RAPID PID-TEST FOR UNLAMINATED SOLAR CELLS

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ABSTRACT: Potential induced degradation (PID) may cause significant performance losses of solar power plants. The high electric potential difference between the encapsulated solar cells and the outer module construction leads to leakage currents with the result of extensive microscopic shunting of the solar cells. Since the vulnerability of the cells to this damaging effect strongly depends on specific product properties and the manufacturing process, preventing PID on cell-level has become an important part of quality assurance. Up to now, PID-testing is predominately done after module assembly with a typical feedback loop of 96–336 h. We developed a new PID test method for unlaminated solar cells which provides equivalent test results in less than 24 h. In this work, the test parameters of the rapid PID-test for unlaminated solar cells have been evaluated and compared to a conventional module PID-test. It was found, that the new rapid PID-test for unlaminated cells is based on the same effect mechanism and the degradation speed can be increased considerably by adjusting the test conditions without losing the qualitative alignment with the conventional module PID-test.
Keywords: degradation, shunts, simulation

1 INTRODUCTION

Potential induced degradation (PID) has raised considerable attention since it may lead to significant performance losses of solar power plants [1]. The high bias voltage (up to −1 kV) between the encapsulated wafer-based p-type silicon solar cells and the outer module construction leads to the exchange of charge carrier via leakage currents with the result of extensive microscopic shunting of PID-prone solar cells [2]. The vulnerability of solar cells to the PID-effect clearly correlates with specific product features or the manufacturing process, e.g. anti-reflection coatings or refractive index [9][6]. When applying a module PID-test, the influences of module construction also becomes part of the test result. Particularly, the properties of encapsulation materials are known to influence the PID-safety significantly [4][6][9]. The specific PID-vulnerability of the solar cells is considered to be the most important input parameter for the resulting PID-safety of the solar module [6][8]. Therefore, the PID-test on cell level is very important for safeguarding the development phase of new solar cell-concepts or process optimization measures in terms of PID matters. Previous approaches for PID-tests with unlaminated solar cells were based on the principle of a corona-discharging setup [9][5][6]. This method is affected by the front metallization, the ambient air humidity and may further cause changes of the ARC properties due to inhomogeneous, local fields. With the new PID-test for unlaminated solar cells, these interactions do not appear.

2 EXPERIMENTAL

The rapid PID-test for unlaminated solar cells simulates the physical conditions of a solar module by means of a test set-up without permanent fixed joints. Fig. 1 shows the basic principle, a press-stack construction of solar glass and filler sheet in loose, unlaminated connection to the tested solar cell, but moderately pressed together by the weight of the top plate. The top plate also functions as positive electrode. The solar cell is placed on the grounded base plate, while a high positive electric potential is applied to the solar glass by means of the top plate. Due to the homogeneous electric potential applied, the PID-causing exchange of charge-carriers is triggered. The cells to be tested can quickly taken in and taken out of the test-setup without any damages. Intermediate performance measurements are possible without significant influences. Key parameters are degradation time, applied bias voltage (max. 13 kV) and temperature (max. 50°C).

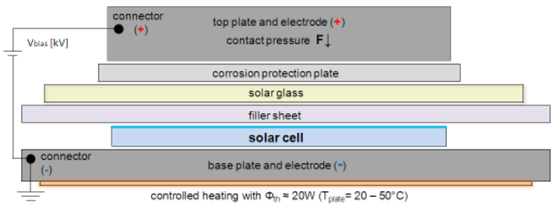

Figure 1: Principle schematic of the press-stack construction used for the PID-test for unlaminated solar cells

