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Intra-grain versus grain boundary degradation due to illumination and annealing behavior of multi-crystalline solar cells

Tabea Luka [a,*], Stephan Großer [a], Christian Hagendorf [a], Klaus Ramspeck [b], Marko Turek [a]

[a] Fraunhofer Center for Silicon Photovoltaics CSP, O.-Eissfeldt-Str. 12, 06120 Halle (Saale), Germany
[b] h.a.l.m. elektronik gmbh, Burgstr. 106, 60389 Frankfurt/Main, Germany

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ABSTRACT

Light induced degradation can cause a severe loss of efficiency on multi-crystalline PERC solar cells (mc-LID) of more than $10\%_{rel}$. In this work, the kinetics of the mc-LID annealing process and its temperature dependence is analyzed. It is shown that the initial efficiency can be partly restored by annealing the cell in the dark. However, the degradation process is not completely reversible and the degradation rates of the first and subsequent degradation cycles are different. Furthermore, lateral variations of the degradation are investigated. Four regions showing a quantitatively different degradation behavior are identified. Mc-LID of the rear contacts shows similar degradation as for standard back surface field solar cells. The degradation of grain boundaries is weaker than intra-grain degradation and thus of particular interest for root cause analysis. Decorated grain boundaries are dominated by other recombination mechanisms suppressing the appearance of mc-LID. Physical explanations for these results of a laterally different degradation behavior and an increased degradation rate after annealing are discussed.

1. Introduction and motivation

Passivated emitter and rear solar cells (PERC) are increasingly entering solar cell mass production [1]. This cell technology yields an efficiency gain of about 1–2% absolute compared to standard aluminum back surface field (Al-BSF) cells [1]. However, it has been shown that PERC-cells can be sensitive to new degradation mechanisms [2]. Mc-LID is a degradation mechanism occurring on multi-crystalline silicon (mc-Si) solar cells. It was first described by Ramspeck et al. who demonstrated that multi-crystalline PERC solar cells are strongly affected [2]. Light induced degradation has been under investigation for many decades [3,4]. The dissociation of iron-boron pairs (FeB-LID) [5–7] and the activation boron-oxygen-defect (BO-LID) [8–10] are the two most studied degradation mechanisms induced by carrier injection. Another recently published light induced degradation on high-performance multi-crystalline material termed sponge-LID was discussed in Ref. [11]. However, it was shown that mc-LID cannot be explained by either of these LID mechanisms [2,12,13]. Fertig et al. compared the degradation of mc-Si PERC cells with Cz-PERC cells and mc-Si Al-BSF cells. It has been shown, that the kinetics of BO-LID, FeB-LID, and mc-LID differ as the mc-LID degradation occurs on much longer times scales than the other two mechanisms. [12].

It is an open question, whether the mc-LID process can be described by a similar three state model as BO-LID. The BO-related degradation includes three defect states which are related by degradation, annealing, and regeneration processes [10]. Kersten et al. showed that mc-LID is induced by an increased excess carrier concentration and that a regeneration of mc-LID occurs under continued illumination at elevated temperatures, similarly to BO-LID [13]. In our work, the annealing behavior of mc-LID is described for the first time. The annealing step, which allows returning to the instable defect state in case of FeB [5] and BO-LID [9], is especially interesting for investigations on the defect formation since it allows generating a well-defined initial cell state. Thus, it can be employed when the total amount of defects causing the degradation needs to be determined or when structural differences between recombination inactive and recombination active defect states are investigated. In our work, a parameter study is performed determining the optimal annealing conditions for an ideal efficiency increase. It is found that the annealing step of mc-LID impacts subsequent degradation rates indicating that the initial defect state is not entirely restored during annealing.

Lateral differences of the degradation on wafers were investigated in Ref. [14,15]. A first analysis of the lateral variation of the degradation on solar cells was presented in Ref. [16]. In this work, the lateral variation of the degradation on mc-Si PERC solar cells is investigated in more detail. Based on light beam induced current (LBIC) measurements, four regions are identified that show a quantitatively different degradation behavior: rear contacts, grain boundaries, intra-grain regions comprising twin grain

* Corresponding author.

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boundaries, and high recombination active areas. The degradation behavior of these areas is investigated over degradation time. It is found that the rear contact regions and some of the grain boundaries show lower mc-LID compared to intra-grain regions. High recombination active areas, i.e. decorated grain boundaries, are rather insensitive to mc-LID since the lifetime is limited by other recombination mechanisms.

