Electroluminescence (EL) studies of multicrystalline PV modules

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ABSTRACT

Higher power generation yield is the prime objective of any solar power plant developer. The quality and reliability of the modules used are therefore a key aspect, with customers placing stringent criteria on cell and module manufacturers with regard to product quality. Electroluminescence (EL) image monitoring, which gives a clear picture of defect distribution across a module, is an increasingly popular quality criterion. Although there are no standard guidelines for accepting or rejecting a module on the basis of EL images, customers are eager to see uniform illumination in the images. This paper reports on a study that focused on EL image analysis and correlation with reliability tests, through subjecting the modules to thermal-cycling (TC) tests and potential-induced degradation (PID) tests. EL images before and after these tests are compared in order to understand the changes in the images with respect to stress. From the results, it is concluded that EL imaging can act as an inline quality inspection tool, but cannot guarantee product reliability.

Introduction

As the need for global electricity exceeds the conventional power generation capacity, all nations are looking to solar PV as an alternative, and incentive schemes are being implemented to encourage solar power plant developers. Crystalline PV technology is demonstrating its success in fulfilling growing energy demands. Each factor of the complete value chain of crystalline PV is important in determining initial investment cost and long-term reliability. Investors are therefore very interested in the quality of the materials used in the development of solar power generation plants.

Solar panels installed in the field will be subject to drastic changes in weather, and there is a potential risk of failure of poor-quality modules. The International Electrotechnical Commission has established some guidelines (IEC 61215) for ensuring the quality of crystalline solar modules [1]. All module manufacturers obtain IEC certification from authorized institutes to demonstrate the quality of their products to their customers. Since this qualification test is time consuming and costly, it is limited to just a few samples. Some of the process-related defects – such as improper tabbing, poor lamination and cell cracks – will not be observed during a visual inspection; moreover, the electrical performance of these defective modules will not differ very much from that of good ones. These defects will get worse over a period of time, however, because of the impact of weather conditions on modules. Online inspection of modules in manufacturing is the only way to address such quality-related issues.

> “There are no standard guidelines for accepting/rejecting a module on the basis of EL images.”

Electroluminescence (EL) imaging of PV modules before and after lamination is an advanced method for ensuring defect-free module manufacturing, but there are no standard guidelines for accepting/rejecting a module on the basis of EL images. Nevertheless, customers like to see uniform illumination in EL imaging.

There have been various studies carried out on EL image correlation with respect to defects. Kirchartz et al. [2] interpreted EL emission intensity in relation to the quantum efficiency of the cell. The operating voltage of an individual cell in a module can also be derived using EL images [3]. The identification of cell cracks, breaks in contact lines and other defects has been established in various studies [4,5].

This paper is aimed at analysing EL images with respect to cell electrical performance. The changes in the EL images before and after the stress tests are also studied in order to understand how these images can be used in terms of assessing reliability.

Theory

A solar cell is basically a p-n junction diode. Under forward-bias conditions, the intrinsic potential across the junction will drop, and majority carriers from both sides will cross the junction and enter the other side, where they become minority carriers. These minority carriers diffuse away from the junction and recombine with the majority carriers. In this process of recombination, photons of a frequency equal to the band gap of the material will be emitted for every electron–hole recombination, a phenomenon called *injected electroluminescence.*

The rate of radiative recombination r on each side of the junction depends on the concentration of majority carriers and on the number of minority carriers injected [6], and is given by $r = Bnp$. Here, n is the electron density, p is the hole density and B is a constant, which will be 10^7 times smaller for indirect band-gap materials than for direct band-gap materials. In silicon-based solar cells, electron–hole radiative recombination probability is therefore lower, since silicon is an indirect band-gap material. Electron–hole creation and recombination are proportional to each other, which means that the internal quantum efficiency of carrier generation can be estimated from the carrier recombination. In this way, EL imaging can be used to map solar cell performance; furthermore, by analysing EL data one can understand the material characteristics in a non-destructive way. This is why EL imaging has gained the attention of the PV industry as an inline quality check in the manufacturing process.