In this work, characteristic values from *I*-*V*-curve measurements at STC with a laboratory flasher were used to characterize the PID-tests with unlaminated cells. The performance of unlaminated cells before degradation has been compared with the result of intermediate measurements or with the final measurement after the PID-test. Of course, as a result of the test procedure without lamination process, the tested cells can also be analyzed with all common characterization methods. To investigate a wide and representative spectrum of PID in interaction with the test parameters to be evaluated, p-type solar cells with five different vulnerabilities to PID were used. In order to obtain a meaningful reference standard, sister cells were used for the construction of three nominally identical modules with the standard format of (1670 × 1000) mm. So each module consists of five different PID-vulnerable strings, each string connected to an individual junction box. Subsequently, the mean of PID induced ΔP_{mpp} of this three reference modules was used to minimize spreading influences. The reference modules have been subjected to a long-term degradation with the actual most common used PID-test for modules. For this, a high negative potential (−1 kV) was applied to the encapsulated strings while the front glass of the modules was covered with grounded aluminum foil [1].

3 RESULTS AND DISCUSSION

Extensive microscopic shunting of the solar cells primarily leads to losses in fill factor. Therefore $\Delta P_{mpp} / P_{mpp}$ [%] is qualified as suitable evaluation criterion for the intensity of PID [6][8][2]. Nevertheless, this correlation was under review within the scope of application of the new rapid PID-test for unlaminated solar cells. Fig. 2 (a) shows a strong correlation between R_{sh} and $\Delta P_{mpp} / P_{mpp}$ [%] of a statistically relevant number of unlaminated p-type solar cells after degradation. Analogous, fig. 2 (b) shows that the losses in P_{mpp} are caused by shunt-induced losses in fill factor, (c) in combination with losses in open circuit voltage for strongly shunted cells. This is in good agreement with a study on single-cell modules by Taubitz et al. [3]. Here a strong correlation between R_{sh} and $\Delta P_{mpp} / P_{mpp}$ [%] was also shown in experiment and PC1D simulation. This shows that the power loss induced by the new test method for unlaminated solar cells is driven by the same effect mechanism on cell level as in conventional PID-module tests.

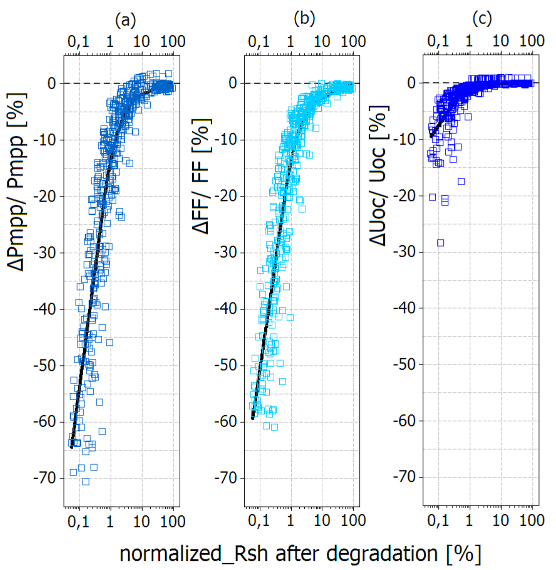

Figure 2: (a) Measured $\Delta P_{mpp} / P_{mpp}$ [%] versus R_{sh} [%] after degradation. R_{sh} is normalized to the initial values before degradation. Analogous (b) measured $\Delta FF/$ FF [%] and (c) measured $\Delta U_{oc} / U_{oc}$ [%]. The data basis consists of 475 individual measurements of unlaminated p-type solar cells with different PID-vulnerabilities after application of various degradation parameters. The black lines are smoothing functions.

Production processes or product features, such as the properties of anti-reflection coatings are known to influence the PID-vulnerability of solar cells. This was shown with conventional module PID-tests [9][7][8]. To compare these facts with the performance of the new rapid PID-test for unlaminated solar cells, samples with five nominal different PID-vulnerabilities were produced. The highest vulnerability is named with v1 and the lowest vulnerability with v5. Ten cells from each batch have been subjected to the rapid PID-test for unlaminated solar cells. Fig. 3 shows the different vulnerabilities to PID in the expected order and the progress of degradation with increasing degradation time. The new test method is able to work out the different PID-vulnerabilities of the cells explicitly. The test results are in accordance with the general experience of conventional module PID-tests.

