Light and current induced degradation in p-type multi-crystalline cells and development of an inspection method and a stabilisation method

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ABSTRACT: Stable solar cells are needed for durability testing of different combinations of module materials. In such a test, significant power losses in full-size modules with multi-crystalline cells after thermal cycling have been observed. This has been related to degradation of the solar cells used and it appeared that this was caused by current induced degradation. This phenomenon is not limited to boron doped Cz-Si, but can also occur in p-type multi-crystalline silicon. Work was done to develop an incoming inspection method for new batches of cells. Also, stabilisation procedures for modules containing cells that are sensitive to degradation have been determined.
Keywords: LID, Qualification and Testing, Stability, Multicrystalline Silicon

1 INTRODUCTION

When different combinations of module materials are tested for durability in for instance thermal cycle testing, stable solar cells are needed to distinguish between the effects of the materials. A number of full-size p-type multi-crystalline MWT modules failed during the early stage of IEC thermal cycle testing, and it seemed unlikely this was caused by a module build error or a wrong combination of module materials. In the quest for the cause, the focus fell on light induced degradation (LID) and current induced degradation (CID) of the cells. The latter was interesting in particularly as IEC 61215 thermal cycle testing is performed in the dark, but with supply of I_{mpp} current above 25°C.

It was already known in the 1970s that boron doped Czochralski-grown silicon (Cz-Si) degraded in performance when exposed to light or when minority carriers are injected in the dark until a stable efficiency is reached. This is due to the formation of a specific metastable boron oxygen complex in the Cz-Si material [1]. It was less common knowledge that the same effect may occur on multi-crystalline material as the same source stated that mc-Si cells are, in most cases, stable under illumination. Other sources mention a maximum efficiency loss of 0.3% absolute [2] or 3% relative [3,4]. Higher values are only reported for solar cells on the basis of UMG silicon, namely 3-5% relative [3].

The thermal cycle modules as mentioned above showed a relative power loss around 5 percent, which is the threshold value for rejection. Information of the wafer quality used was not available.

In this work three batches MWT cells of different suppliers were characterised on both LID and CID. The first batch was only tested on module level, the other two both on cell and module level. It must be emphasised that the wafer properties were not known as only finished cells had been received. An overview of the cells used is given in Table I.

Table I: Details of the cells used

Batch	Wafer type	Cell type	Efficiency
A	mc p-type	MWT	16.9%
B	mc p-type	MWT	16.6%
C	mc p-type	MWT	16.5%
D	mc p-type	H-pattern	18.4%

Also a few p-type multi-crystalline H-pattern cells were used. The research focused on developing a practical method for measuring LID/CID sensitivity as an inspection method for new batches of solar cells. A second item was to find a practical method to stabilise modules with sensitive cells to make durability testing of such modules possible.

2 THE FIRST SIGNS OF CID

Four full-size multi-crystalline p-type MWT modules showed a significant power loss during the early stages of thermal cycle testing with current. These full-size modules already showed a loss of close to 5% in power output after 100 cycles (halfway through the test). A series of 4-cell mini-modules with the same combination of module materials had passed 600 thermal cycles (i.e. 3xIEC test requirement) with a maximum power loss of only 1.1%. The only difference in the module build-up was the cells; for the full-size modules a new batch of cells (bath A) had been used. The first indication that the cells of batch A were causing the loss in power was that the change in the IV-curve (see Figure 1) could not be explained by any module defect. Module degradation typically shows a loss in fill-factor for interconnection issues and a loss in current for, for example, discolouration of the encapsulant. Also, no differences were seen between initial EL and DLIT images and images after thermal cycle testing. However, in this case a simultaneous decrease of I_{sc} and V_{oc} was observed and the fill factor decreased only two percent.

