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Defect formation under high temperature dark-annealing compared to elevated temperature light soaking

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ABSTRACT

In the last years, significant progress has been made regarding an understanding of light induced degradation at elevated temperature observed on PERC solar cells (LeTID). Nevertheless, the detailed root cause is still under discussion. Latest results show that a similar degradation occurs by annealing lifetime samples in the dark without carrier injection. In this work, we show that mc-Si PERC cells degrade and recover at high temperature without carrier injection. As the lateral appearance and the recovery behaviour agree with what is known about LeTID, it is likely that the same defect is observed. However, even after recovery the treatment in the dark does not result in LeTID stable cells. A subsequent illumination leads to a further power loss. This subsequent degradation differs from the first degradation in its kinetics and its lateral appearance. Based on these results it is concluded that two recombination active defect states are activated by LeTID. These recombination active defect states can be distinguished by annealing the samples without carrier injection before illuminating the samples. However, a high temperature anneal activates also additional defects, which might lead to a more pronounced degradation. Thus, a high temperature treatment is not recommended for LeTID testing neither as substitution nor as pretreatment prior the LeTID test.

1. Introduction and motivation

Illumination, or more generally speaking the injection of excess carriers, at elevated temperature can lead to a significant power loss at PERC solar cells, generally known as LeTID [1], mc-CID [2] or mc-LID [3]. Latest results show that not only multi-crystalline silicon (mc-Si) solar cells are affected. Czochralski and float-zone samples also exhibit degradation similar to mc-Si solar cells [4–6]. Thus, any PERC module can be prone to severe degradation under field operation conditions. Hence, a more fundamental understanding of LeTID and its effects on the PV market is relevant in order to develop mitigation strategies and long-term reliable modules. Furthermore, standardized test schemes, which are close to relevant operating conditions and at the same time timesaving, are requested to guarantee widespread LeTID stable PERC modules.

Several LeTID-defect models are currently under discussion. However, it is still unsolved if one recombination active defect state is causing the degradation [7], or if more than one recombination active defect state is activated by LeTID [8,9]. Until now, no clear evidence separating two LeTID defects is presented. Recently, Chen et al. described the degradation and recovery of lifetime samples that occurs by a dark anneal (DA) of the samples without charge carrier injection through light soaking (LS) or current injection [10]. The DA degradation showed some analogies to LeTID, as a similar capture cross section ratio was measured and both degradation conditions lead to a stronger degradation when a high firing temperature was used during sample preparation [10]. However, previous investigation also showed that a DA can lead to a temporary recovery of activated LeTID defects [3]. Fung et al. showed that DA leads to either degradation or recovery depending on the state in which the LeTID defect are (as-fired or activated) [2]. They also showed that even LeTID regenerated samples degrade again after a dark anneal. However, with each DA-LS cycles the LeTID degradation extent is reduced [2]. Fung et al. explain these observations by a reservoir of precursors which is emptied by a dark anneal [2].

The here presented investigations are linked to these DA investigations. Degradation cycles consisting of a dark anneal (DA) treatment at 170 °C and light soaking (LS) at 75 °C are investigated on mc-Si PERC solar cells. Our investigations exceed the previous investigations by tracking the cell parameters throughout the DA and the LS treatment. This allows connecting the DA and LS at different defect states to directly compare the effects of these two degradation types. Furthermore, for the first time, lateral investigations of the defects activated by a DA are presented and compared to the phenomenological appearance of the rather well studied LeTID based appearance.

Based on our results, the comparability of the DA and the LS

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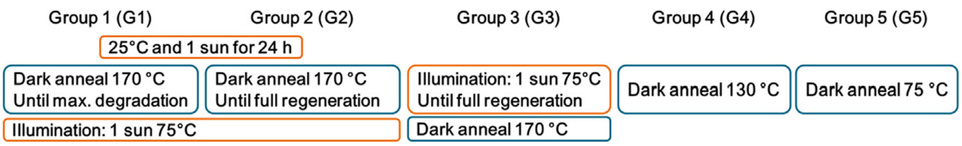

Fig. 1. Schematic of experimental procedure.

degradation and currently used defect model are discussed. Here special focus is set on the possibilities and potential difficulties of rapid LeTID testing.

2. Experimentals

2.1. Experimental set up

The investigated samples are industrially produced PERC solar cells, which show strong LeTID. The cells from one batch were separated into 5 groups. Three samples of group 1 and 2 underwent a pre-treatment illuminating the samples at 25 °C and 1 sun for 24 h. As the samples showed only a minor efficiency change, the FeB-LID due to iron can be neglected. Also BO-defects play a minor role as they are largely activated after this pre-treatment, however, no recovery but a degradation is observed by the subsequent dark anneal treatment. Next, the cells passed a number of subsequent temperature and light soaking treatment steps as presented in Fig. 1. Samples of group 1 and 2 were first treated in the dark at 170 °C without carrier injection (dark anneal). The dark anneal was frequently interrupted for IV, EQE and LBIC measurements, performed under standard test conditions on the cell analysis system LOANA. Subsequently, the samples were illuminated at one sun at 75 °C (LeTID treatment). During this treatment the V_{OC} was in situ measured at the test setup at elevated temperature. The LeTID treatment was also frequently interrupted by measurements under standard test conditions on the cell analysis system LOANA. Cells of group 3 have seen these treatment steps in reversed order. Cells of group 4 and 5 were treated without carrier injection at 130 °C or 75 °C.