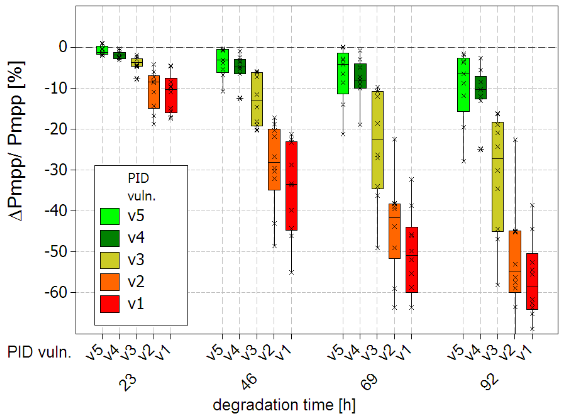

Figure 3: Effect of specific PID-vulnerable samples to the result of degradation. Test series with five nominal different PID-vulnerabilities. Highest vulnerability is v1, lowest is v5. Applied voltage is 13 kV; degradation temperature is 34°C.

For the conventional module PID-test, the accelerating effect of bias voltage has been investigated with the result of increasing PID with increasing bias in the range of 100–1500 volts [4]. Another module test was reported with a bias voltage up to 12 kV. It was concluded, that bias voltage has a linear impact on PID acceleration [5]. For the comparison experiment with unlaminated solar cells, PID-prone cells with highest vulnerability (v1) were degraded with a voltage bias in a range of 0.6 kV to 13 kV.

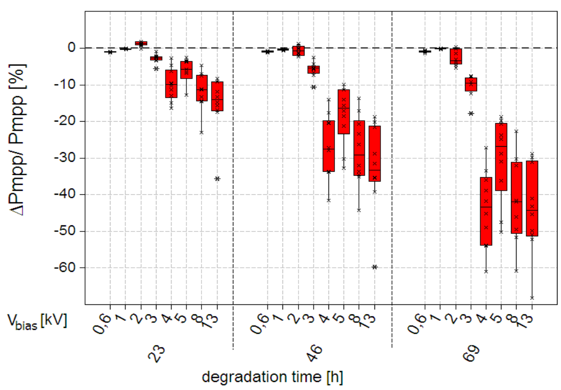

Figure 4: Effect of the applied bias voltage to the result of degradation. Test series with PID-vulnerable cells (v1). Degradation temperature is 34°C.

Fig. 4 demonstrates the accelerating effect of applied bias voltage to the PID-effect and the progress of degradation with increasing degradation time. The voltage induced acceleration seems to saturate at a bias voltage of 4–5 kV. This effect was not reported from module PID-tests so far. For this test set-up, bias voltage higher than 13 kV obviously does not enhance the degradation speed. This effect also might be caused by the principle of the test set-up. Nevertheless, this comparison shows basically the same agreement between the PID-test for unlaminated solar cells and the conventional module PID-test in terms of the accelerating effect of applied bias voltage.

For conventional module PID-tests, a higher degradation temperature was found to be a considerable acceleration factor in terms of PID [4]. In previous investigations an acceleration factor of roughly twenty was mentioned by increasing the temperature by 30 K [5]. In order to confirm this effect of acceleration also for the test conditions of the rapid PID-test for unlaminated solar cells, medium PID-prone cells (v3) have been subjected to different degradation temperatures in a range of 30°C to 50°C. Fig. 5 shows a strong dependency of the temperature to the PID-effect for tested unlaminated solar cells as well.

