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EVALUATION OF INLINE HIGH-INTENSITY ILLUMINATION TREATMENTS AGAINST LETID

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ABSTRACT: High-intensity illumination treatments are a versatile method to reduce the performance loss of solar cells due to LeTID since they can be applied at any point of time between cell fabrication and module assembly. We evaluate the potential of these treatments using a true inline treatment tool and commercially available PERC solar cells. To test the stability of cell performance after the treatments, the cells were exposed to 0.15 suns and 75 °C at open circuit. These conditions are close to a recent testing standard suggestion and allow estimating the cell stability over the typical operating lifetime of solar modules. The results show that there is a window of process parameters which improves the stability of solar cell efficiency without compromising the efficiency immediately after the treatment, i.e. before the stability test. The treatments result in an estimated gain of ~3 % in the amount of energy produced by the cells during the operating lifetime of a solar module, corresponding to a reduction of LeTID-related energy yield losses by up to ~50 %. Importantly, this gain is achievable with belt speeds compatible with high throughput inline processing.

Keywords: Degradation, Manufacturing and Processing, Multicrystalline Silicon

1 INTRODUCTION

Recently, high-intensity illumination treatments (HIIT) have been found to be a promising post-processing approach for the mitigation of not only the well-known boron-oxygen light-induced degradation (BO-LID) [1] but also light- and elevated temperature-induced degradation (LeTID) [2–4]. What is particularly interesting about HIIT is its versatility: In addition to its LeTID mitigating capability by itself, HIIT can in principle easily be combined with other mitigation methods earlier in the process flow such as modified pre-firing anneals [5,6] and firing temperature profiles [6,7], which have recently been suggested as cure against LeTID but are yet to be proven fully efficient in industrial solar cells. Further, such a post-processing method can also be adopted after the solar cell fabrication, e.g. by module manufacturers interested in reducing the impact of LeTID in their products.

Requirements of high throughput and cost-efficiency pose restrictions not only on the available HIIT processing time but also on the technical specifications of the treatment tool that may affect the breakthrough of this technology to industrial use. In this work, we study the HIIT of commercially available mc-Si PERC solar cells (a suitable test system due to low BO-LID) with an inline-capable device enabling industrial throughput [1]. In the inline tool, samples moving on a conveyor belt heat up purely through illumination while air cooling enables adjusting the temperature profile to a certain extent. By using a wide range of process parameters, we assess the practical benefits and limits of inline HIIT e.g. from LeTID stability and throughput points of view. Our emphasis is on short treatment times of 4 – 34 s, which is a timescale that combines high throughput with a small to moderate factory footprint.

2 EXPERIMENTAL

The inline HIIT tool (RRS-LID from Rehm Thermal Systems GmbH) uses laser-based high-intensity illumination and has been introduced before [1]. In this work, we used commercially available mc-Si PERC solar cells. The sample temperature was monitored *in-situ* with an infrared (IR) camera. The temperature given by the IR camera was corrected to avoid a distortion caused by the presence of excess carriers (plasmonic effects) as described in Ref. [8]. After the inline treatment, samples were illuminated under 0.05 suns at room temperature for 48 h to assure that all BO defects are either in the degraded or the regenerated state rather than the annealed state. Subsequently, a high-intensity flash light was used to dissociate iron-boron (FeB) pairs fully, after which LeTID testing was done at 0.15 suns and 75 °C at open circuit to be close to recently suggested standard conditions of 1 sun and 75 °C at the maximum power point [9]. For characterization, the samples were removed from the LeTID test conditions and measured promptly for their IV parameters to avoid FeB pairing before the measurement. The IV-measurements were done at standard testing conditions using the LOANA solar cell analysis system from PV-Tools GmbH [10].

3 RESULTS AND DISCUSSION

3.1 Temperatures and intensities during the treatments

The inline HIIT process is characterized by the illumination intensity over treatment time and the resulting sample temperature profile. As the sample temperature profile and the illumination intensity profile are not fully independent, we have chosen in this work to adjust the illumination intensity profile such that the sample temperature during the treatment stays as close as possible to a pre-defined plateau target temperature. Our strategy is to maximize the illumination intensity, and therefore the kinetic rate of the desired regeneration effect at the target temperature, without compromising the lateral temperature uniformity across the sample during the treatment. We adjust the illumination intensity profile longitudinally within the device to achieve the sample target temperature as fast as possible (typically < 2 s), after which the temperature is held as constant as possible over the remaining process duration. This approach is illustrated in Fig. 1, which shows the laterally averaged temperature and illumination intensity profiles (left and right axis, respectively) of the mc-Si solar cells in the case of two processes corresponding to different target temperatures of 300 °C and 400 °C. Note that, in

