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LETID – A COMPARISON OF TEST METHODS ON MODULE LEVEL

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ABSTRACT: Light and elevated Temperature Induced Degradation (LeTID) can lead to significant power losses within the first months or years of PV module operation. Comparably slow degradation rates and the superposition of degradation and regeneration processes challenge the design of time- and cost-efficient but reliable test procedures. We investigate performance changes of commercially available standard modules and mini-modules during LeTID tests at different test conditions, varying test temperature and injection level. When increasing temperature and injection level, we observe significant differences between the acceleration of degradation and regeneration processes as well as the amount of detected degradation for monocrystalline and multicrystalline PERC modules. This has to be taken into account when performing accelerated LeTID tests.
Keywords: LID, PERC, Degradation

1 INTRODUCTION

The first known observations of degradation now referred to as Light and elevated Temperature Induced Degradation (LeTID) have been published in 2012, when Ramspeck et al. had discovered unexpected high power losses for mc-PERC solar cells in a light soaking experiment at elevated temperatures [1]. Based on slow progressing degradation, strong temperature dependence and independence from the dopant, they proved that the degradation was not caused by the well-known Light Induced Degradation (LID) mechanisms, B-O complex formation and Fe-B pair dissociation [1]. Similar results have been achieved by Fertig et al. under field-relevant conditions [2].

As shown by Kersten et al. [3], current injection in the dark can lead to similar degradation behavior as light soaking at the same carrier injection level. It is therefore also referred to as carrier induced degradation (CID) [4]. After a period of time, full regeneration can be observed under the same conditions that lead to degradation [3] but on a significant longer timescale [5]. Both, degradation and regeneration, are accelerated by temperature and injection level [3,4]. The kinetics of LeTID have been studied on lifetime samples [5] and cells [6] based on multi-PERC, showing Arrhenius-like behavior [5] and an almost linear dependency on the excess charge carrier density [5,6].

Though LeTID has been first observed in p-type mc-Si PERC Solar Cells [1], it has been shown that also Cz-Si [7] and FZ-Si [8] can show similar degradation behavior under carrier injection at elevated temperatures. Besides PERC, also Al-BSF technologies have been shown to be potentially sensitive, though to a significantly lower extent [1,2].

The degradation rate and the severity can be influenced by various factors like the brick height [3], firing profiles, i.e. peak temperature [9] and heating/cooling rates [10], or annealing steps [11]. Even modules of the same type might therefore behave differently in LeTID tests. Low wafer thickness has been linked to faster regeneration and lower degradation extent [12]. Some module manufacturers claim to be able to suppress LeTID by adapting production processes and published data on module degradation show high variations in sensitivity [13,14].

LeTID test methods on module level are often based on a proposal by Hanwha Q CELLS [3], which was recently discussed as LeTID detection method for IEC 61215. In this approach, a current (usually I_{SC}-I_{MPP}) is injected in the dark at 75 °C module temperature. The operation mode at this current value is referred to as MPP (Maximum Power Point) mode, because the excess charge carrier density is similar to MPP at irradiance with 1 sun. The injection level is therefore in a typical range for field conditions. However, this approach requires timescales of several weeks to reach maximum degradation, which makes it time- and cost-intensive.

Increasing the temperature and the injection level e.g. to 85 °C and V_{OC} mode can accelerate the test significantly. However, since degradation and regeneration are assumed to evolve at the same time, and published data showed higher performance losses at low injection level [3], high acceleration of the regeneration process might bear the risk of not detecting the whole extent of field-relevant degradation.

In this work, we compare data resulting from LeTID tests on different commercially available module technologies at 75 °C, I_{SC}-I_{MPP} and accelerated test conditions of 85 °C, I_{MPP}. On mini-module level, we performed experiments under light and dark conditions, including mono-PERC, multi-PERC, mono-Al-BSF and Silicon Heterojunction (SHJ) samples. Based on the results we draw conclusions with regard to LeTID test conditions and trends in the behavior of different technologies.

2 INVESTIGATIONS ON STANDARD MODULES

2.1 Test conditions

We compare LeTID test results of commercially available modules of 15 different types from five manufacturers that have been tested at TestLab PV Modules, Fraunhofer ISE, using current injection in the dark (Carrier Induced Degradation, CID) at elevated temperatures. As it is usually the case in module quality testing, information about cell production or possible prior stabilization processes by the manufacturers were not available. In the first experiments, the voltage was also applied during heating and cooling phases. However, as the set point temperature was usually reached after approximately 30 minutes, we assume the influence to be insignificant.