A module to be tested is forward biased in a dark environment. Since silicon is an indirect band-gap material, the band-to-band radiative transition rate is lower and the intensity of light emitted under forward bias from a silicon solar cell is much reduced; the background while taking the image therefore needs to be dark. When a module is forward biased, the applied current will be distributed across the cell through the front-contact grid lines (which are used for the collection of photogenerated current). The injected carriers (forward current) in the emitter recombine with the available holes, and light is emitted. The spatial intensity distribution of emitted light depends on the cell properties, in other words on the materials and process used.

In a typical module production process, various types of EL image can be identified (Fig. 1), but there is no global standard with regard to acceptance/rejection criteria on the basis of the image. The main objective of EL inspection is to detect cell cracks and other process defects (such as improper tabbing), but customers are very particular about seeing a uniform and bright EL image across the modules without any signs of dark areas on the cells: this is because of limited studies of EL images and their correlation with reliability. It is therefore important to understand the technical reasons for the various types of EL image and the corresponding effects on module performance in long-term operation.

Image analysis

The intensity of emitted light determines the brightness of the EL image: the higher the intensity, the brighter the image. A solar cell under forward bias emits more light only when the injected carriers recombine radioactively. The radiative recombination rate depends on two factors: 1) defect centres, and 2) injected carriers.

Metallic impurities in a silicon wafer induced during ingot growth will occupy energy levels in the forbidden gap of silicon and act like minority-carrier trap centres. In a solar cell, if the substrate wafer is free from such defect sites (recombination centres), then the probability of radiative recombination of the injected carriers with the holes will increase, and the intensity of emitted radiation will be high. The open-circuit voltage of a solar cell is a direct measure of material purity [7]: the higher the purity, the higher the V_{oc}. Thus, the cells with higher open-circuit voltages appear bright in an EL image, because of a higher radiative recombination rate; on the other hand, cells with lower open-circuit voltages will appear dark.

> "The higher the V_{oc}, the brighter the EL image."

In Fig. 2, cells with different electrical parameters are arranged from A to F in ascending order of V_{oc}. The values V_{oc}, I_{sc} and FF for each cell are tabulated next to the image; by comparing these

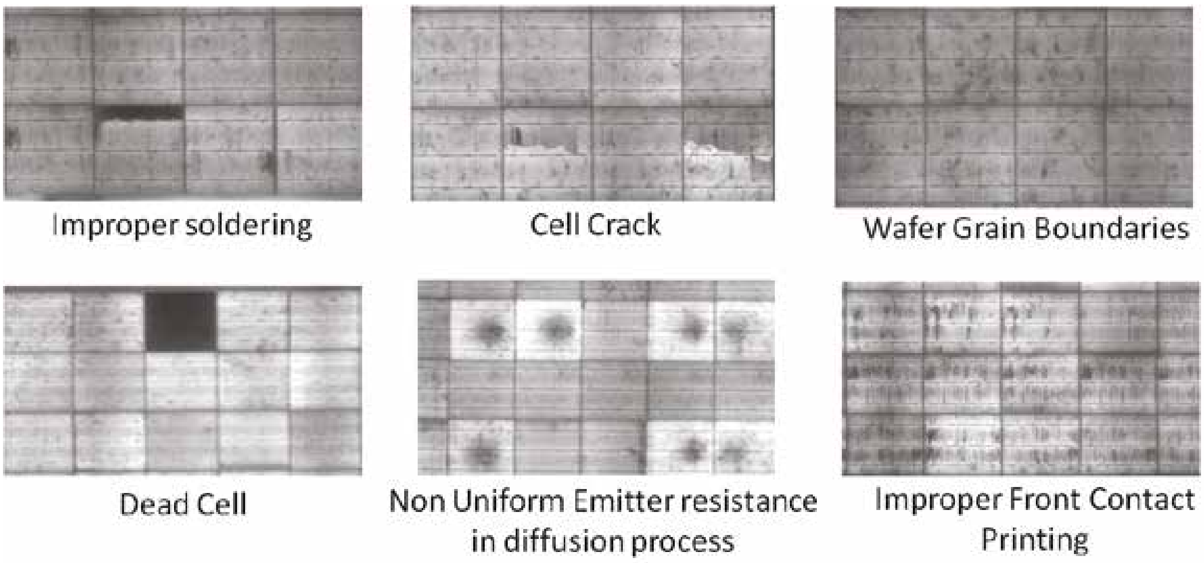
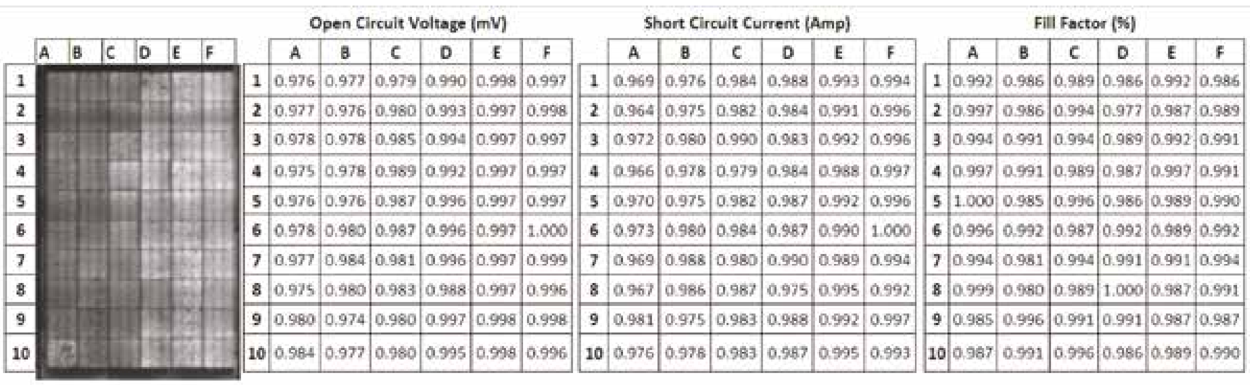


