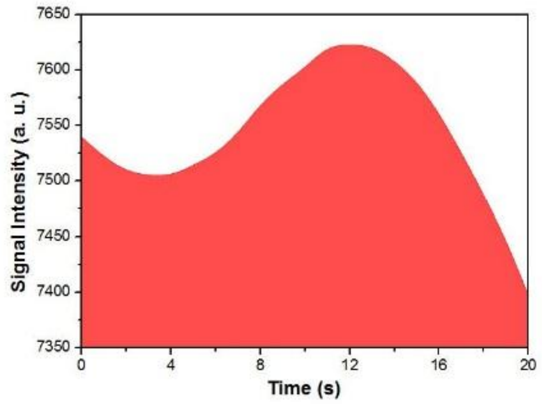

Figure 2: Fluctuations of the total signal detected by our cost-effective InGaAs CCD during 20 seconds in a partially sunny day (G = 700 W/m^2).

3 DEVELOPMENT OF A DAYLIGHT EL SYSTEM

3.1 Main components

Our approach to perform daylight EL measurements use three main components: an InGaAs CCD (hereinafter, CCD), a laptop and a power supply. Nowadays, high resolution InGaAs CCDs are still expensive. We have use a cost-effective InGaAs CCD (640 x 512 pixeles) as a proof of concept, demonstrating that our system allows, in spite of the resolution, to acquire high quality daylight EL images. The laptop will control the measurements; a proper interconnection between the three elements is mandatory. An appropriate software control was developed using LabVIEW, because of the advantages of this programming language for the control of different hardware components. In fact, one of the most important requirements of the CCD is the use of an USB connection, and the possibility of remote software control. In this same way, a precise control of the power supply is mandatory. Moreover, the uniqueness of our in-house developed software requires strict control of the times at which the power supply is turned on and the images are captured by the CCD. Aiming to this, an innovative forward biasing process has been developed.

3.2 Key aspects

The signal collected by the CCD will contain both the EL signal and the ambient noise, which needs to be filtered to extract the proper EL image. For instance, the use of adequate external filters can be beneficial for this purpose, such as band-pass filters around the NBE emission of Si (Fig. 1). However, software filtering methods are indispensable.

One of the main clues to perform good-quality EL measurements is to avoid direct light reflections from the panel, since this will increase the ambient noise substantially. For this reason, a proper orientation of the CCD with respect to the panel is very convenient.

Another key parameter to be controlled is the exposition time of the CCD. Large exposition times are beneficial, trying to collect as much EL signal coming from the Si panel as possible. However, the ambient light noise also grows linearly with the exposition time, Fig. 3. This should not necessarily be a problem if the filtering process is correctly developed. However, the increase of the exposition time has a limit, due to the saturation level of the CCD. This is especially critical for high irradiation conditions. In our approach, the selection of the exposition time is achieved automatically, in such a way that the saturation level of the CCD is never reached.

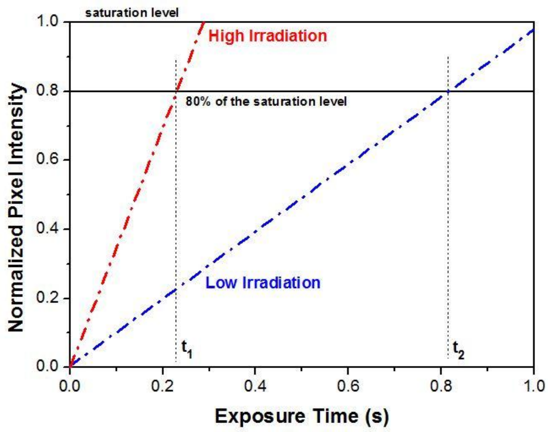

Figure 3: Increase of the total signal collected by the CCD as a function of the exposition time for two irradiation conditions. The saturation level of the CCD and a predetermined lower value of 80% of the CCD saturation level are indicated.

Two additional key points, which are always essential to conduct any modality of EL measurement, and especially relevant for large PV plant analysis, if one wants to carry as many EL measurements as possible, are both the way to polarize the panels (or strings) and the way to fix and control the CCD movements. These challenges should also be addressed for the case of daylight EL, with the advantage of being performed with solar light. On the contrary, some specific problems appear for the case of daylight EL, particularly for large irradiation conditions and hot days, such as those related to CCD heating, correct visualization in the screen of the laptop, etc.