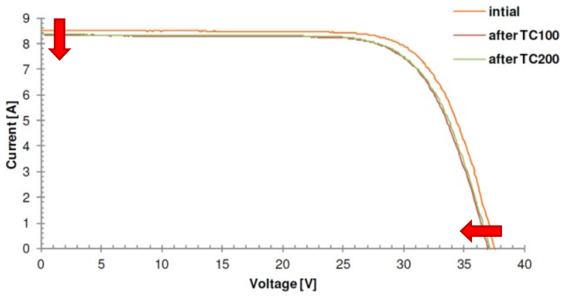

Figure 1: The STC-measurements of a 60-cells module subjected to thermal cycle testing showed a striking phenomenon: both the open voltage and the short current decreased whereas the fill factor loss was limited.

The flash test results of one of the modules are shown in Figure 2. Measurements were performed after 100 and

200 cycles, but in the figure the corresponding period of current supply was used as the variable. In IEC61215 the I_{mpp}-current is applied at forward voltage only in the temperature range from 25 to 85°C. A single thermal cycle period in this test was 4 hours and thus the period of current supply was 1.9 hours per cycle and 384 hours per TC200 test.

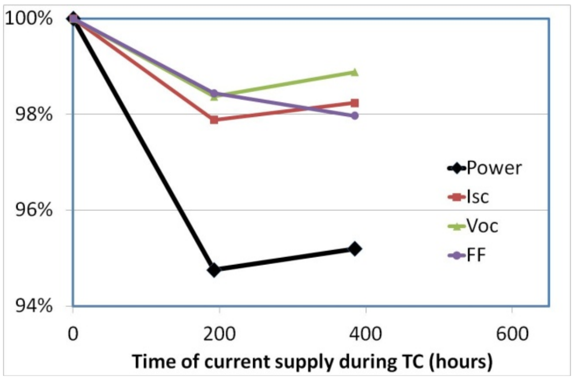

Figure 2: The relative flash test results of the module from Figure 1 as a function of the period of actual current supply above 25°C.

To find the cause of the failure (temperature or current) two tests were performed in parallel. One test was to cycle several cells from the same batch and from other batches in a rapid temperature cycle. The number of cycles and the temperature range were the same as in thermal cycle, but the cycle time was shorter and no current was applied. The cells were measured in a Wacom sun simulator (SunSim) before and after the test. No degradation was measured. It was therefore unlikely that temperature cycling had caused the failure of the modules. Another test was to apply 8A current at room temperature (30°C) and in the dark to a module of the same build. This resulted in a power drop of 3.5% after 628 hours (see Figure 3). Please note that the highest degradation rate was in the first hour with a loss of 0.6% and after 24 hours the loss was already 1.6% .

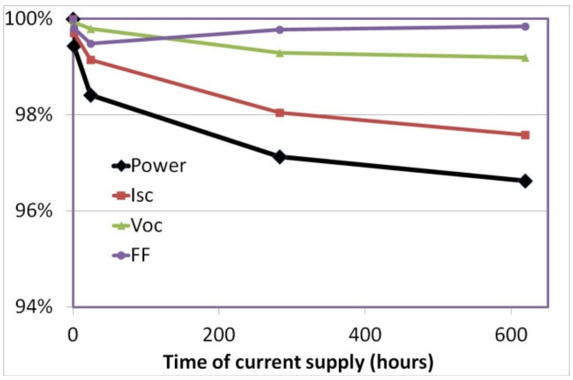

Figure 3: For the simulation of TC-current only, a module using the same cells as in the initial modules was used. Degradation was already seen in the first hour of the test and again both V_{oc} and I_{sc} dropped whereas the fill-factor showed only a slight decrease.

These results show that it is the current and not the temperature change that results in degradation of these cells, and therefore this is the cause of failure in the modules made with these cells.

3 CID ON MINI-MODULE LEVEL

In a build of 4-cell MWT-modules, multi-crystalline p-type cells from batch B were used. Due to the experience with CID sensitive cells of batch A the new build was tested in thermal cycle with and without current supply. The results are shown in Figure 4.