Figure 1. Various types of EL image in a standard module manufacturing line.



Open Circuit Voltage (mV)

	A	B	C	D	E	F
1	0.976	0.977	0.979	0.990	0.998	0.997
2	0.977	0.976	0.980	0.993	0.997	0.998
3	0.978	0.978	0.985	0.994	0.997	0.997
4	0.975	0.978	0.989	0.992	0.997	0.997
5	0.976	0.976	0.987	0.996	0.997	0.997
6	0.978	0.980	0.987	0.996	0.997	1.000
7	0.977	0.984	0.981	0.996	0.997	0.999
8	0.975	0.980	0.983	0.988	0.997	0.996
9	0.980	0.974	0.980	0.997	0.998	0.998
10	0.984	0.977	0.980	0.995	0.998	0.996

Short Circuit Current (Amp)

	A	B	C	D	E	F
1	0.969	0.976	0.984	0.988	0.993	0.994
2	0.964	0.975	0.982	0.984	0.991	0.996
3	0.972	0.980	0.990	0.983	0.992	0.996
4	0.966	0.978	0.979	0.984	0.988	0.997
5	0.970	0.975	0.982	0.987	0.992	0.996
6	0.973	0.980	0.984	0.987	0.990	1.000
7	0.969	0.988	0.980	0.990	0.989	0.994
8	0.967	0.986	0.987	0.975	0.995	0.992
9	0.981	0.975	0.983	0.988	0.992	0.997
10	0.976	0.978	0.983	0.987	0.995	0.993

Fill Factor (%)

	A	B	C	D	E	F
1	0.992	0.986	0.989	0.986	0.992	0.986
2	0.997	0.986	0.994	0.977	0.987	0.989
3	0.994	0.991	0.994	0.989	0.992	0.991
4	0.997	0.991	0.989	0.987	0.997	0.991
5	1.000	0.985	0.996	0.986	0.989	0.990
6	0.996	0.992	0.987	0.992	0.989	0.992
7	0.994	0.981	0.994	0.991	0.991	0.994
8	0.999	0.980	0.989	1.000	0.987	0.991
9	0.985	0.996	0.991	0.991	0.987	0.987
10	0.987	0.991	0.996	0.986	0.989	0.990

Figure 2. Cells are arranged from A to F in ascending order of open-circuit voltage.