After reaching steady state, the test conditions were:

- IEC-Draft: 75 °C ± 3 °C, I_{SC}-I_{MPP}
- Accelerated test: 85 °C ± 7 °C, I_{MPP}

A temperature control sensor was placed on the rear side of one module in the middle of the climatic chamber. The temperature of all tested modules and the applied voltages were monitored during the test.

The comparably high uncertainty given for the module temperature in the accelerated test was only reached in two test intervals with temperatures of up to approximately 91.5 °C due to Ohmic heating of the modules at I_{MPP}. In most test intervals, the temperature at steady state could be controlled to 85 °C ± 3 °C.

Unless otherwise stated, the modules were tested without any prior treatment as BO-LID stabilization.

Changes in module performance were detected by intermediate measurements at STC at CalLab PV Modules, Fraunhofer ISE with a total relative uncertainty of 1.8 % and a long term reproducibility below ± 0.5 %.

2.2 Test results

Characteristic performance changes during LeTID tests at 75 °C and I_{SC}-I_{MPP}, as proposed for IEC 61215, are displayed in Figure 1. The module types included in the comparison consist of different cell technologies: mono-PERC, multi-PERC, cast-mono-PERC and multi-Al-BSF. For each PERC module type, two samples were available for the test. In the illustration, full and half markers of the same color and shape identify different samples of the same module type.

All modules show degradation, with a trend to lower sensitivity of mono-PERC (-2 % to -3.6 %) and higher variety of the sensitivity of multi-PERC and cast-mono-PERC (-3.8 % to -7.5 %) within the testing time. With the exception of one mono-PERC module of type C, all tested module types show progressing degradation during at least 800 h. For none of the modules the beginning of the regenerating phase has been observed within the testing time, indicating that further testing might have led to a higher amount of degradation. After a storage time of eight months, which led to a small recovery (0.3 % and 0.5 %), the Al-BSF module and one multi-PERC module of type M were tested further up to a total testing time of more than 1500 h. In total the combination of storage and further testing led to additional degradation of -0.8 % (multi-PERC M) and -0.3 % (Al-BSF N) without indications for the start of the regeneration phase.

Due to the slowly proceeding degradation, it is highly time consuming to reach the maximum performance loss of all module technologies with these test conditions. Defining a stop criterion might be a possible solution to reduce testing time, but could lead to an underestimation or overestimation of sensitivity, depending on the degradation speed.

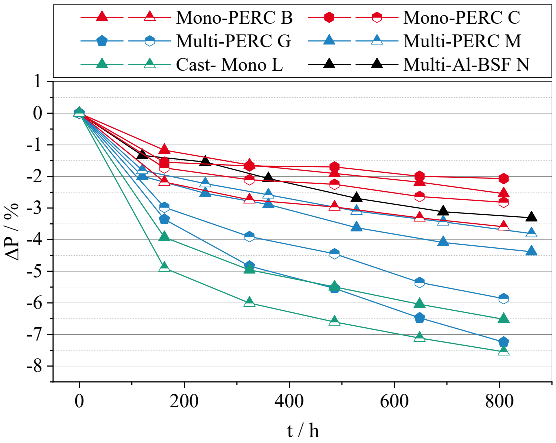

Figure 1: Progress of relative power change during LeTID testing at 75 °C, current injection in the dark, I_{SC}-I_{MPP}.

Increasing the temperature and injected current to 85 °C and I_{MPP} on multi-PERC modules led to the LeTID test results shown in Figure 2. As not all module types have been tested with both, 'fast' and 'slow' test conditions, the blue markers identify performance changes of modules, which can be compared to test results at 'slow' LeTID test conditions on modules of the same type.

By increasing the current to I_{MPP}, an injection level slightly beyond Voc mode is achieved.

Due to the acceleration, we observe the beginning of the regeneration phase of all tested multi-PERC modules, excluding type P, within 400 h. A broad range of maximum degradation between -1.5 % (type P) and -9.2 % (type G) was measured. In case of type P, accidental consecutive current injection at temperatures beyond 30 °C led to a non-stable performance increase due to recovery after the fourth test interval (see Figure 2). The result of the modules of type G (-9.1 % and -9.2 %) can be directly compared to two modules of the same type that have been tested at 75 °C and MPP mode (see Figure 1). Under these test conditions, only -5.9 % and -7.2 % performance losses were measured, as degradation was probably still proceeding after the testing time of 808 h.

