STRUCTURAL ANALYSIS OF THIN FILM SILICON PV MODULES BY MEANS OF LARGE AREA LASER BEAM INDUCED CURRENT MEASURMENTS

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ABSTRACT: The spatial variation of key properties of large area silicon thin film PV modules is investigated using a Laser Beam Induced Current (LBIC) system. The system produces a very detailed current mapping of devices, allowing the identification of spatially varying structural defects of photovoltaic modules. It allows for efficient defect detection as well as investigations of localised performance variation. In this paper, the results are shown for large area single junction amorphous silicon modules from different manufacturers that have been installed outdoors for more than two years. Several defects are identified as probable sources of poor performance and low efficiency of some devices. Some of the major contributions to these defects are likely to occur during the production process while some are developed during outdoor exposure.

Keywords: LBIC, a-Si, module

1 INTRODUCTION

Spatial homogeneity of material quality is one of the most important factors that determine the overall performance of photovoltaic (PV) devices. One small sub-optimal area can considerably deteriorate the performance of the entire PV module. Thin film technologies can be strongly affected by this because unlike crystalline silicon technologies, they cannot utilise cell sorting and hence have greater potential to suffer from cell mismatch losses. This is amplified for larger area modules (required for cost effective production), with higher numbers of cells connected in series. There is a clear need to minimise losses due to parasitic resistances and the relatively high resistivity of the TCO layers utilised for the contacting of such modules and hence spatially resolved investigation of modules is important for enabling these technologies to reach their full potential.

In order to identify non-visible structural defects in thin film PV modules without destructive testing, several approaches are commonly used. Methods available are for example thermography or photoluminescence measurements, which are both utilising modern CCD arrays to take pictures of the modules. The advantage of these methods is the relative speed of these measurements but the disadvantage is that they are limited by the CCD resolution, typically limiting defect detection to the scale of mm, when applied to whole modules. Here an optical scanning solution is chosen, with a resolution of 10s of µm across the module. A laser beam induced current (LBIC) system has been developed for the investigation of large, multi-cell solar modules. LBIC systems are not uncommon for wafer characterisation [1, 2], however there are rarely found in large scale, module-size, multi-cell applications. The problem is that the signal recovery becomes increasingly difficult with the number of cells and noise rejection becomes important in the signal analysis.

Structural defects may also develop over time. A specific example is amorphous silicon devices undergoing Staebler-Wronksi degradation. This paper reports on the measurements of one particular set of amorphous silicon modules, which have shown highly variable performance during a long-term investigation. The modules are part of a study of amorphous silicon modules sold in the third world and represent a good cross section of what was available in one particular market. The intention of this work was to see if localised, visually non-apparent defects could be identified to explain such variation.

This is done by means of the LBIC system. The paper will demonstrate that the stability of the laser is orders of magnitude better than the variations of material quality detected across the devices, ascertaining that the observations are real material effects and not artefacts of the laser itself. As expected, the single junction amorphous silicon modules demonstrate a variety of deficiencies which explain the variation of the outdoor performance observed in the long-term monitoring at CREST.

2 LBIC SYSTEM

The Centre for Renewable Energy Systems Technology (CREST) at Loughborough University has developed a large area LBIC system, which is shown schematically in **Figure 1**. A detailed description of the CREST LBIC system setup, structure and hardware components has been published previously [3, 4], and only a short description will be given here.

Small areas in separate cells or the whole module can be scanned by use of a two-dimension laser scan head, motorised focusing system and custom made control software. The system allows modules up to 1.5 m x 1.5 m to be investigated, although at the extremes the angle of incidence is above 5°, which is not ideal. The signal recovery is done via a pre-amplifier and a lock-in amplifier, which allows the pickup of minute currents.