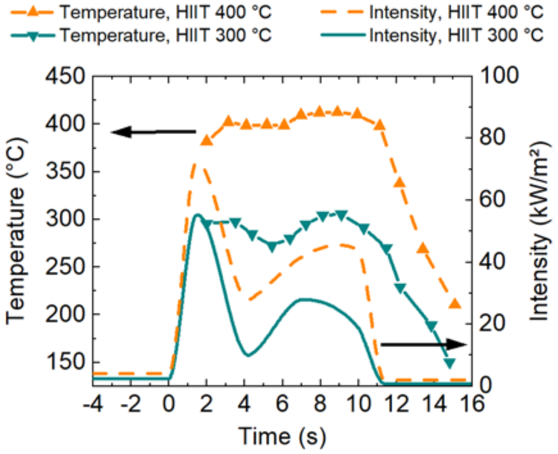


Figure 1: Temperature profile (left axis) and intensity profile (right axis) of high-intensity illumination treatments performed on the mc-Si solar cells corresponding to two different target temperatures of 300 °C and 400 °C. The moment when the samples enter the direct illumination field of the lasers has been selected as the zero point of the time axis.

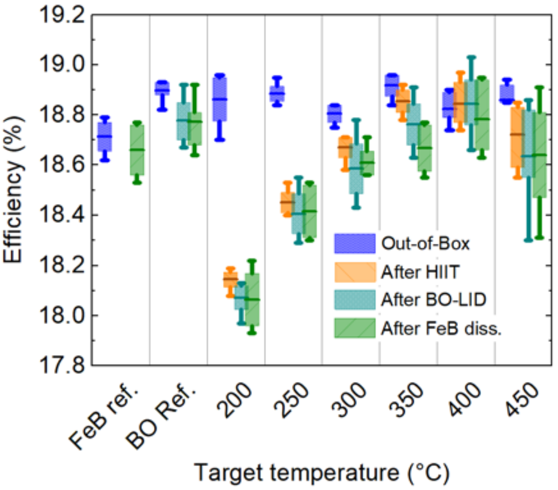


Figure 2: Efficiency of commercial mc-Si PERC solar cells before and immediately after 11.4 s HIIT processes at different target temperatures, as well as after full degradation and dissociation of the BO and the FeB defects, respectively. Also shown are non-treated references for the BO and the FeB defects (BO ref. and FeB ref., respectively). Shown are the 25% quartiles (boxes), the average value (lines inside the boxes), and the maximum-minimum variation (whiskers).

Fig. 1, the moment when the samples enter the direct illumination field of the high-intensity illumination source has been selected as the zero point, and that about 4 s before and after the regions of direct illumination the samples are subject to low intensity stray light within the device. To maintain an even target temperature of the sample, we vary the process intensity up to an order of magnitude over the treatment.

3.2 Efficiencies of the mc-Si solar cells before and immediately after HIIT

Fig. 2 shows the efficiency of commercially available mc-Si PERC solar cells before (out-of-box) and immediately after HIIT treatments at different target temperatures (before LeTID testing). Note that all treatments of Fig. 2 were performed at a constant belt speed corresponding to a treatment time of 11.4 s, and that the term “out-of-box” is used here to signify that the samples have stayed in the dark at least 48 h before the measurement (i.e. they are in the FeB paired state). The figure also includes two reference groups. First, “FeB ref.” consists of cells measured in the out-of-box state and then flashed to dissociate the FeB pairs. Second, “BO ref.” includes cells that were first BO degraded, followed by FeB dissociation. The results from these two reference groups show that both the BO and the FeB defects play only a small role in the studied samples. As the BO degradation and the FeB dissociation steps also have only a minor impact on the samples of Fig. 2 consecutive to HIIT, any further degradation in a later LeTID test is unlikely to derive from either the BO or the FeB defects.

After the inline HIIT at 300 °C and above, the efficiencies in Fig. 2 remain close to the out-of-the-box values. On the other hand, below 300 °C, the inline HIIT process reduces the efficiency considerably. This behavior qualitatively resembles earlier observations, where the effective lifetime of symmetric HP mc-Si lifetime samples was observed to reduce after a short HIIT period under 30 kW/m² below 250 °C, whereas at 250 °C and above a HIIT of a similar intensity and timescale was observed to increase the effective lifetime monotonously [11]. However, in our case this threshold temperature seems higher than in Ref. [11]. This difference may be related to a slightly lower average intensity used for the inline HIIT at process temperatures below 300 °C than in Ref. [11]. Another option is that the stray illumination in the inline tool, which illuminates the samples even after exiting the direct illumination field of the lasers (see Fig. 1), leads to a slight degradation of the samples immediately after the process in the case of HIIT below 300 °C. In Fig. 2, it is also noteworthy that the variance of efficiencies increases after the highest temperature process at 450 °C. This behavior, associated with reduced fill factors, is likely due to contact resistance degradation earlier reported in this temperature regime [12].