Module types J and K were also tested in a slow LeTID test: after initial LID testing (60 kWh/m² at 55 °C ± 5 °C), a LeTID test was performed at 70 °C ± 3 °C, 885 h, MPP mode, whose results were not added to Figure 1. The maximum measured performance losses of -4.2 % (type J) and -4.3 % (type K) after LID and LeTID testing are comparable to the losses at 85 °C and Impp between -4.2 % and -5.0 % (see Figure 2). Also for these modules the start of the regeneration phase was not seen in the slow test within the testing time.

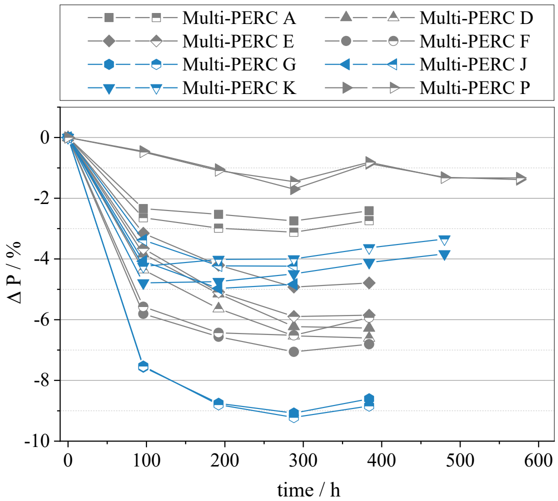

Figure 2: Progress of relative power change of multi-PERC modules during LeTID testing at 85°C, current injection in the dark, I_{MPP}.

The progress of measured performance changes of mono-PERC and cast-mono-PERC modules at 85 °C and I_{MPP} is given in Figure 3. The module temperature of type cast-mono-PERC L reached approximately 94 °C in the second test interval due to Ohmic heating. As the maximum performance change was already measured after the first test interval, the maximum amount of degradation was not affected by the higher temperature and we include the results into the comparison. The maximum detected degradation of type cast-mono-PERC L under the accelerated test conditions of -5.1 % and -6.5 % is slightly lower than the maximum degradation found for modules of the same type after 808 h CID at 75 °C and I_{SC}-I_{MPP} (see Figure 1). The in-situ measurement of the voltage, that was applied to keep the current constant, shows a minimum after approximately 20 h in the first test interval (see Figure 3), indicating that not the whole amount of degradation was detected after the test interval of 96 h. Compared to the multi-PERC modules, the increase of temperature and injection level led to significantly higher acceleration of the degradation and regeneration processes of cast-mono-PERC.

The tested mono-PERC modules did not show significant degradation in the test at 85 °C and I_{MPP} (see Figure 3). The maximum performance losses of -1.1 % and -1.2 % were detected for two modules of the types B and H after the first test interval. The in-situ voltage measurement during this interval (not shown) did not reveal clear indications for significantly higher degradation during the test interval as it was the case for the cast-mono modules. As modules of types B and C showed higher degradation in the range of -2.1 % to -3.6 % during the LeTID test at 75 °C in MPP mode (see Figure 1), we assume that the higher injection level and the higher temperature accelerated the regeneration process so strongly that less degradation was reached. Possible BO-stabilization processes on the mono-PERC cells might be one reason for the different behavior.

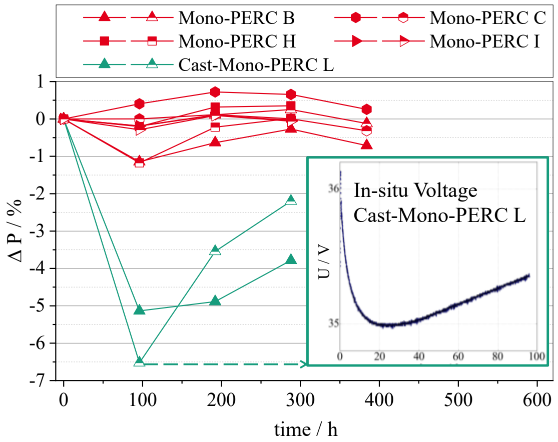

Figure 3: Progress of relative power change of mono- and cast-mono-PERC modules during LeTID testing at 85°C, current injection in the dark, I_{MPP}; Inset: In-situ voltage measured during the first test interval on a module of Type L.