3.3 Software development

Our software was developed in order to resolve the aforementioned problems, and to create a friendly and quick screening system. In particular, an automatic procedure was settled up to select the right exposition time avoiding CCD saturations. For this purpose, a live image of the modules is recorded, and the EL intensity histogram is evaluated. An automatic procedure allows selecting the largest exposition time avoiding the saturation of any CCD pixel.

Also critical, in certain cases, is the correct visualization of the EL images, which for sunny days can hardly be correctly visualized in the laptop. For this purpose, an automatic procedure has been developed to auto adjust the contrast of the images (Fig. 4). This allows, for instance, ensuring an optimum EL image, without the need to perform any post-procedure processing to improve the quality of the images.

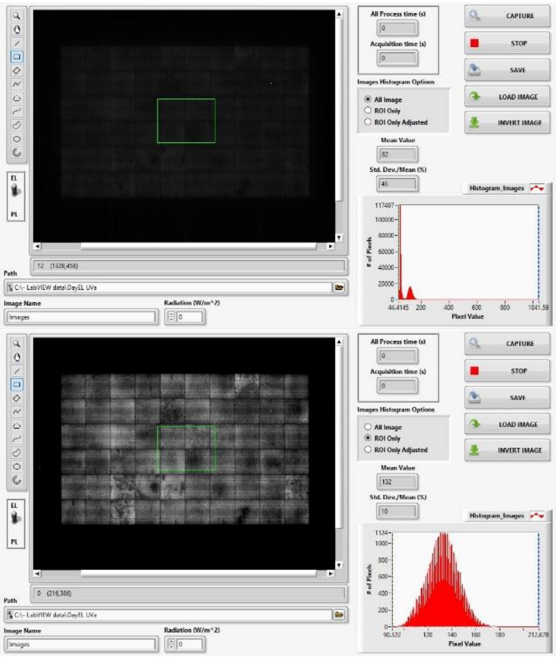

Figure 4: Automatic process developed to adjust the contrast of the EL images. Top: bare EL image; bottom: corrected EL image.

4 RESULTS

4.1 EL results

Fig. 5 shows the daylight EL image of a mc-Si test module obtained with our system on a sunny day at large irradiation conditions (G=850 W/m^2). As observed, the quality of the images is quite satisfactory, allowing to distinguish even small features and defects in the individual cells. The exposition time of the CCD was automatically fixed, being the total acquisition time (t_t) of this image 10 s. In order to assess the importance of the exposition time on the measurements, Fig. 5 also shows the EL image obtained on the same test module at very low-light conditions (G=70 W/m^2), without suitable exposition time adjustment (t_t=12 s). The saturation of some areas of the module leads to a much lower quality of the EL image.

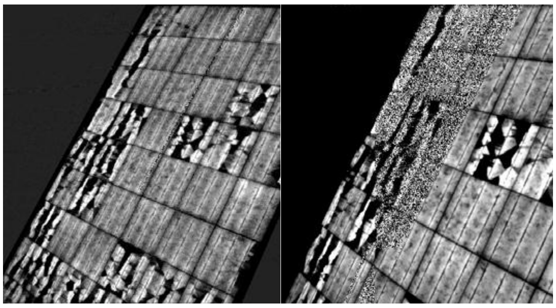

Figure 5: Right: daylight EL image on a mc-Si test module on a sunny day (G=850 W/m^2, t_t=10 s) by adjusting automatically the exposition time. Left: day light EL image on the same mc-Si test module at much lower irradiation conditions (G=70 W/m^2, t_t=12 s) with an incorrect exposition time.

As a proof of concept, this new tool has been tested on a PV rooftop (very low tilt angle) based on Cz-Si modules (Figs. 6 and 7). By biasing a complete string of 14 modules, the CCD was positioned in such a way to photograph six modules, as shown in Fig. 6. Despite the low focus angle, the quality of the EL image allows inactive-cell areas, finger interruptions and soldering issues be easily detected.

