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INITIAL DEGRADATION OF INDUSTRIAL SILICON SOLAR CELLS IN SOLAR PANELS

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ABSTRACT: In the lifetime of a solar panel, efficiency is degrading continually because panel components are ageing during outdoor exposure (OE). This degradation is mainly due to humidity, temperature, system bias effects and solar irradiation. The solar cell itself may be suffering different degradation mechanisms like light, temperature and potential induced degradation (LID, TID and PID [1]). The focus of this paper is the initial degradation of solar cells within the first hours of operation, which is generally associated with LID. In this work, differences in degradation mechanism for multi and mono cells are investigated for cells and panels based on p-type crystalline silicon. The quality of silicon material is essential as shown in a material comparison. Low and high base resistivities are investigated and different silicon purities ranging from standard feedstock material of different qualities to material based on upgraded metallurgical (UMG) silicon are compared. Interestingly no clear difference between the LID of industrial multi- and mono-crystalline cells was found. However, UMG cells show a higher degradation rate partly due to a mechanism identified as temperature induced degradation (TID) that occurs in parallel to LID.

Keywords: Degradation, Reliability, Silicon Solar Cell

1 INTRODUCTION

Initial degradation of solar panels occurs in the very first hours of operation in the field. After a short time the power stabilizes on a certain level relative to initial STC power. Since this degradation affects the total panel lifetime the level of LID is an important parameter for yield simulations and cost-effectiveness of a solar system. Initial degradation of solar panels is generally tested during certification according to IEC standard [2]. Before the accelerated lifetime testing starts the panels are exposed to 5kWh/m²: the so called “preconditioning”. Eight panels are then divided into different test sequences, of which one includes outdoor exposure (OE) of a single panel to 60kWh/m² under load. To pass qualification the panels have to show less than 5% degradation after each test and for a full sequence less than 8%. A degradation of 5% would have a drastic impact on the commercial evaluation of a project.

For preconditioning of panels based on crystalline silicon only the energy dose and Voc condition is defined by the standard. To better compare the tests, the following items should be defined in the standard:

- Light source / spectrum (natural sun light, halogen or xenon lamp, ...)
- Injection level (intensity, condition Isc/Voc/Pmpp)
- Cell/panel temperature
- Duration of the test

In the literature many investigations were carried out on different temperature levels for example 25-140°C mainly with 1 sun illumination [3], with very interesting results that need further study to clarify if they are relevant for yield of a PV system.

The standard for thin film panels prescribes 40-60°C for light ageing [4] while for crystalline silicon no temperature range is defined. As will be shown (depending on the LID mechanism) temperature has a strong influence on the degradation rate of wafer based silicon solar cells.

2 TEST PROCEDURE

In this work only finished cells and panels are investigated. In most cases wafer properties are not (well) known. Microscopically, LID affects the minority carrier lifetime of the bulk silicon material. On the cell level this parameter cannot be simply measured. For a cell or panel the IV parameters like Isc, Pmpp and Voc are determined before and after LID. Since these three conditions are associated with different injection levels and all three vary with bulk lifetime which is also injection dependent they are not similarly affected by LID [5]. Also the FF may change depending on the lifetime degradation [6].

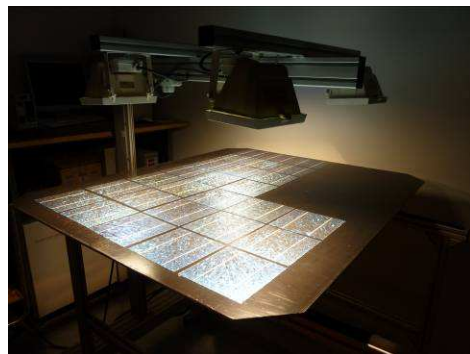


Figure 1: Setup for LID test of cells

The light source for degradation of solar cells in this study is an array of halogen lamps as shown in figure 1 where UV light is blocked by a glass in front of the lamp. The degradation conditions are an illumination level around 400W/m² and temperature of approximately 65°C. First the cells are annealed at 200°C for 30 minutes then they are placed on a metal plate that leads to an almost homogeneous temperature distribution. The cells were periodically measured between the test steps after cool down to room temperature until the average power of a batch is stabilized after a time step of ~24hr.