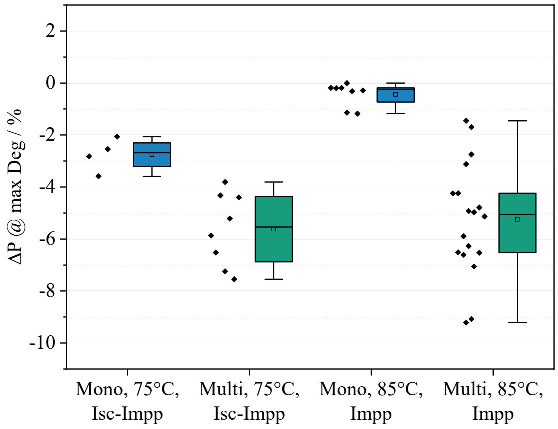

Figure 4: Maximum performance losses detected for mono- and multi-PERC modules during LeTID tests.

2.3 Trends in technologies

An overview of the maximum detected degradation for mono-PERC and multi-PERC modules tested under standard and accelerated LeTID test conditions is given in Figure 4. Please note that there have been variations in total testing time, and especially at 75 °C, I_{SC}-I_{MPP}, additional degradation would probably have been reached in further test intervals. Also, we included data of test intervals with slightly higher temperature deviations than given above ($|U| > 3$ K), and data from LeTID tests after light soaking at 55 °C. In the latter cases the total degradation of both tests was used for the comparison, as LeTID might already have occurred during the LID test at 55 °C. Cast-mono PERC modules have been categorized as multi-PERC in this comparison.

Though LeTID is not only an issue of multicrystalline cell technologies, there is a clear trend of lower sensitivity in mono-PERC modules in our data. One possible explanation for the lower sensitivity of the tested mono-PERC modules is prior BO-stabilization by the module manufacturers. As shown in [7], BO-stabilization processes can limit the extent of LeTID degradation.

For multi-PERC modules we see a wide range of sensitivity, suggesting that some module suppliers are able to reduce LeTID by controlling their manufacturing processes.

Under accelerated test conditions of 85 °C and I_{MPP}, almost no degradation is seen for mono-PERC. As explained above, we assume that these conditions might accelerate the regeneration process in mono-PERC cells in a way that leaves field relevant degradation undetected. For the multi-PERC modules included into our investigations, the degradation extent observed in both test methods in the given time is comparable. However, it must be emphasized that the maximum degradation extent probably has not yet been reached in the case of 75 °C and I_{SC}-I_{MPP}.

The given trend has been seen on 15 module types of 5 manufacturers and should not be generalized for all modules available on the market.

3 INVESTIGATIONS ON MINI-MODULES

3.1 Test approach

To enable a comparison of cell technologies under LeTID test conditions, we performed light soaking and current injection tests at elevated temperatures. 6-cell laminates were prepared at Fraunhofer ISE using commercially available mono-PERC, multi-PERC, mono-Al-BSF, and silicon heterojunction (SHJ) cells (each cell technology from the same type).

We did not perform any prior BO-LID stabilization procedures, since all field relevant effects, which might proceed during the chosen test conditions, should be investigated.

The current injection test was performed at the above discussed 'slow' LeTID test conditions of 75 °C ± 5 °C and MPP mode ($I_{SC} – I_{MPP}$).

The light soaking test was performed in a climatic chamber with integrated AAA solar simulator, according to IEC 60904-9, at 85 °C ± 5 °C (module rear side). During the test, the modules were operated in MPP.

The performance measurements have been conducted at STC at CalLab PV Modules, Fraunhofer ISE, with the same long term reproducibility as mentioned above for commercial modules (± 0.5 %).

3.2 Current injection at 75 °C and MPP mode

The performance change during 900 h of current injection (Carrier induced degradation, CID) at 75 °C in MPP mode (I_{SC}-I_{MPP}) for different cell technologies is shown in Figure 5. For the mono- and multi-PERC samples, the progress and amount of degradation are in the range of the LeTID tests on standard modules. The maximum detected degradation was -2.2 % and -2.7 % for mono-PERC and -5.2 % and -6.0 % for multi-PERC, respectively and was measured after the last test interval indicating, that further testing would have led to additional degradation.