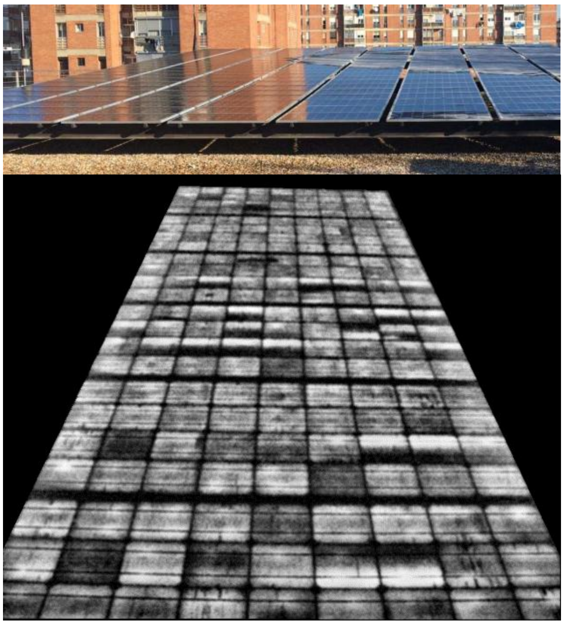

Figure 6: Top: Cz-Si PV rooftop (low tilt angle) surveyed with our system. Bottom: daylight EL image of a section of a 14 panels-string (G=650 W/m^2, t_t = 10 s).

As can be observed in Fig. 7, image resolution allows the minor and major EL defects such as metallic finger interruptions, cell breakage (dead regions), heterogeneous cell activity, soldering issues and cell inhomogeneities to be clearly detected and evaluated.

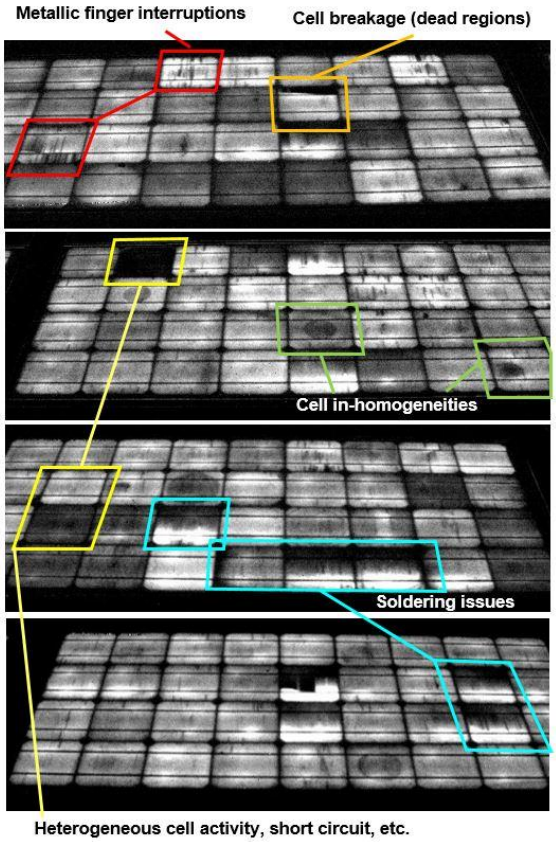

Figure 7: Daylight EL images of four individual panels of the first line of panels of the the Cz-Si PV rooftop tested. (650 W/m^2, t_t = 10 s for each image).

The present daylight EL approach has also been tested at high irradiation conditions. For instance, Fig. 8 shows a daylight EL image recorded on a cloudless, summer day in Madrid (27th of July 2017), at 13.00h (G=1050 W/m^2, t_t = 17 s). The image corresponds to a 60-cell, high-performance PERC module. The quality of the EL image (Fig. 8) is high enough to distinguish bulk defects, cell cracks, etc. on the individual solar cells.

4.1 PL results

The daylight EL system can be also adapted to allow PL imaging (PLi). In PLi, the panels do not need any external DC bias. In fact, the sunlight is used as the excitation source to create the corresponding e-h pairs, which the recombination generates the luminescence signal. This signal is also collected by the CCD, being conveniently filtered from the ambient noise by the above-mentioned software method.

Fig. 9 shows the PL image of the same previous PERC module. Again, the high-quality of the image allows the detection of major and minor defects in the panel. The advantages to obtain both the EL and PL images of a same module, or even the possibility to obtain only the PL images (without the need to use large power supplies to bias strings) makes of this method a very potential tool for new developments in the characterization and inspection of solar panels.