The graph in figure 2 shows the evolution of the key parameter of a mono crystalline solar cell during the first few hours of an LID test. After the test the cells are

stored in the dark for at least 24hr and are finally annealed a second time.

Panels are exposed to natural sunlight when temperature and illumination are high enough, total irradiation is $>5\text{-}10\text{ kWh/m}^2$. No annealing steps were included.

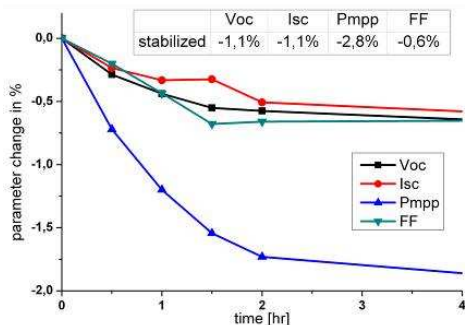


Figure 2: IV parameter degradation of a mono cell during LID test

The LID test is part of the solar cell release process at SOLON. Cell suppliers are evaluated and the LID level is compared to a specified criterion, thereby high quality cells are selected for production.

3 TEST RESULTS FOR SOLAR CELLS

The level of LID for a p-type crystalline silicon cell depends basically on the following items:

- Feedstock quality (impurity concentration)
- base resistivity / net doping [7]
- silicon crystallization (Defect and doping distribution)
- Wafering and Cleaning (Surface contamination) [8]
- Cell process (defect diffusion, gettering effects)

On the material side, concentration of impurities is detrimental for LID. Boron, oxygen and iron are the most important elements influencing the level of LID as it is broadly discussed in the literature [9, 10]. There are two main lifetime reducing defects. One is the formation of boron-oxygen (BO) complexes. The other is the interstitial iron formed when iron-boron pairs (FeB) dissolve upon exposure to light.

3.1 Mono crystalline cells

For mono-crystalline cells based on Czochralski (Cz) silicon BO-defects are dominant since during Cz growth oxygen is incorporated to a significant amount in the silicon material. Iron plays a much smaller role but it was shown that iron in case of insufficient gettering may have an effect [11] also in mono crystalline material. For typical material a strong temperature dependence of the degradation was found. In figure 3 the power degradation over time is shown for varying cell temperatures under low constant illumination of $\sim 100\text{ W/m}^2$. The cell was recovered between the tests by a 30 minute annealing at 200°C .

For 30°C no significant degradation was observed after 90 minutes. With rising temperature degradation rate increases until at temperatures around 100°C total degradation decreases again because temperature is high enough for defect disintegration. The level of LID and degradation rate is depending on the temperature since

defect formation and annihilation have different activation energies [12].

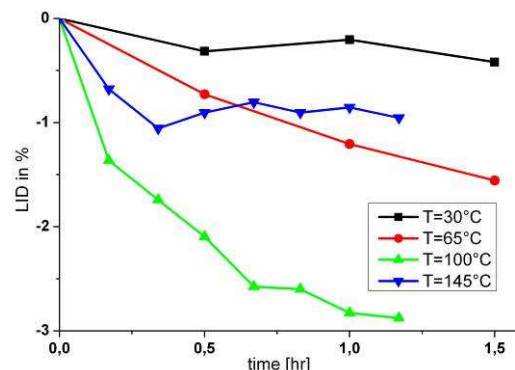


Figure 3: Temperature dependence of cell LID with high boron and oxygen concentration.