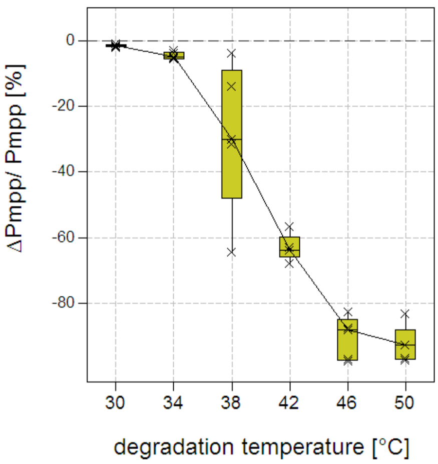

Figure 5: Effect of the temperature to the intensity of degradation. Test series with medium PID-vulnerable cells (v3). Degradation time 23 h; applied bias voltage 13 kV.

When comparing fig. 4 and fig. 5, it becomes obvious that the intensity of degradation depends much stronger on the sample temperature than on the applied bias voltage. This is especially true considering that for both test series even different PID-vulnerable samples have been used. The understanding of the acceleration factors, used for the rapid PID-test for unlaminated solar cells, was of fundamental importance for the quantitative alignment with the conventional module PID-test, particularly with regard to the implementation of multiple test-setups. Since the bias voltage can be applied very accurately and uniformly to the test-setups, it has been found practicable, to push the limits for the bias voltage first. The acceleration effect of the sample temperature is known to be Arrhenius-like [3]. This implies that temperature deviations or inhomogeneities at a higher temperature level would probably lead to larger scattering of the test results. In consideration of this, a degradation temperature at the lowest possible level, slightly above room temperature, could be qualified as suitable standard setting. With this approach, it becomes possible to obtain valid rapid PID-test results in less than 24 h, equivalent to conventional module PID-tests with a typical feedback loop of 96–336 h.

It was also of great importance whether the degradation induced power loss of the reference modules and the power loss of the unlaminated cells under the use of the qualified acceleration parameters can be aligned to each other. For this comparison the mean power loss of all five tested unlaminated samples from the test series with different PID-vulnerabilities v1–v5 (= 50 cells), see fig. 3, has been plotted over time and compared with the mean power loss of the reference modules. As expected, the degradation for the unlaminated cells under the use of the qualified acceleration parameters proceeds considerably faster compared to the reference module test, see fig. 6a. In fig. 6b the test data of the unlaminated cells is stretched with the time-factor 20 for the visual alignment to the module-test data in order to demonstrate that the acceleration of the PID-test for unlaminated cells takes place with the same curve shape. In this comparison, an acceleration factor of about 20 was achieved. It can be concluded, that the rapid PID-test for unlaminated cells can be flexible aligned to conventional module PID-tests with high accuracy.

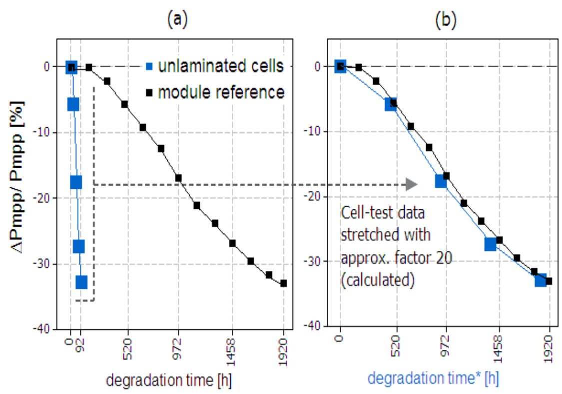

Figure 6: (a) Comparison of the mean power loss of all five tested unlaminated cell-sets (50 cells) from the test series with different PID-vulnerabilities with the mean power loss of the reference modules and (b) qualitative optical alignment of the cell-test data to the reference module and determination of the acceleration factor. Test conditions for the module reference standard: −1 kV, aluminum foil on front, 25°C. Test conditions for the unlaminated cells: Applied voltage 13 kV, temperature 34°C.