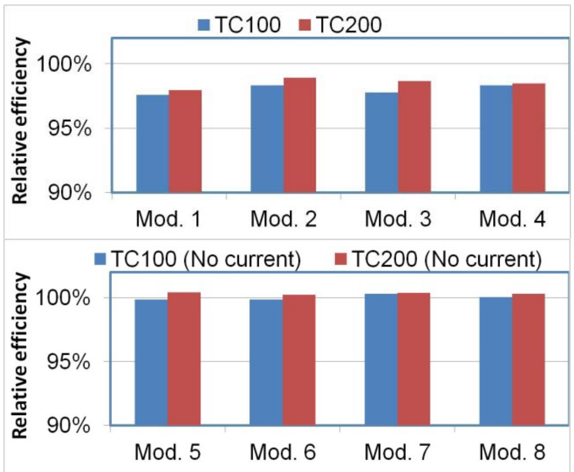

Figure 4: The top graph shows the relative efficiency in a thermal cycle test with current supply and the bottom graph without for 4 modules with cells from batch B. Both graphs show the intermediate test results and the final results.

Again degradation in the first part of the thermal cycle test is found in the case of current supply and no degradation is found without current supply. This shows the effect can be repeated on module level and that the cells of batch B are CID sensitive as well. However, the degradation found is around 2 percent which is much lower than with batch A cells.

4 THE LINK BETWEEN CID AND LID

4.1 Experiment set-up

The aim of this work was to establish if the link between CID and LID as found in the literature could be observed for the cells investigated. This experiment was executed on cell level with MWT-cells from batch B and a few H-pattern cells, see Table II. The experiments were performed in parallel.

Table II: Cell testing on CID/LID sensitivity

Test	MWT-cells	H-pattern
• Illumination with in situ IV-characterisation	V	-
• Illumination	V	V
• Current supply	V	V

4.2 Illumination in the SunSim

One MWT cell was placed with open circuit for 65 hours in the SunSim and the IV-curve was measured every hour. The cell was illuminated by a Xenon lamp at 1 Sun (1000 W/m^2) for 55 minutes every hour. Then the illumination was stopped for 5 minutes to let the cell cool down. A standard IV-measurement was done at the end of this period. Thus, the effective illumination period was nearly 60 hours. The cell was stored in the dark after this experiment and later was used in a regeneration experiment, see 4.5. The results of both the 65 hours illumination test and the regeneration experiment are shown in Figure 5.

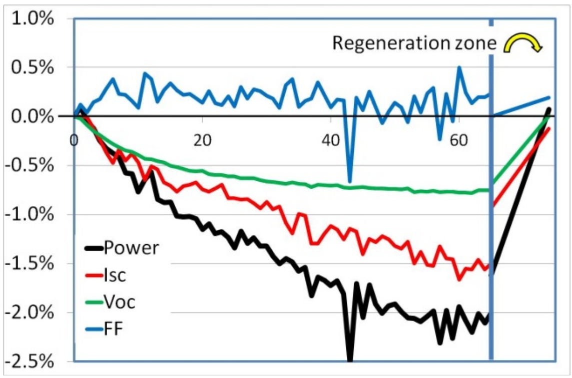

Figure 5: Relative electrical parameters of a cell from batch B during illumination at 1 Sun. The graph also contains the electrical parameters after cool down and after a regeneration experiment.

It is clear that this cell of batch B was sensitive to LID which led to a power drop of 1.6% after re-measuring. It was not clear if degradation was stabilised at the obtained dose of 60 kWh/m^2.

4.3 Illumination in the Suntest XXL

The SunSim is a dedicated machine for accurately measuring cells. It is normally not available for long term illumination tests. Therefore the Atlas Suntest XXL was used for illumination experiments. The test chamber contains three Xenon lamps for the daylight simulation of eight 156 mm solar cells. With an irradiation setting of 50 W/m^2 in the spectral range of 300-400 nm, the total irradiation is approximately 1 Sun (1000 W/m^2). The black standard temperature setting (BST) was 60°C. Figure 6 shows the set-up.