The found temperature dependence is in good agreement with published data where BO annealing effects were investigated for temperature as low as 111°C [12]. The influence of illumination level on the LID of cells with BO defect was investigated and as in [13] the dependence for BO defect formation is marginal. It can be concluded that for the LID test of mono crystalline cells besides test time the temperature level is the dominant parameter while the illumination level is less important.

Besides using n-type or gallium doped wafers one way to reduce LID is to use lighter doped wafers. But not boron alone is to be reduced also oxygen and iron contamination have to be avoided.

3.2 Multi crystalline cells

For multi crystalline material both defects BO and FeB are important. In the following example the curve of a multi solar cell is presented. A fast initial degradation occurred and the power stabilized after 24hr at -2% as shown in the following figure.

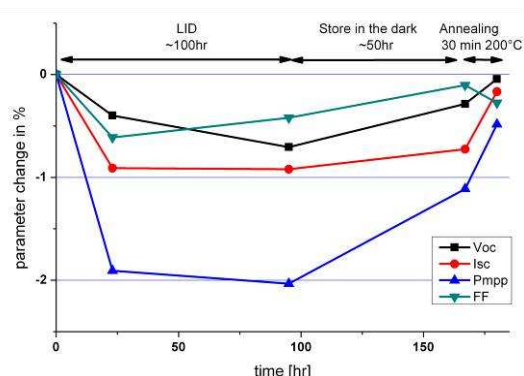


Figure 4: IV parameter during LID test of a multi cell

During dark storage the cell regenerated by 0,9% – this recovery in the dark is typical for interstitial iron that originates from light induced dissociation of FeB pairs. The iron re-associates during dark storage with boron to FeB pairs and accordingly power is increased again. An annealing at the end of the test recovered 0,6% this is attributed to the BO defect while the rest of $\sim 0,5\%$ is mainly caused by FF variations in the measurement.

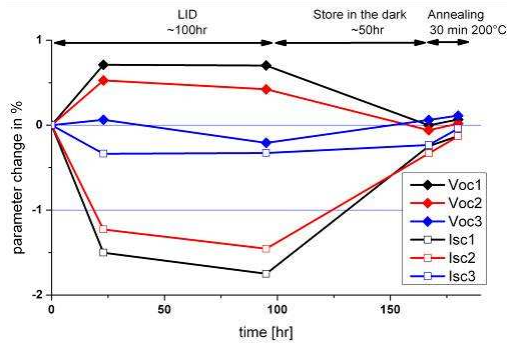


Figure 5: Irregular behavior of multi cells with low doping and high metal contamination

The example in figure 5 shows the degradation curve of three 8 Ωcm multi samples, two are heavily contaminated with iron while the third one is less affected. In case of the contaminated samples Isc and power degraded by around 1,5% while Voc increases by 0,5% which may be explained by injection level dependence simulated in [14]. During dark storage these two cells recover to their original state within 0,3%. The less contaminated cell does not show this special behavior it only degrades by 0,4%. All cells recover in the final annealing step where BO defect is dissolved and the cells gain only around 0,2% because of the low doping level.

The variation of LID from one cell manufacturer using different wafer suppliers was investigated concerning LID. The result is shown below in figure 6, average degradation on the cell level was found to be in the range of 2,0-3,5% depending on the cell and wafer quality.

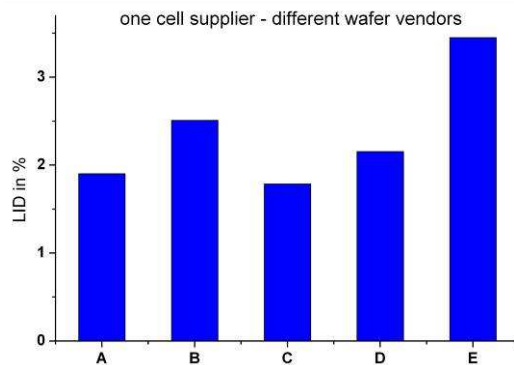


Figure 6: Average LID of cells from one supplier with different wafer base materials.