The maximum degradation of the two mono-Al-BSF samples of -2.2 % and -2.8 % was measured after 10 h and after 20 h of testing, which is in a characteristic timescale for BO-LID. During subsequent testing, continuous regeneration was observed. However, the samples did not recover to their initial value within the performed testing time. The SHJ samples show a slow degradation of I_{SC}, leading to a maximum performance change of -1.2 % after 900 h (see Figure 7). As there was no degradation detected in V_{OC}, the performance loss is most likely due to a different degradation effect and we do not see any indication for LeTID on SHJ.

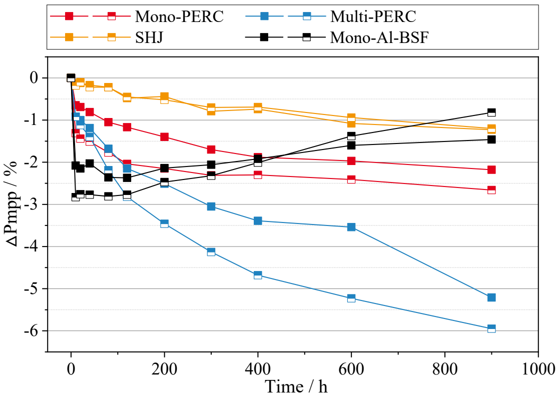

Figure 5: Progress of relative power change of Mini-Modules tested at 75°C, current injection in the dark, MPP mode.

3.3 Light Soaking at 85 °C and MPP

In the Light Soaking experiment at 85 °C and MPP, we observed performance changes as depicted in Figure 6. While the maximum degradation of the multi-PERC samples was probably reached during the last testing interval between 330 h and 590 h, the maximum degradation observed for the mono-PERC laminates was measured after 20 h. Compared to the results of current injection at 75 °C, the temperature increase clearly leads to a different acceleration of the degradation and regeneration processes of the two tested PERC sample types. The detected amount of degradation was -1.6 % and -2.4 % for mono-PERC and -5.2 % and -5.5 % for multi-PERC. In particular for the mono-PERC samples we might have missed the point of maximum degradation due to the measurement intervals.

Instead of degradation, the SHJ samples show positive performance changes due to light soaking, leading to a total power increase of 1.5 % and 1.6 % after almost 600 h. The efficiency increase is caused by a significant increase in FF of 1.3 % to 2.3 % due to series resistance improvement and a slight increase in V_{OC} of 0.3 %. These values correspond well to results published by Kobayashi et al. [15]. We assume the positive changes to be caused by annealing effects leading to an improvement of the passivation and the ITO layer metal contact properties.

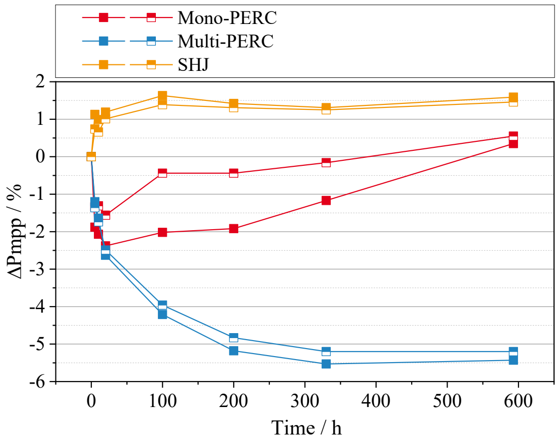

Figure 6: Progress of relative power change of Mini-Modules during light soaking with 1 sun at 85 °C in MPP.

3.4 Discussion

The relative changes in performance parameters at the measurement of maximum detected degradation or, in case of light soaking on SHJ, after the last test interval, are displayed in Figure 7 for both test procedures. The degradation seen for the Al-BSF samples is assumed to be dominated by BO-LID. The SHJ samples did not show any indications for LeTID, yet, the I_{SC} degradation seen in the CID test at 75 °C is also observable on one sample under light soaking at 85 °C. During light soaking, the performance change of SHJ is dominated by positive changes in FF and V_{OC}. In case of the mono-PERC samples, the temperature increase led to acceleration by more than a factor of ten until the maximum power drop. The maximum degradation measured in the light soaking test is slightly beyond the value in the current injection test at 75 °C. This could be due to the intervals between the measurements, or due to the acceleration of the regeneration process. Yet, the values are still in a comparable range. For the tested multi-PERC samples the amount of degradation in both test methods is comparable. The acceleration of degradation and regeneration was significantly lower than for mono-PERC, but still in a range that could shorten testing times by a factor of two.