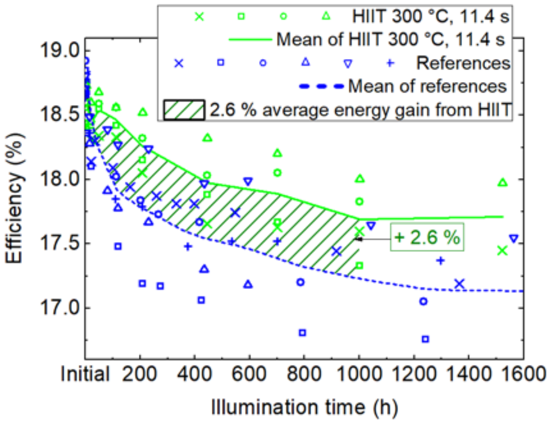


Figure 3: Efficiency during the LeTID test after an 11.4 s HIIT process at 300 °C. Non-treated references are shown for comparison. The shaded area between the means of the two different groups illustrates the energy yield gain potential of solar cells after HIIT.

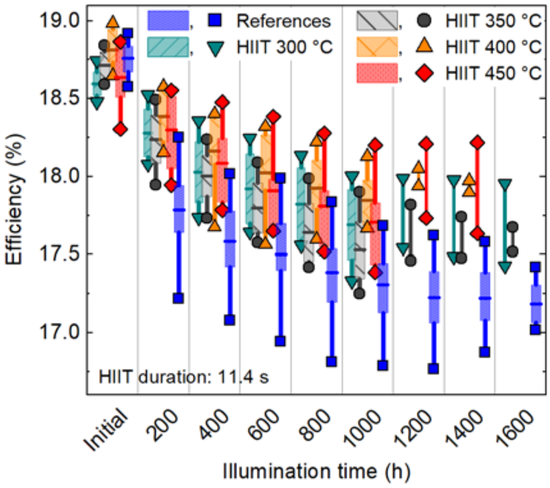


Figure 4: Efficiency distribution of solar cells after 11.4 s HIIT processes at different target temperatures, plotted as a function of the LeTID testing time. Non-treated references are shown for comparison. Note that the efficiency was interpolated from measurement data exemplified in Fig. 3 at 200 h intervals, and that the calculation is based on 4-6 samples per group until 1000 h and at least 2 randomly selected samples beyond 1000 h. Shown are the 25% quartiles (boxes), the average value (lines inside the boxes), and the maximum-minimum variation (whiskers with symbols).

Table I: Energy yield gain of solar cells that were HIIT processed for 11.4 s during 1000 h of LeTID testing compared to non-treated references. Also shown is the estimated reduction in the energy yield loss due to LeTID based on the 1000 h LeTID test.

HIIT temperature	300 °C	350 °C	400 °C	450°C
Energy yield gain	2.6 %	2.1 %	3.2 %	2.6 %
Reduction in energy yield loss due to LeTID	38 %	31 %	48 %	38 %

3.3 LeTID behavior of the mc-Si solar cells after HIIT

After the HIIT process, the cells were subjected to the LeTID test together with non-treated references. The LeTID testing conditions were selected based on a recent testing standard proposal, 1000 h of which was estimated to correspond to approximately 20 years of field operation in Central European climate conditions [9]. Fig. 3 shows the effect of the LeTID test on the cells HIIT treated for 11.4 s at 300 °C and on the untreated reference cells. The results show that although both of the cell groups degrade, the HIIT treated cells are on average more stable with a smaller spread of efficiencies between individual cells. We can now estimate the energy gain potential of inline HIIT by integrating the average efficiency curves of both the HIIT treated cells and the references with respect to time, and by dividing the former integral with the latter. The shaded area between the two groups illustrates this energy gain potential for the treatment at 300 °C, which amounts to a 2.6 % increase in the total energy yield during the first 1000 h.