According to SOLON's cell release process cells suppliers have to indicate when a new wafer vendor is qualified. By testing the new wafer suppliers the risk of high LID is reduced. However, the batch to batch variation is not detected which is approached by random process inspections.

If just a small number of cells are investigated one has to keep in mind that in a single batch of wafers LID may vary because boron, oxygen, iron and other impurities vary with ingot and block position. The graph in figure 7 shows the variation of LID from the middle part of an ingot where top and bottom part was capped, compare to [15].

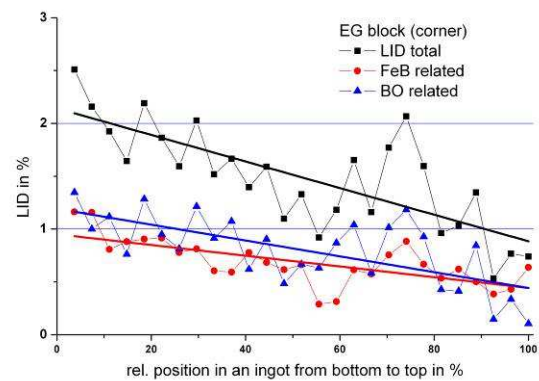


Figure 7: Multi crystalline ingot height dependence of LID separated in BO and FeB related degradation.

The data shows that in multicrystalline cells both defects related to interstitial iron and boron oxygen complexes can be relevant. Depending on feedstock material, crystal growth, wafer cleaning and gettering in the solar cell process these defects are more or less pronounced.

3.3 Multi crystalline cells from UMG silicon

In cooperation with a wafer and cell supplier UMG material was investigated without special adaption (relative to standard silicon) of crystallization and cell process. The cells with known ingot position and base resistivities were investigated in the LID test. While in the n-type region (not visible) of the ingot efficiency improved during LID the p-type part of the ingot showed high degradation especially in the part with high net doping with a base resistivity lower than 0,5 Ωcm were LID is ranging from 4 to 10%, see figure 8 and 9.

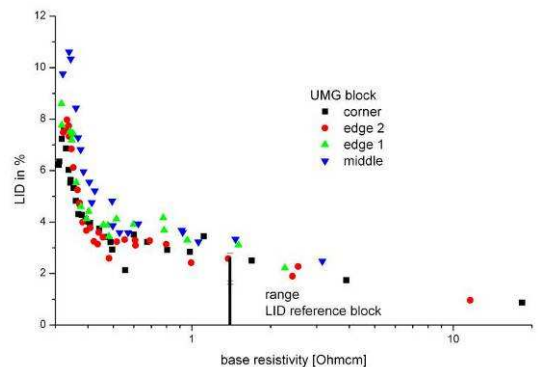


Figure 8: Correlation of wafer base resistivity from UMG ingots (corner, edge and middle part of a block) to LID of the finished solar cells.

This dependence shows that for cell processes based on UMG Si contamination with impurities and net doping must be controlled accurately to reduce LID to an acceptable level. The best way to reduce LID for UMG cells seems to be increasing the base resistivity to around >1 Ωcm and controlling the oxygen and other impurity levels.

Some industrial UMG cells were tested concerning their LID performance. Compared to standard cells a significantly increased LID was found. Typical results were in the range of 3-5% LID which is better than heavily affected cells in the upper graph but below the expectations for power stability.

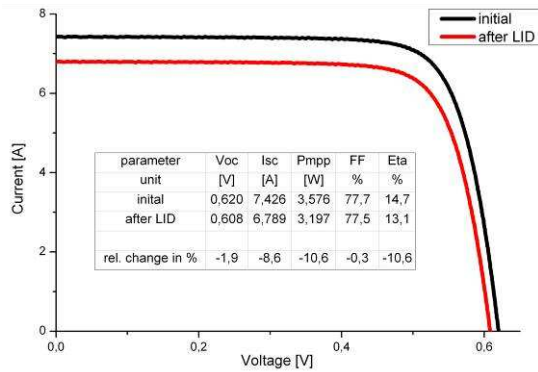


Figure 9: IV curve of a heavily contaminated UMG cell before and after LID (not optimized processes).