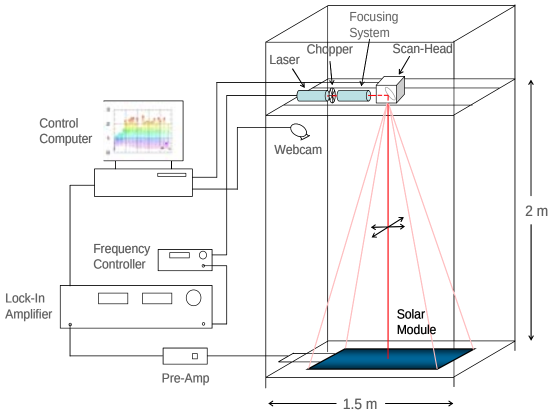

Figure 1: Schematic of the LBIC system

Building work required the system to be moved and recommissioned, which was used to carry out an analysis of repeatability and identify avenues for further improvements. The LBIC system is currently equipped with a HeNe laser with the wavelength of 632.8 nm and power (continuous wave) of 0.5 mW. Laser beam stability crucially determines the uncertainty of the measurement as its intensity is nearly always a linear driver of the current produced by the PV module. It must be constant throughout the whole measurement period or at all times if one measures for comparison purpose between modules. Currently, the time for each measurement depends on the scanning area, the resolution (step width between two points) and time constant. For some initial measurements it may take only a few minutes, however a full analysis of large modules measured with high resolution may need a day to complete. Although one should mention that the system currently is not optimised for speed and can almost certainly be improved by an order of magnitude.

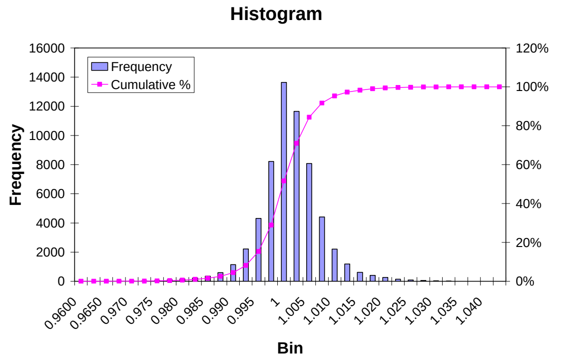

Figure 2: show the histogram and cumulative percentage curve of normalised intensity data measured from photodiode for a week, binned with an interval of 0.0025.

The intensity of the laser beam was measured via a photodiode placed on working plane. The photodiode generates a current directly proportional to the incident intensity and crucially the device employed here is guaranteed to be a stable detector. Measurements were taken every 10 seconds to give a dataset of over 60,000 intensity samples during a one week period of continuous laser operation. The data was normalised to the average and binned into intervals of 0.0025 (0.25%) shown as a histogram in **Figure 2**. During the measurements the thermal stability of the laboratory was not as good as it should have been (the laboratory is currently being commissioned), a thermal oscillation of about ±5^{o}C introduced some additional error. According to **Figure 2**, the variation of laser intensity measured by photodiode is within ±3.75%, with the flanks all being associated with extreme temperatures. The standard deviation is 0.62%.

Empirical evidence also shows that the dispersion of intensity data during standard working hours is slightly higher than that during night time or at the weekend. This is attributed to the shifting of temperature due to the shutdown of the air conditioning outside working hours. When operating, it shifts the temperature in the area to its setpoint value. The room temperature during the experiment varies in the range of 23.6 ± 5 ºC with a pronounced thermal oscillation during day time. With the temperature now being within 2^{o}C of the setpoint of 25^{o}C, it can be expected that the system has a reduced error.

3 PV MODULES IN THE TEST

The aim of this work was to identify the reasons for the otherwise unexplained low performance of some amorphous silicon modules. The set of modules to be investigated here is part of a study where modules were bought blindly by a re-seller in a third world country and submitted to indoor and outdoor performance testing. Some of the amorphous silicon modules performed very well over the years, but the cross section reported upon here is largely problematic (with one control sample of a good device).

These modules have been installed outdoors in the UK for more than two years. All of them were installed the same day and underwent the same testing history. The module power; nameplate rating, and simulator measurements before and after 2 years of outdoor exposure, is shown in **Table 1**. They are all rated at 13 W. However, the measurement by solar simulator before outdoor installation shows that initial power of modules A, C and D are slightly higher that rated power, while that of module B is nearly 40% less than rated power. After two years of outdoor installation, as expect, all modules show degradation. Module A shows the least power degradation with less than 17.5% while module B shows the highest degradation with more than 50% of the initial measured power, the reason for this will be given later in 4.4.

Table 1: Rated Power and initial and final (after two years) measurement by solar simulator

Module	**Power (W)**		
	Rated	Initial	Final
A	13	13.38	11.04
B	13	7.74	3.66
C	13	14.42	9.29
D	13	16.22	8.68

4 SCAN RESULTS

The samples of single junction amorphous silicon modules are measured by the LBIC system in order to identify distinguishing features. The aperture area was cleaned before each measurement. Only parts of the scanning images have been chosen to illustrate defects identified. Images are not to scale; the easiest reference that can be obtained from the images is the width of the cell which is 1 cm for module A, B and C while module D is 1.1 cm. An indicator for the cell length is indicated by a scale on the image.