To compare the results of the LeTID test clearly in terms of the means and distributions between HIIT treatments, the efficiencies during the test were interpolated at regular time intervals of 200 h and converted into boxplots. Fig. 4 shows these plots in the case of the 11.4 s HIIT at the different target temperatures. Note that the cells HIIT processed below 300 °C were excluded from the LeTID test due to the low initial efficiencies in Fig. 2. This graph illustrates how all the tested HIIT target temperatures increase the mean and reduce the spread of the efficiencies compared to the references.

In Fig. 4, the treatment at 400 °C results in slightly more stable LeTID behavior on average than the rest of the treatment temperatures. However, a clear temperature dependent trend is not visible, possibly at least partly due to the wide variation in LeTID behavior between individual cells also visible in Fig. 3. Table I shows the average energy gain of the HIIT processed solar cells of Fig. 4 as compared to the non-treated references of Fig. 4, calculated based on the time integral of the efficiency from 0 h to 1000 h such as in Fig. 3. Also shown in the table are the corresponding fractional reductions in energy yield loss due to LeTID. The results show a relatively narrow variation between 2.1 % and 3.2 %, corresponding to a 31 % to 48 % reduction in the energy yield loss due to LeTID, depending on the treatment temperature. Hence, in the case of the investigated mc-Si PERC solar cells, the 11.4 s treatment provides an improved stability within a wide window of processing temperatures.

It is notable in Fig. 4 that, unlike in other studies [4,13], increasing the temperature of the regeneration treatment does not seem to have a clear negative impact on the achieved stability. For example, in our upcoming study, the stability was observed to reduce significantly when the treatment temperature of HIIT was increased [14]. This implies that the temperature-dependent behavior of LeTID is sample type dependent. In the mentioned study, the decrease of stability with treatment temperature was hypothesized to derive from the existence of an earlier proposed reservoir state [15] which would release additional defect precursors at high temperatures, whereas at a lower optimum temperature region the release from the reservoir would be much slower. The lack of the described kind of destabilization with increasing temperature in the commercially available solar cells of this work implies the absence of such a reservoir. Whether it is the thermal history, the silicon material, the surface passivation, or some other factors that determine the existence and the size of this type of precursor reservoir in different types of samples requires further research.

Due to the importance of belt speed in view of the throughput of an inline process, the effect of different belt speeds, corresponding to a treatment time variation of 4.26 – 34.1 s, was investigated using the HIIT target temperature of 350 °C. Additionally, to find the limits of the potential of inline HIIT, two cells were processed 15 times with the process corresponding to the 11.4 s HIIT at 350 °C. The results are depicted in Fig. 5, which shows surprisingly similar mean values of the efficiency during the LeTID test for the cells treated a single time considering that the treatment time varies widely between 4.26 and 34.1 s. Increasing the number of treatments to

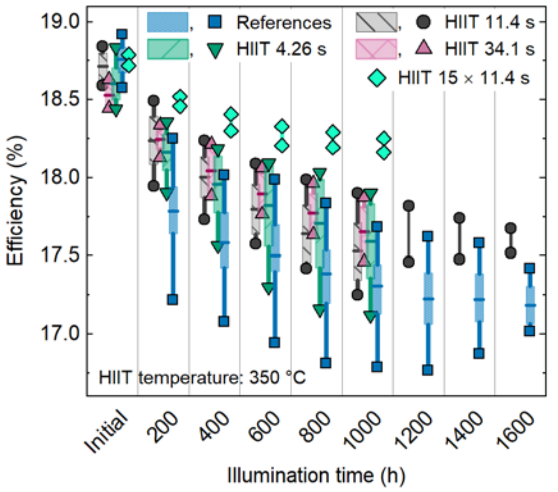
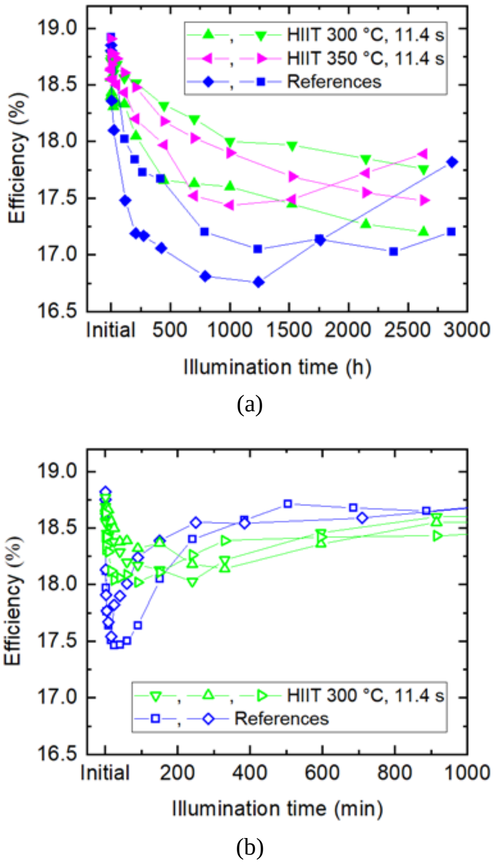