During testing of UMG cells an interesting behavior of some UMG cells was found. At the end of an LID experiment storage in the dark did not lead to power recovery and only a part of the power could be recovered by annealing. The irreversible part was mainly FF degradation.

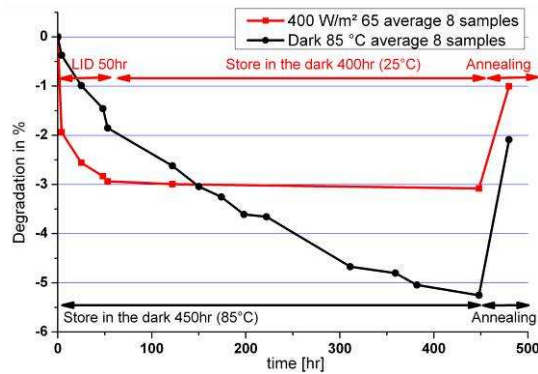


Figure 10: LID and temperature induced degradation of UMG samples. The power can only partially be recovered by an annealing step.

This was more closely investigated in another experiment where the effect of temperature treatment (85°C) for ~450hr was tested the cell power decrease continually and in the end only a half of the ~6% degradation could be recovered by an annealing step, again storing in the dark did not change the outcome (figure 10). This degradation occurred just by elevated temperature in the dark and is thereby called temperature induced degradation (TID). The recoverable part of the TID is attributed to a BO related defect. That formation of BO by temperature treatment is occurring was investigated in [16].

By dark storage and annealing Isc and Voc could be fully recovered while FF is not recovered. To some extent this could be explained by contact degradation but it is unlikely that this leads to a power loss of 3%. The series resistance did not increase by more than 5%, but a drop of ~70% in shunt resistance was found. To identify the root cause for this change of junction properties more experiments are needed.

When the curves of LID and TID are compared it is obvious that LID is occurring much faster but at least with this simple setup it is not possible to distinguish between temperature and irradiation effects since in the LID test both effects are occurring in parallel. In the

panel section results for UMG cells will be compared to TID findings on cell level.

3.4 Comparison of LID for different cell suppliers

During testing potential cell suppliers and monitoring the cells in the production sixty cell batches were tested. The tabular summarizes the statistical results for the tested batches during a certain period of time.

Table I: Statistic Values of LID for different cell technologies

Silicon type	Average LID of cell batches			
	Mean	Median	Min	Max
Mono	2,1%	1,8%	0,3%	5,1%
Multi	1,5%	1,4%	0,6%	3,5%
Multi UMG	4,0%	4,0%	1,9%	6,7%

The graph in figure 11 shows more detailed the frequency distribution of average LID of cell batches. Along with a long list of other tests the level of LID and the variation in a batch determines if a cell passes the specified criterion.

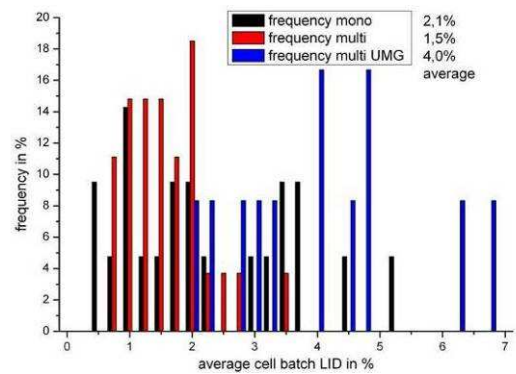


Figure 11: Distribution of LID tests on the cell level for mono, multi and UMG cells.