The scanning results clearly show that in each module there is considerable performance variation between cells, this is normal but only one sample (sample D) is relatively uniform with only one cell performing below the remainder. Several more critical defects are identified such as short-circuiting between two cells, dot-like defects and damage from water ingress. The number and type of such defects differ from module to module.

4.1 Photocurrent variation

Although during production each cell in a module is processed synchronously, i.e. deposition and scribing at the same time, the scanning results show that there is a considerable variation of current generation among the separate cells.

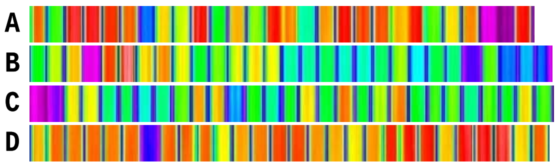

Figure 3: The images show the variation of current signal among cells in each module which represented by spectrum colour code; redder means stronger signal while bluer means poorer signal.

Figure 3 shows the variation of photocurrent signal between cells in each module. The images display part of the scan, covering every cell in the module. The signal strength is represented by the range spectrum colour; redder means stronger signal while bluer means poorer signal. As is shown in

Figure 3, there is a considerable variation of photocurrent signal between cells. Module D seems to be the most uniform photocurrent in the field, since nearly every cell is red. Interestingly, all modules have one or two cells that are much worse than the remaining areas, with virtually no contribution. This is indicated by blue or purple colour, in module B for example in the 4 cells on the right. One should keep in mind here that the modules were chosen because they had known performance issues. Also, the modules have been in the field for 2 years and will have experienced significant degradation, although they experienced a prolonged hot spell and will be at the peak of their seasonal performance cycle.

4.2 Micro Short-circuits

Figure 4 displays the defects from the scanning results of module A and C. Each image covers a scan area of 15 cm^2. Specifically, they show small micro-short-circuits in the interconnection area of two adjacent cells. One can see in both images A and B there is a “bridge” joining two cells together. This introduces a short circuit between two cells, which is affecting but not fatally reducing the performance of the module, largely because the small width of this micro-short has a relatively high resistance, thus not too much current is lost due this defect. While in images C and D, the defects widen into the semiconductor area but don’t cause a short-circuit.

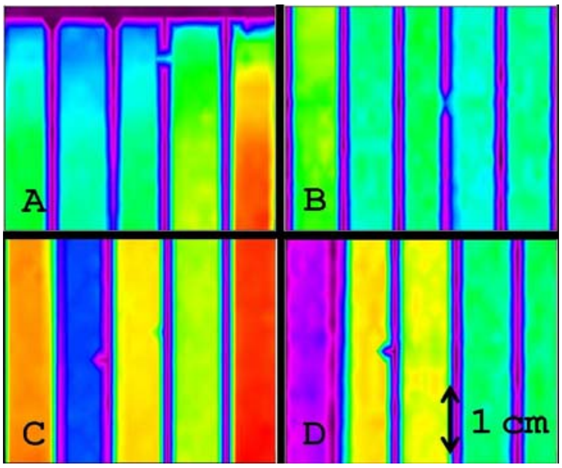

Figure 4: LBIC scanning shows short-circuiting in the interconnection area between two adjacent cells. Images A, B and C are the measurements of module C while image D is that of module A. The dark area on top of image A is the edge of module metal frame.

In the case of commercial modules, this type of defect most probably occurs during the cell separation process after the semiconductor deposition. The cell separation for thin film technology is normally done by a laser scribing. The type of laser i.e. wavelength is determined by the semiconductor material. The uniformity and the stability of the laser power during scribing process are the most important as well as good parallel setup of the separate scribes. Any change of laser properties could lead to the presence of such defects.

4.3 Dot-like defects

Another type of defect found on the modules is shown in **Figure 5**. In this case the defects have a dot-like shape, with only small dimensions. These are as not visible to naked eyes although some can be visually identified once one knows they are there. Generally speaking, they do not affect the visual appearance of the modules. It is difficult to determine their clear boundary. With the LBIC scanning, it displays the sharp edge of the defects and also to what extent that it damages the cells.

As shown in **Figure 5**, image A and B are the scanning from one corner of module A while images C and D are the scanning of module D and C respectively. The LBIC scanning results show the presence of defects. Some just have lower current compared to the surrounding area such as the top green dot area in the second cell from the right of image C, while some are almost inactive such as the one with a dark area in the middle. Moreover, in image C apart from the dot-like defect, the faded blue area in the middle of the second cell from the right, there is an inactive area at the end of those three cells. Such an area is the edge of the module next to the metal frame.