2.2. Experimental results

2.2.1. Electrical cell parameter

The 170 °C dark anneal leads to a significant degradation of the charge carrier lifetime on solar cells, which is reflected in a V_{OC}-decrease, see Fig. 2. Subsequent to the degradation, the recovery starts resulting in reobtaining almost the initial V_{OC} and efficiency. This behaviour is observed on all investigated samples, with differences in the kinetics and degradation extent. These observations agree with the results on lifetime samples. [10]

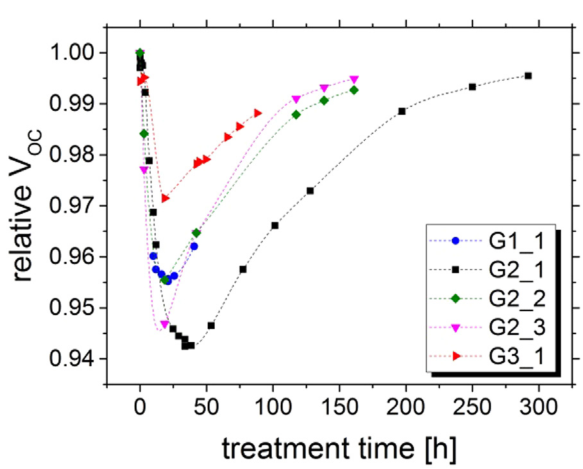

Fig. 2. Relative V_{OC} over dark anneal treatment time at 170 °C. Only sample G3_1 was exposed to a LeTID-treatment prior to the dark anneal. The dashed lines are guides to the eyes.

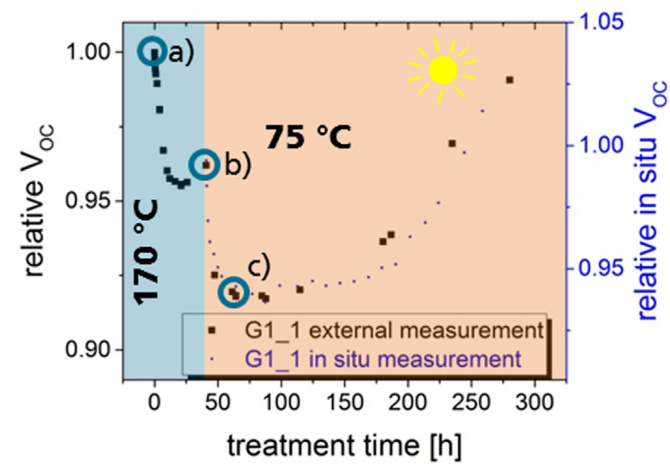

Fig. 3. Relative V_{OC} over treatment time, first a dark anneal-treatment at 170 °C until maximal degradation, followed by light soaking at 75 °C (LeTID-treatment). LBIC images taken at cell state a), b) and c) are shown in Fig. 8.

However, subsequent light soaking shows that not all LeTID defects are activated by the 170 °C dark anneal. When the point of maximal degradation through dark anneal is passed, see b) in Fig. 3, the samples degrade further when exposed to typical LeTID test conditions at 75 °C and one sun illumination, see Fig. 3. After the further degradation the samples regenerate up to its initial value under LeTID-conditions. Thus, also the defects activated by a dark anneal are deactivated under illumination. Even after passing through a complete degradation-recovery-cycle by dark anneal, the samples are not stable but show again a degradation and regeneration under the typical LeTID test conditions, see Fig. 4.

Applying the treatment steps in reversed order (first the light soaking at 75 °C followed by the 170 °C dark anneal) results also in a second degradation, see Fig. 5. However, the degradation extent is significantly reduced. This is obvious by comparing the degradation

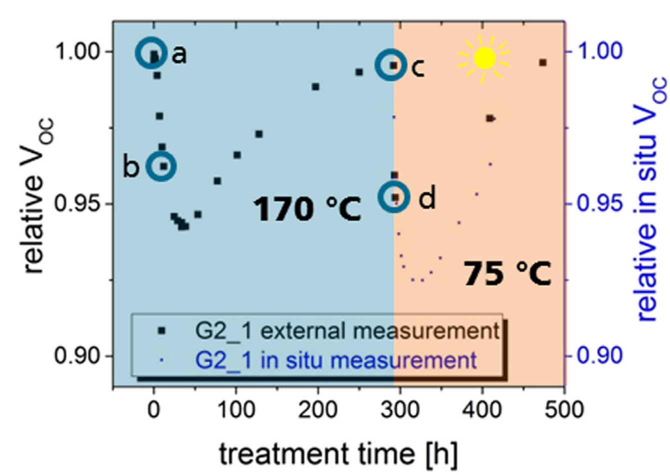

Fig. 4. Relative V_{OC} over treatment time, first a dark anneal at 170 °C until recovery, followed by light soaking at 75 °C (LeTID-treatment). LBIC images taken at cell state a), b), c) and d) are shown in Fig. 10.