Surprisingly many mono crystalline cells degrade in the same range as multi crystalline cells - around 1,5% but depending on the wafer material and cell supplier runaway degradation of up to 5% was found what increases the overall average for mono crystalline cells. Multi crystalline material seems to be limited to a degradation <3% which is only reached in rare cases. These runaways are only topped by cells based on UMG silicon where batch degradation up to 6,7% occurred with single cells degrading by more than 10% but also depending on supplier and batch also relatively stable UMG cells were tested with average degradation below 2%.

4 TEST RESULTS FOR PANELS

4.1 LID of panels

Testing LID on panel level averages the LID of sixty solar cells. A large batch of panels with cells from different suppliers were investigated concerning their stability in OE tests where irradiance was controlled to be >5-10kWh/m² but panel temperature not in all cases.

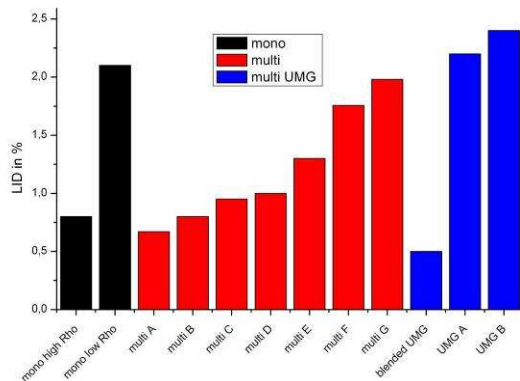


Figure 12: LID on panel level for mono, multi and UMG cells as well as blended UMG.

The results of different OE tests are summarized in the bar chart in figure 12. Outdoor test time was not constant for all panels but irradiation was always $>5\text{-}10\text{kWh/m}^2$, because at least five summer days with good weather were included and panel temperature of $40/50^\circ\text{C}$ at least should have been reached. Each bar represents average LID of two to seven panels with cells from one cell supplier. Typical panels with multi crystalline degrade by around 1% but depending on the supplier also rates close to 2% may occur. The batch based on blended UMG was the batch with the lowest degradation (0,5%) while panels with pure UMG lost 2-2,5% in power. The panels with two types of mono crystalline cells show very different behavior one supplier degrades by 2,1% while the other cell type is much more stable with less than 1% degradation. The main difference between the two mono suppliers is the wafer base resistivity while the stable one uses high resistive material the other uses low resistive material which is much more prone to the BO defect. Comparing the LID of all investigated panels one can conclude that cells with low degradation show LID $<1\%$ independent if mono or multi crystalline cells are investigated. For both types degradation up to 2% was found in this test. Only panels based on UMG cells show an LID even higher than 2%.

In all cases the most prominent degradation channel is Isc followed by Voc and FF all three contributing to power degradation.

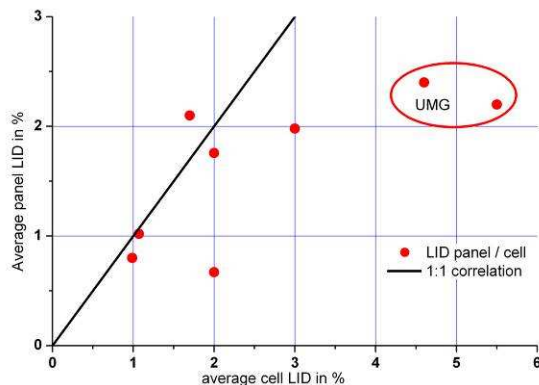


Figure 13: Comparison of LID on cell and panel level

Figure 13 compares results from LID tests of suppliers on cell and panel level. Some measurements fit well together in the range 1 to 2% but in the case of cells with high degradation on cell level especially the UMG cells

degradation the 1:1 correlation does not hold. This can be explained by variations from cell to cell or batch a batch together with measurement uncertainties. In case of UMG cells the irreversible degradation has a large impact.