The possible cause of these dot-like defects could be impurity contamination during the production process e.g. inclusion of dust particles into the module or the glass substrate already presenting some impurities. An alternative could be inhomogneities in the metal contact layer, that the current in this area is for one reason or another is not collected effectively. As a consequence of these defects, the device may suffer from reduced absorption in certain areas. More importantly, if this area is not only contributing to the current but also presents an electrical path around the junction, this can be – or develop into – a shunting path, which can affect the performance of the module adversely. Given that the area also produces less current, it will also operate at slightly higher temperatures, which can further the propagation of any deficiencies. Thus this might be a reason for progressive degradation.

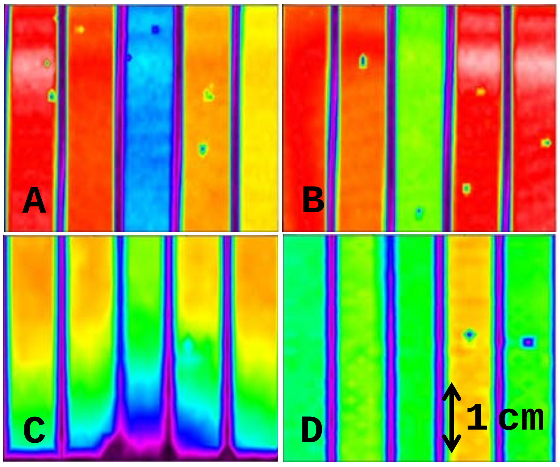

Figure 5: The scan shows a number of dot-like shaped defects. Images A and B are the scanning at one corner of module A. Image C and D is the measurement from module D and C respectively.

4.4 Humidity Ingress

After being installed outdoors for more that 2 years, the scan results clearly indicate that this module is affected by the humidity entering the laminate and that the seal was insufficient. The area shown in purple is where the humidity affected the semiconductor layer severely. It covers more that 10 cells and accounts for more than 10% of the total module area. The first cell on the right is so badly damaged (not shown) that it doesn't contribute to the overall device output any more and acts as a high-resistance contact only. Thus it does not contribute to generating any photocurrent but also introduces a very severe resistive penalty onto the overall performance.

This effect is obviously visible by the naked eye, but the LBIC is a good tool to map the progress of this effect. This is the worst module in the whole group, power generated from this module reduces to nearly half compare to the others, although all modules had identical ratings in the beginning. It appears that this particular lamination process is not up to withstanding long term degradation. Indeed, modules of another manufacturer sold in this region had shown similar problems in early batches (later remedied). The manufacturer of module 'B' is a relatively new entry onto that particular market and may very well go through the same learning curve (however,, this particular module was significantly out of manufacturers rating in the beginning, which would indicate that the QC in this manufacturer needs improving).

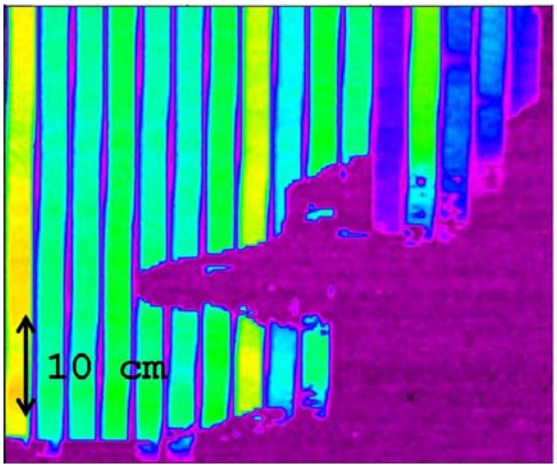

Figure 6: The scan result of module B illustrates the area on the module where the humidity is entering into the laminate and rapidly degrades the semiconductor layer. The shown spot covers more than 10% of the overall module area.

5 CONCLUSION

The large area LBIC system at CREST generates the current mapping of PV modules. It allows mapping defects and gives clues for possible causes of poor performance. Type and number of defects vary from module to module. They may result from the production or be established later during the outdoor operation. This very detailed local investigation of large area devices by scanning LBIC system has shown that it is an efficient characterisation tool which will allow a significant improvement of production processes, material quality and thus performance of thin film photovoltaic technology

It is shown that in the cross section of the market investigated here, which was chosen for its known difficulties to achieve name-plate performance values and should not be taken as a general representation of this particular technology, that in the majority of cases the underperformance was caused by a single cell working significantly worse than the remaining ones. Thus it is not the whole module degrading, it is a single cell. One module in particular showed insufficiencies in the lamination process, resulting in humidity ingress which in turn starts affecting the performance of the module severely as the semiconductor effectively gets washed out progressively.

6 REFERENCES

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