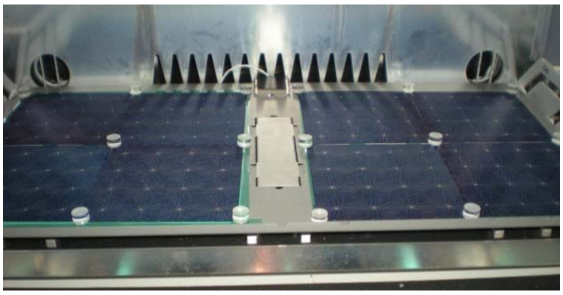

Figure 6: The test chamber of the Suntest XXL with 8 solar cells. Small glass loads hold the cells in place and the back of the cells was electrically isolated from the bottom plate by a plastic sheet.

Seven MWT cells from batch B were illuminated in the Suntest for 134 hours. At three intervals the Suntest was stopped to characterise the cells in the SunSim. The efficiency results of four cells are shown in Figure 7. The highest degradation rate was in the first part of the test. It is striking that the efficiency drop varies widely between 1.8 and 2.8%. The result on an H-pattern cell will be discussed in 4.4.

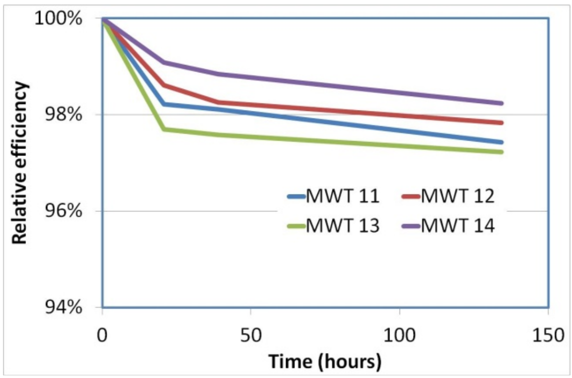

Figure 7: The drop in efficiency of four cells from batch B during daylight simulation in the Suntest XXL.

4.4 Current supply

So far, CID results were obtained on module level. To develop an incoming inspection method on cell level, chucks were needed for making electrical contact to the MWT cells. For an H-pattern cell it was sufficient to clamp the cell between two aluminium plates that acted as electrodes. The result of an H-pattern cell with current supply is shown together with an illuminated cell in Figure 8.

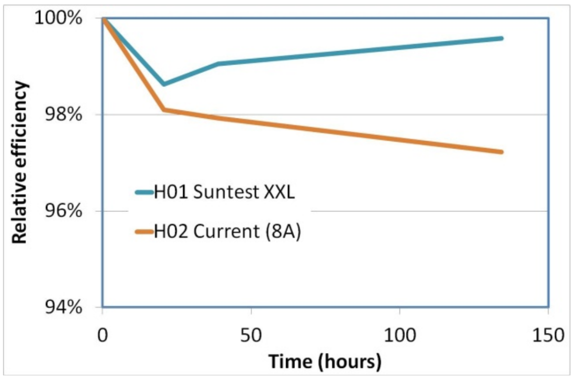

Figure 8: The efficiency of a p-type multi-crystalline H-pattern cell under illumination in the Suntest XXL (H01) or with current supply in the dark (H02).

Figure 8 indicates a relation between LID of cell H01 and CID of cells H02. The recovery of H01 under illumination is remarkable and not yet explained. The power drop of 2.8% for H02 is in the same range as found for the batch A cells.

The second observation that CID and LID are related is found in the LID sensitivity of batch B cells. The CID sensitivity of these cells was already described in Section 3.

4.5 Regeneration

Two clear observations for the relation between CID and LID were found. In the case of LID it is possible to regenerate cells by annealing them. To get more proof for the expected relation between the two degradation effects the regeneration test was also performed on all cells used for illumination and current supply, as well as a control cell that was kept in the dark. All cells were annealed at 200°C for 20 minutes and the results are shown in Figure 9.

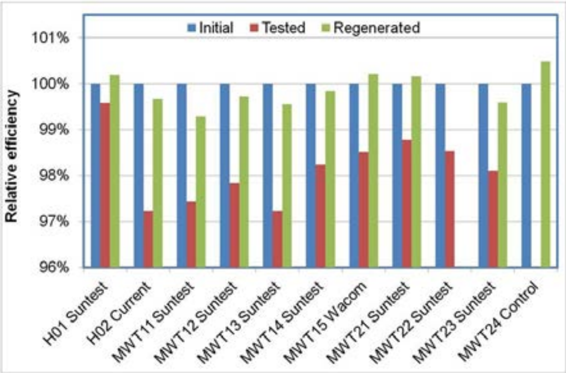

Figure 9: Two H-pattern cells and several MWT cells from batch B were degraded by illumination or current supply and after that annealed.