4.2 Outdoor Test Conditions

One panel with UMG cells, which were known to be prone to LID, was placed outdoors in march 2010 in Berlin for 4 days total irradiation was $>5\text{kWh/m}^2$, the maximum temperature of the panel was well below 25°C during the whole time. After OE all IV parameters were constant within 0,3%, no power degradation was found. The conclusion of this test is that LID has to be determined at elevated temperatures which are likely to occur in the field, e.g. 50°C . This is crucial for the result at least for BO related degradation.

4.3 Temperature Induced Degradation

Panels with cells made from UMG material were compared to panels made with standard cells. The panels with UMG cells degraded significantly higher than standard panels with typical multi or mono crystalline cells during Damp Heat test ($T=85^\circ\text{C}$; 85% relative humidity and 1000hr) as shown in figure 14. Cells from the same batch as UMG_A degraded at 85°C in the dark and after 450hr (see section above) an Isc degradation of 2,4% was found which is comparable to the drop on panel level in DH after 1000hr.

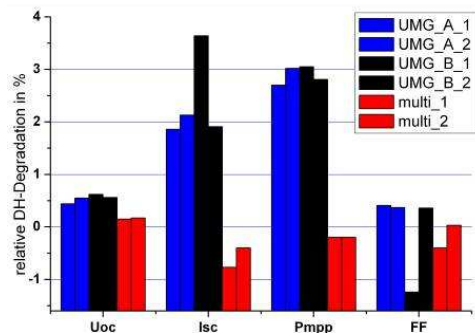


Figure 14: Comparison of panels with standard and UMG cells in DH test with same panel design. (Error: too high measured Isc-degradation for UMG_B_1 leads to FF increase)

Regardless if the cells are encapsulated or not Isc and Voc degrade during temperature treatment at 85°C .

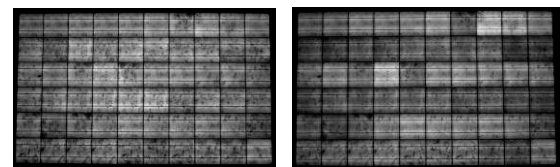


Figure 15: EL images shows variation in degradation of UMG cells in a panel tested in DH (initial left, post right)

An EL image comparison in figure 15 shows that the brightness variation of UMG cells across the panel is larger after the DH test. This can be explained by the varying TID of single cells where cell to cell variations were found. This variation can lead to mismatch losses because of serial cell interconnection.

Irreversible FF losses as on the cell level are not detected during DH test of panels – contact of the cell to

air seems to be crucial for this degradation canal. The question if long term reliability is affected by this mechanism needs further investigation. To study OE and performance of UMG cells in different climates test sites in Arizona, Italy and Germany are equipped with panels with UMG cells. Because of the difference in temperature, humidity and irradiation varying degradation and performance are expected. UMG will be tested along with other cell technologies to better understand if long term stability and yield are also for UMG on an acceptable level for high quality products.

5 CONCLUSIONS

Results from initial degradation of solar cells and panels were presented. LID varies for each group of cells made from mono, multi and UMG silicon. It was shown that standard mono crystalline cells can outperform multi cells concerning LID. Depending on wafer quality both multi and mono can be stable within 0,5-2%, but many degrade by more than 2% and some mono cells up to 5% (multi up to 3,5%). Compared to the average degradation of standard cells, UMG cells and panels showed significantly increased LID. On cell level this is accompanied by an irreversible FF degradation partly because of decreasing shunt resistance. The reason for this irreversible behavior needs further study.

To make LID tests of cells and panels more comparable, test conditions especially a temperature range (e.g. 50-70°C), time (e.g. >48hr) and irradiation dose (e.g. > 5/10kWh/m²) should be agreed upon – this should also be implemented in the IEC standard.

At SOLON, cells are investigated extensively and cell suppliers are evaluated by the LID test. Thereby cells (and wafers) suppliers with low LID are selected in order to guarantee high quality panels and yield.

UMG cells are currently not part of the SOLON portfolio but they are monitored outdoors at different climatic locations and compared to other cell technologies.

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