As an example of application, the test was applied to another experiment. Here a new set of experimental cells without relation to the former samples was used. For crosschecking, a reference module was constructed with sister cells. This time, the reference module was heated to 49°C during degradation, in order to reduce the needed testing time for the crosscheck. Table 1 shows the PID-test results of the unlaminated cells after 23 h. Whereas the PID-prone cells with setting A and B show significant losses in P_{mpp} already after 23 h, the PID-effect of less vulnerable cells from setting C, D and E cannot not yet significantly be distinguished by their losses in P_{mpp}. But for less PID-prone samples, the evaluation of ΔR_{sh} can be well used as an early indicator for PID, even before the extensive microscopic shunting leads to losses in P_{mpp}.

Setting	delta_Pmpp [%]	delta_FF [%]	delta_Rsh [%]
A	-5,6	-5,8	-99,3
	-3,8	-3,3	-98,5
B	-7,4	-8,1	-99,2
	-6,9	-7,3	-99,4
C	-2,3	-1,1	-92,7
	-2,5	-1,3	-97,1
D	-1,5	-0,2	-46,4
	-1,6	-0,1	-41,1
E	-1,4	0,1	-6,6
	-1,4	0,1	-19,7

Table 1: Test results of unlaminated cells with different vulnerabilities to PID (two cells per setting). Degradation time 23 h, applied voltage 13 kV.

Fig. 7 shows the string-wise performance measurements and electroluminescence images of the crosscheck module before and after degradation. Since the crosscheck module was subjected to harder test conditions at a degradation temperature of 49°C for 80 h, the losses in P_{mpp} are considerably higher than the test results of the unlaminated cells. But also this comparison shows a good qualitative agreement between the PID-test for unlaminated solar cells and the conventional module PID-test even for smaller differences of the settings C, D and E.

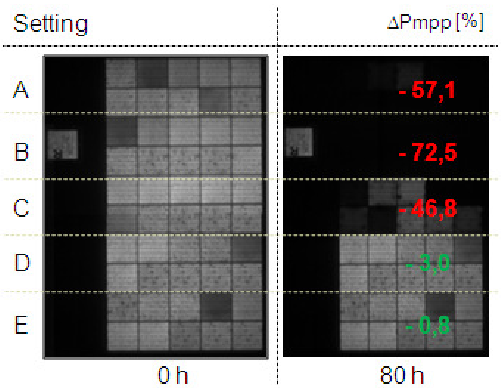

Figure 7: EL-images and performance measurement of the crosscheck PID-module (ten cells per setting = one string). Test conditions: −1 kV, aluminum foil on front, degradation temperature 49°C.

4 SUMMARY

The rapid PID-test for unlaminated solar cells was found to be qualitative equivalent to the conventional module PID-test. The Degradation is subjected to the same mechanism, losses in P_{mpp} because of extensive microscopic shunting of the solar cells. In comparison with the conventional module PID-test, it could be shown, that the degradation behavior of the samples, degraded by means of the rapid PID-test for unlaminated solar cells, follows the same principles in terms of applied voltage, temperature and degradation time. The degradation speed can be adjusted flexibly by varying the electric potential applied and the sample temperature. Alignments with other conventional module PID-test procedures are possible. By appropriate setting of the acceleration parameters, the rapid PID-test for unlaminated solar cells can provide valid test results in less than 24 h, equivalent to conventional module PID-tests with a typical feedback loop of 96–336 h. In contrast to the module PID-test with standard format of (1670×1000) mm, which only provides the mean value of performance losses from normally 60 encapsulated cells, the new method for unlaminated cells provides an individual result for each single cell without any interchanges of the module construction process. Therefore, the variance of a cell sample batch can be studied in more detail. Consequently, for the evaluation of specific PID-risks on cell level, cost intensive equipment and time consuming module construction is not a necessary requirement. Fields of application are multivariation testings (DOE) during the development phase of new solar cell-concepts, securing PID-safety during process optimization measures and quality assurance respectively process control of cell production lines.

5 ACKNOWLEDGEMENT

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