The recovery of the cell performance is visible for all samples, either degraded by light or by current. This is an indication that the mechanism is that of the oxygen-boron complex formation as described in literature [1].

5 MEASUREMENT PROCEDURE FOR MODULES

Modules need to have a stable output before starting the IEC reliability tests. More test data was needed to find typical values for the total power loss, the time to reach a situation with a negligible degradation rate and the power loss in the first twenty-four hours.

5.1 Experiments

The focus in extended testing was on characterising a new series of MWT-cells from batch C, but a few cells of batches A and B were included as well. The tests were performed on cell and module level and an overview is given in Table III.

Table III: Testing MWT-cells from batch C

Test	Current	Light	Outdoor
Cell level	V	V	-
Module level	V	-	V

5.2 Results on cell level

For the current supply on cell level a dedicated chuck was available (see Figure 10) and for the application of light the Suntest XXL was used with the same settings as before (see 4.3).

Figure 10: Chuck for applying current through an MWT-cell. The sunny side of the cell is placed on the isolated bottom plate as the measurement should be done in the dark.

A first result is shown in Figure 11 where the LID sensitivity of cells of three batches is compared. The work described in this paper was initiated when modules failed in thermal cycle (see Section 2) and the cells were from batch A. Figure 11 shows these cells are very sensitive to LID and the loss on cell level is comparable with that of the CID effect on the modules in Section 2, namely 4 to 5 percent power loss. The cells of the other batches show a loss of around 2 percent.

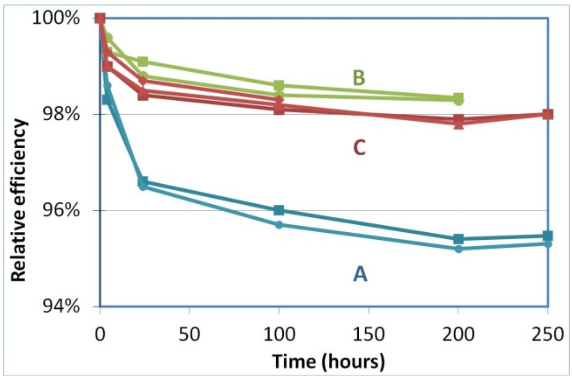

Figure 11: The relative efficiency of cells from three batches during daylight simulation in the Suntest XXL.

The exact irradiation dose for stabilising the cells varies per cell batch. A dose of 100 kWh/m^2 is sufficient for cells of batches B and C, maybe up to 150 kWh/m^2. The cells from batch A need a higher dose, possibly around 200 kWh/m^2. In all three cases a light soaking of 24 hours at 1000 W/m^2 will give a good indication if the cells are sensitive to LID and CID. In a single batch of wafers LID may vary because boron, oxygen, iron and oter impurities vary with ingot and block position [3]. Therefore it is advised to take several cells from a batch for testing.

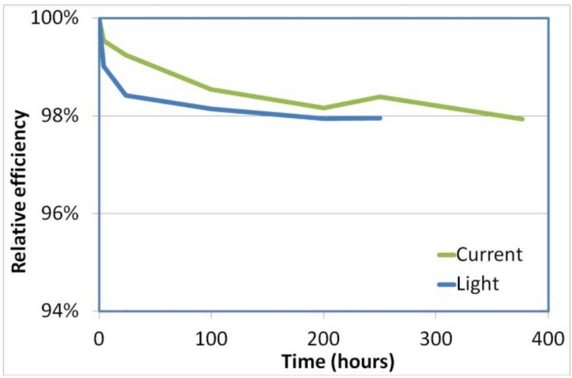

Figure 12: The relative efficiency of batch C cells and two different test methods.