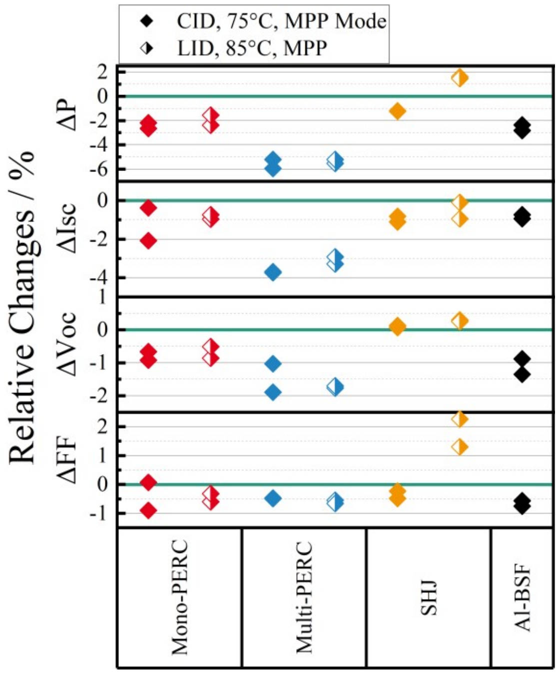

Figure 7: Relative changes in performance parameters at the time of maximum detected degradation, or after the last test interval, if no power degradation was observed (SHJ in light soaking).

4 CONCLUSIONS

We compared LeTID test methods and results for various module types. Current injection in MPP mode at 75 °C can detect significant degradation extents for various cell technologies, but the required timescales of several weeks until the maximum degradation is reached are too long for module quality testing. In our experiments, we therefore did not see the beginning of the regeneration phase at these conditions and maximum degradation in significant longer testing time would probably have been higher than the values achieved. Our results demonstrate that accelerating LeTID test conditions can affect the timescales and observed amount of degradation in diverse module technologies differently. For three Multi-PERC module types tested at Fraunhofer ISE, increasing the temperature and injection level at the same time (85 °C and I_{MPP}) led to maximum achieved degradation comparable with results generated at 75 °C and I_{SC}-I_{MPP} but after significantly shorter time. For mono-PERC samples however, we observed that some field relevant degradation remained undetected in the fast LeTID test at 85 °C and I_{MPP}. One possible explanation is significantly higher acceleration of the regeneration process of the tested mono-PERC modules compared to the multi-PERC modules at higher temperature and injection level.

For one LeTID sensitive cast-mono-PERC type, we observed comparable maximum degradation in both test methods, but with faster degradation and regeneration than seen for other Multi-PERC modules. We conclude, that even among modules categorized as ‘multi-PERC’, strong variations may occur in temperature or injection level dependency of LeTID. In order to obtain reliable quality test results for different cell technologies in a reasonable time, further optimizations of test conditions are possible.

In LeTID experiments on mini-modules we achieved comparable maximum degradation under current injection and light soaking at different temperatures in MPP mode for one sample type of mono- and multi-PERC, respectively. This approach will be tested with additional module types and compared with an outdoor test in the future.

All indoor testing methods are accelerated tests compared to field behavior. Under real operation conditions, variations of temperature and irradiance can lead to additional effects like recovery at low temperatures [16] and the proceeding of degradation and regeneration highly depends on the location. Test results as achieved on module level in this work therefore mainly aim to be used for module quality evaluation.

Comparing test results of all tested module and mini-module types, we observed a trend that mono-PERC modules show a lower LeTID-sensitivity than LeTID susceptible multi-PERC modules. For multi-PERC, we observed a wide range of different sensitivities. The tested SHJ samples did not show LeTID in our investigations as expected, but positive light soaking effects, that have also been mentioned in literature [15]. Considering the number of tested module types, these results should be viewed as a trend and especially for cast-mono-PERC, also contradicting results are known from literature [1], hence caution must be exercised when our results are generalized.

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