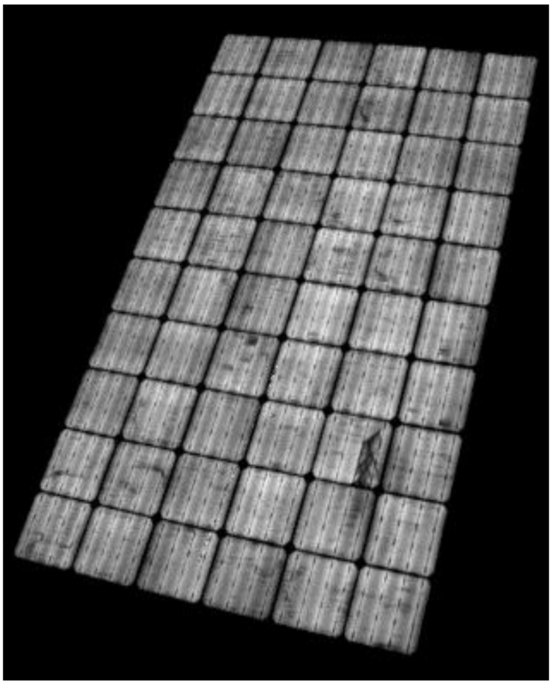

Figure 8: Daylight EL image of a high-performance PERC module (G=1050 W/m^2, t_t = 17 s).

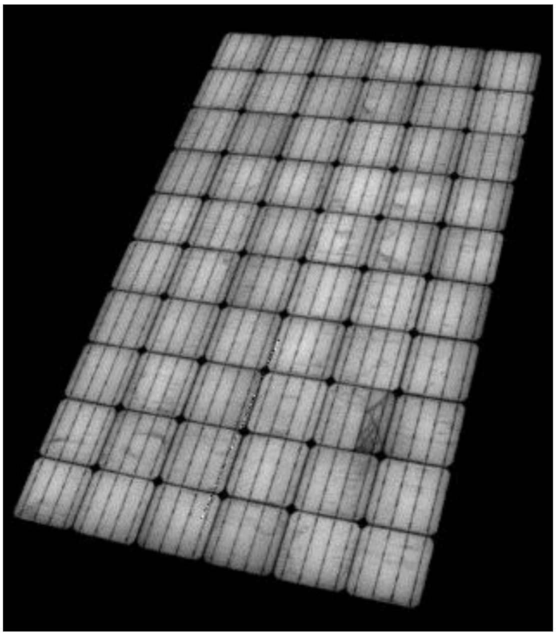

Figure 9: Daylight PL image of a high-performance PERC module (G=1050 W/m^2, t_t = 17 s).

5 CONCLUSIONS

A friendly and cost-effective system for daylight EL testing has been developed. Good-quality and quick EL images of c-Si modules, even under high irradiance conditions, can be obtained. The system also allows recording PL signals, with no need to polarize modules.
The advantage of this tool is the easiness and high speed of the EL measurement process, given the current limitations of this valuable defect screening technique

when performing EL test on-site.

6 REFERENCES

[1] T. Fuyuki, H. Kondo, T. Yamazaki, Y. Takahashi, Y. Uraoka, "Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescence", Appl. Phys. Lett. 86, 2005, 262108.

[2] O. Breitenstein, J. Bauer, K. Bothe, D. Hinken, J. Müller, W. Kwapil, M.C. Schubert, W. Warta, "Can Luminescence Imaging Replace Lock-in Thermography on Solar Cells?", IEEE J. of Photovolatics, 1 (2011) 159-157.

[3] S. Koch, T. Weber, C. Sobottka, A. Fladung, P. Clemens, J. Berghold, "Outdoor electroluminescence imaging of crystalline photovoltaic modules: comparative study between manual ground-level inspections and drone-based aerial surveys", 32th EU PVSEC, Munich 2016, pp. 1736-1740.

[4] M. Navarrete, L. Perez, F. Domínguez, G. Castillo, R. Gomez, M. Martinez, J. Coello, V. Parra, "On-Site Inspection of PV Modules Using an Internationally Accredited PV Mobile Lab: A Three-Year Experience Operating Worldwide", 31st EUPVSEC, Hamburg 2015, pp.1989-1991.

[5] L. Stoicescu, M. Reuter, J.H. Werner, "DaySy: Luminescence Imaging of PV Modules in Daylight; 29th EUPVSEC, Amsterdam 2014, pp. 2553-2554.

[6] M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, "Quantifying the risk of power loss in PV modules due to micro cracks". 25th EUPVSEC, Valencia, 2010, pp. 3745–3752.

[7] T. Potthoff, K. Bothe, U. Eitner, D. Hinken, M. Kontges, "Detection of the voltage distribution in photovoltaic modules by electroluminescence image". Progress in Photovoltaics: Research and Applications 18, 2010, 100.

7 ACKNOWLEDGEMENTS

This investigation has been financed by the Spanish MINECO/CDTI project, ref. IDI-20151194, the Spanish MINECO project, ref. ENE2014-56069-C4-4-R and the Junta de Castilla y León project, ref. CP16/58.