5.3 Results on module level

The testing on module level had been limited to a single 4-cell module with 8A current supply (30°C) and one for outdoor light soaking (open circuited). The cells were from batch C.

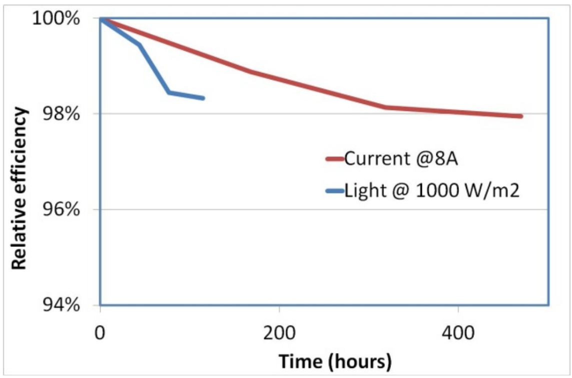

Figure 13: The relative efficiency in time for a current supplied module and a naturally light soaked one. The time line of the latter was recalculated as if a steady light source had been used.

The current soaked module degraded more slowly in comparison to a module that is light soaked at 1 Sun. The power loss at stabilisation will be about 2 percent, a value that was also found in cell level experiments. Light soaking is a faster method for stabilisation than the method with current if an artificial light soaking installation is available. However, in a northern European country like the Netherlands it takes 2-3 weeks in summer to reach an outdoor irradiation level of 100 kWh/m^2, but in winter it takes 3 Months. Without any artificial light soaking capacity, current supply might be an acceptable method for module stabilisation.

6 DISCUSSION

It was shown that multi-crystalline p-type cells of three batches of MWT cells and one batch of H-pattern cell were found to be sensitive to LID and CID.

This work focussed on identifying LID/CID problems in batches of wafers that had to be used in modules for durability testing of material combinations, rather than on revealing the exact degradation mechanisms. In this respect it should be mentioned that not only the formation of the boron-oxygen complex could have played a role in LID, but also dissociation of iron-boron-pairs into isolated interstitial iron and substitutional boron [1,4] and surface instability at the SiN:H/Si interface [5]. It will be interesting to distinguish between the different effects in future work. A fourth degradation phenomenon with an unknown mechanism has been reported for p-type multi-crystalline cells on the basis of UMG silicon wafers [3]. It has been identified as temperature induced degradation (TID). Dark storage of the cells during 450 hours at 85°C resulted in a power loss of almost 6 percent. Only half of this loss could be recovered in an annealing step.

In this work for the case of batch B and C cells the 2 percent efficiency degradation is in the range that is observed by others for LID. The 5 percent degradation of batch A is out of this range. It is possible that these cells were made from UMG silicon wafers.

The work showed that two methods are available as an incoming inspection method. Due to differences in wafer quality – that varies over the block – several cells per batch should be tested. Measuring the IV-curves of cells before and after light soaking will show if the cells are sensitive to LID/CID. The method with current may also be used. This method might be more practical in the case that the cells are already part of a module, depending on the weather forecast and whether an artificial light soaking installation is available.

Full stabilisation of modules needs much more irradiation then the pre-conditioning according to IEC61215, in which a dose of only 5 kWh/m^2 is prescribed. Our results show that values of 100-200 kWh/m^2 at 60°C will be more appropriate. Naturally, the question can be raised if full stabilisation is necessary in durability testing. To save time and cost, a shorter stabilisation period may be considered in which for instance a residual LID/CID effect of 0.5 or 1 percent power drop in thermal cycle is acceptable.

7 CONCLUSION

Our work confirms that p-type multi-crystalline cells can be sensitive to LID and CID. A maximum power loss of 5 percent was found. This is undesired if the cells are used for modules to test different combinations of materials.

Stabilisation of modules that have to survive durability tests may be done before durability testing by current application, artificial light soaking or natural light soaking. The last method may require a long soaking time depending on the local weather conditions.

The prescribed pre-conditioning light soaking dose of 5 kWh/m^2 in IEC61215 is too low for stabilising modules with LID/CID sensitive cells.

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