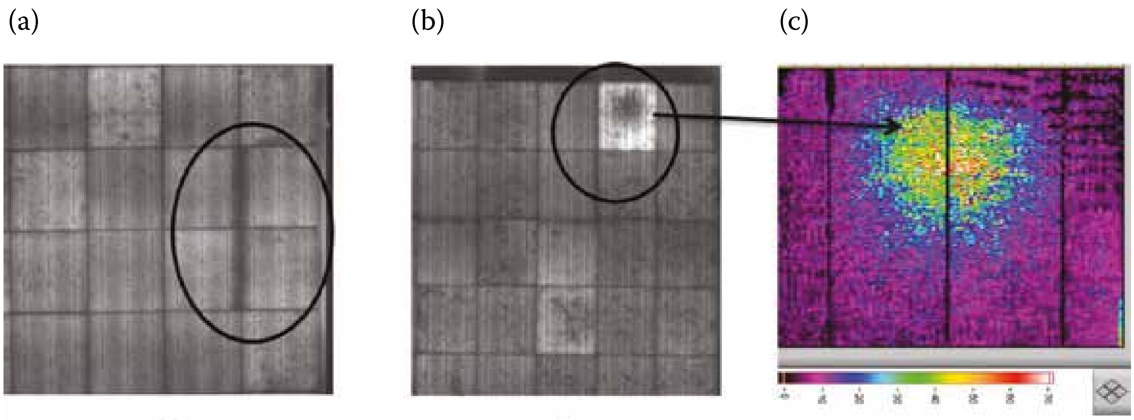


Figure 3. (a) Impurities at the edge of the wafer act as recombination centres and show up as dark areas on the cell edges in the EL imaging test. (b) High contact resistance due to non-uniform sheet resistance during the diffusion process. (c) Contact resistance scan of the central dark area of the cell in (b).

parameters to the bright and dark cell images, it is clear that the higher the V_{oc}, the brighter the EL image. The short-circuit currents and fill factors play no role in the image brightness intensity. The raw wafer quality and diffusion process are two critical parameters which determine the V_{oc} of the cell and the EL image intensity.

Fig. 3 shows two different defects highlighted by EL imaging: wafer related and process related. A dark area at the edge of the cells during the EL test is shown in Fig. 3(a); these cells are made from wafers that have more metallic impurities at one edge than over the rest of the cell area. During ingot growth, all impurities will accumulate at the top, bottom and sides of the ingot, and will act as minority recombination centres. Consequently, wafer manufacturers will chop the top, bottom and sides off the ingot to make defect-free wafers. If the amount of chopping on the sides is not sufficient, then some of the wafer will exhibit this kind of defect. Since these are bulk impurities, it is very difficult to remove them during the cell processing steps.

Fig. 3(b) shows a dark area in the centre of the cell. In this dark area the contact resistance between the silver grid lines and the emitter is high (Fig. 3(c)); as a result, the applied current does not flow through this area. Thus there were no injected carriers in this area to recombine, and thus it has a dark appearance. This kind of defect is due to non-uniform emitter formation in the diffusion process.