Figure 5: Interpolated efficiency distribution of solar cells after single 4.26 – 34.1 s HIIT treatments at a target temperature of 350 °C (boxplots) and a repetition of the 11.4 s treatment at 350 °C 15 times (tilted squares), plotted as a function of the LeTID testing time. Non-treated references are shown for comparison. Note that the efficiency was interpolated from measurement data exemplified in Fig. 3 at 200 h intervals, and that the calculation is based on 4-6 samples per group until 1000 h and at least 2 randomly selected samples beyond 1000 h. Shown are the 25% quartiles (boxes), the average value (lines inside the boxes), and the maximum-minimum variation (whiskers with symbols).

15 leads to a significant further improvement of stability, which further corroborates the fundamental stabilizing effect of the HIIT. However, the increased number of repetitions leads to a total treatment time of almost 3 min, which in most cases is too long for an inline process without decreasing the production throughput or increasing the physical length and therefore the factory footprint of the HIIT tool excessively. In our upcoming study, we verified that stability after short HIIT improves with increasing treatment intensity up to 150 kW/m² [14]. Therefore, to improve the HIIT further, possibilities of improving the regeneration effect for example by increasing the achievable intensities while the target temperature remains constant should be investigated. Although the treatment at 34.1 s on average results in a slightly more stable LeTID behavior and smaller spread of the data than the two shorter treatments, most of the benefits of HIIT at an inline-feasible timescale are already visible at the 4.26 s treatment time corresponding to an industrial scale throughput.

3.4 Very long term LeTID behavior

To investigate the very long term behavior of the HIIT processed solar cells, the LeTID test was continued for part of the cells beyond 2500 h. Fig. 6 (a) illustrates these results for the 11.4 s HIIT treatments at 300 °C and 350 °C, as well as for the references. It is noteworthy that beyond 2500 h both of the references in Fig. 6 seem to be regenerating, whereas only one of the HIIT processed cells shows regeneration behavior at this point of the LeTID test. Hence, there appears to be a crossover point between 2000 h and 3000 h when the efficiency of the references surpasses the efficiency of the HIIT processed samples. To investigate this further, both HIIT processed



(a)

(b)

Figure 6: Comparison of different stability testing conditions. (a): 0.15 suns and 75 °C. (b): 2 suns and 140 °C.

cells and references were subjected to an accelerated test at 2 suns and 140 °C. As shown in Fig. 6, although the amplitude of the LeTID cycle is much lower in the case of the accelerated test (b) than in the standard test (a), a qualitatively similar crossover point as in the standard test can be observed between 60 min and 200 min of the accelerated test. This type of crossover behavior has also been reported earlier [2], and can represent a concern in modules installed in regions of hot climate where LeTID proceeds faster than in the field conditions of Central Europe, and where 1000 h of standard LeTID testing would not anymore be enough to cover the majority of the predicted operating lifetime of solar modules in the field.

4 CONCLUSIONS

Commercially available mc-Si PERC solar cells were subjected to inline high-intensity illumination treatments at a wide range of treatment temperatures and belt speeds. Significant improvement in the stability of mc-Si cells against the standard LeTID conditions was achieved without modifications to other steps in the manufacture process flow of the solar cells. In particular, the treatments resulted in a ~ 3 % increase in the total energy yield during a test time corresponding to the majority of the operating lifetime of solar modules in the Central European climate conditions. This improvement corresponds to a reduction in the energy yield losses associated with LeTID by up to ~50 %. Importantly, these improvements are achievable with high belt speeds corresponding to a throughput of several thousand full size cells per hour. On the other hand, very long term experiments showed signs of a crossover point after which the efficiency of the references climbed back above that of the HIIT treated cells. This crossover point may be reached within the operating lifetime of solar modules in the field in very warm climate conditions, and therefore the energy yield benefits of HIIT most likely depend on the installation location of the modules containing the treated cells. Although further improvements in the treatment or combination with other LeTID mitigation strategies are needed for the mass production of fully stable cells in the future, the inline high-intensity illumination treatments enable significant stability benefits already at present in moderate climate conditions. In the future, the combined effect of HIIT together with other mitigation methods of LeTID upstream in the solar cell process flow should be investigated to understand if added stabilization benefits can be achieved.

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