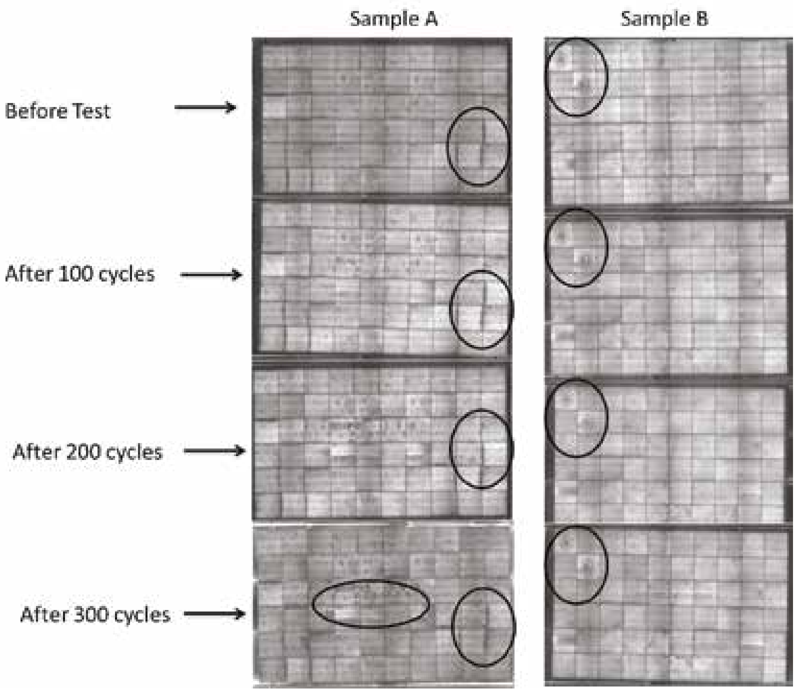


Figure 4. EL images of the modules before and after the TC tests. Sample A consists of a module with a few cells that are constructed from a defective wafer, whereas Sample B consists of a module with some cells exhibiting a processed-induced defect.

Reliability studies

In the examples discussed above, the first defect is due to the raw wafer, and the second is due to the process. To understand how these two defects affect module performance over a period of operation in the field, modules constructed from a combination of good and bad cells were subjected to thermal-cycling (TC) tests, and the EL images analysed after every 100 cycles.

In Fig. 4, Sample A contains some cells that have been created from a wafer with edge defects; Sample B has a few cells with process-induced defects (as discussed earlier). From the EL images it is clear that there is no significant change in the defective cell images, even after 300 TC cycles. In the case of Sample A, it is also observed that some of the cells with a good EL image before the TC test now exhibit dark patches (indicated in the centre of the bottom image for Sample A) after 300 cycles of TC. This confirms that even though there are cells yielding a dark EL image, due to either raw wafer issues or processes-related issues, they are not necessarily the cause of degradation.

At the same time, cells with a good EL image become degraded after a few cycles of TC. Therefore, all the dark

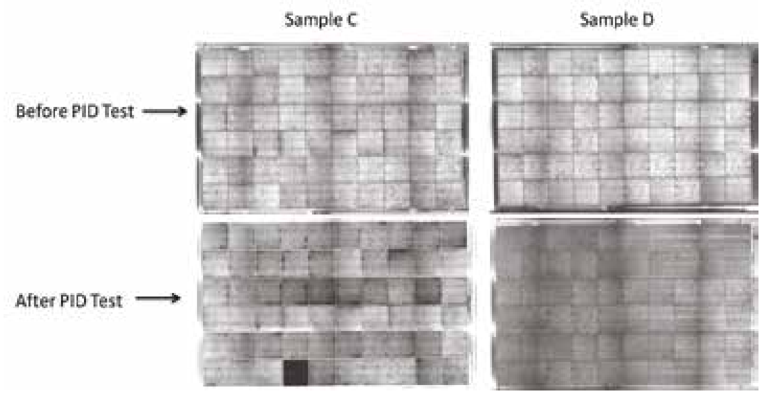


Figure 5. EL images before and after the PID test.

image cells do not necessarily affect module reliability; moreover, it is not guaranteed that cells with a uniform EL image will retain the same performance over a long period of operation in the field. This was also observed in the case of the potential-induced degradation (PID) tests, in which modules were subjected to 1,000V reverse bias for 96h. Before the PID test, all the cells had a uniform EL image; however, one cell which had a good EL image before the PID test was found to have a dark image after completion of the test (see Fig. 5).

Conclusions

EL imaging is an effective technique for inline quality checking in a module manufacturing line. The technique is mostly used before lamination in order to remove the defects and to avoid reprocessing of the product. Since there are no global standards for EL criteria in relation to accepting or rejecting the product, all manufacturers and customers have very stringent requirements in terms of having uniform and bright EL images of the entire product.

> "EL imaging can only help to detect defects and cannot guarantee product reliability."

The effects of cell cracks and tabbing defects are reflected in reduced electrical performance; the use of EL imaging can enable the defective cells to be replaced by good ones. Image brightness is a function of cell V_{oc}: the higher the V_{oc}, the brighter the image. It is evident from the present study that cells which already display a dark image are not significantly affected, even after 300 cycles of TC; moreover, cells initially with a good image can exhibit dark patches after TC testing. Similarly, in the PID tests some cells with initially a bright EL image displayed a dark image after completion of the PID cycle. Thus, EL imaging can only help to detect defects and cannot guarantee product reliability.

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