2. Experimental setup and results

2.1. Experimental setup

Industrially produced mc-Si PERC solar cells were investigated that show a severe efficiency loss of up to $15\%_{rel}$ in the first hours of illumination at elevated temperatures. The base resistivity was determined to be 1.5–1.7 Ω cm corresponding to a boron doping concentration of $8\times10^{15}-1\times10^{16}$ cm^{-3}. Degradation was performed under a Xe-lamp at an irradiation intensity of 1 sun. A heating plate held the cell temperature at 75 °C. To evaluate the degradation, the cells were removed from the degradation stage and measured under standard test conditions at 25 °C. The effective diffusion length was obtained by measuring the LBIC signal at different wavelengths between 405 nm and 980 nm using the solar cell analysis system LOANA. The LBIC laser spots have a diameter of 100 – 200 μm. Based on the LBIC data the effective diffusion length image was calculated according to the IQE model presented in Ref. [17]. The degraded cells were annealed in the dark in an oven to guarantee a homogenous cell temperature. The oven temperature was varied between 80 °C and 200 °C.

2.2. Annealing process and effects on further degradation cycles

In a first step, the mc-Si PERC solar cells were subjected to mc-LID at 75 °C and 1 sun for 9 h. Then, the partially degraded PERC cells were annealed by a temperature treatment in the dark which causes an efficiency increase. The relative efficiency over annealing time compared to the non-degraded initial state is displayed in Fig. 1. It becomes apparent that the initial efficiency was not completely restored. The maximum efficiency gain of $10\%_{rel}$ was obtained by annealing in the dark at 200 °C. At this temperature, the annealing is very fast and does not show any further effect after 5 min. Annealing at 150 °C leads to a slightly smaller but comparable efficiency gain. However, the annealing process is much slower and takes about 150–200 min until the efficiency saturates. An annealing experiment at 80 °C did not show any increase in efficiency and was stopped after the first hour.

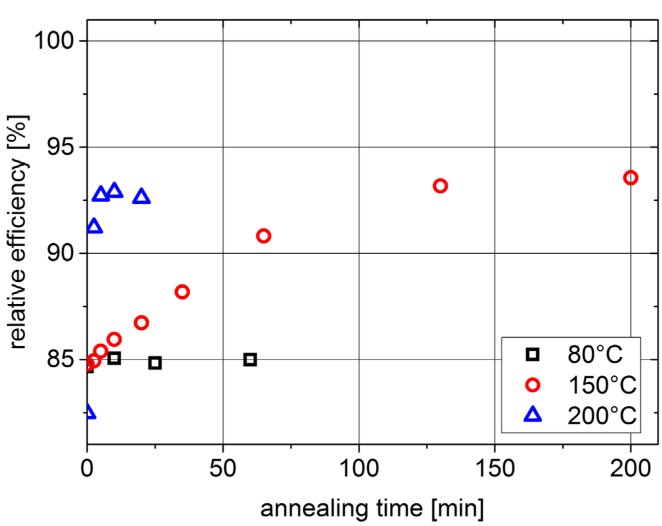

Fig. 1. Relative efficiency compared to the undegraded initial state during annealing of a degraded mc-LID sample in the dark at 80 °C, 150 °C, and 200 °C. The initial efficiency was not completely restored. Annealing at 150 °C and 200 °C resulted in the same maximum post-annealing efficiency value, while the annealing at 80 °C did not show any efficiency increase within the first hour.

Typical defect annealing rates for BO-LID in Cz-mono-Si wafers are around 0.1 s^{-1} for 200 °C and 0.004 s^{-1} for 150 °C [9]. Thus, the BO-annealing would reach a saturated state after approximately 1.5 min at 200 °C annealing temperature and after 200 min at 150 °C, respectively. Even though our experiments were performed on mc-Si solar cells where the BO-degradation is expected to play a minor role, the results of Fig. 1 are not conclusive as to the observed defect type. Based on the annealing rates only, a BO-related effect cannot be excluded. The temperature dependent annealing rates of mc-PERC cells investigated in our experiments are comparable to mono-Si cells with BO-LID.

In order to demonstrate that the observed effect is not related to the BO defect, additional degradation experiments were performed. A room temperature degradation step was included, since the well-known BO – degradation occurs already at room temperature under illumination. First, the solar cell was illuminated with 1 sun intensity at 25 °C for 1440 min. Then a high temperature degradation step at 75 °C and 1 sun illumination followed for 5100 min. After the degradation, an annealing step at 200 °C with no illumination was applied for 5 min. Then, the cycle of low and high temperature degradation has been repeated. The result of this experiment is shown in Fig. 2 where the relative change in open circuit voltage V_{oc} compared to the undegraded initial state of the first and the subsequent degradation is shown. First, it was observed that the initial room temperature degradation step at 25 °C for 24 h does not lead to any significant solar cell degradation. As the BO-defect generation rate is about 3×10^{-3} min^{-1} at 25 °C [9], the 24 h illumination phase would result in an observable degradation if the BO defect is involved. Also FeB defects can be excluded, since after 24 h of one sun illumination at 25 °C the majority of FeB pairs are dissociated [6]. In our experiment, the initial degradation within the first low temperature phase at 25 °C is negligible compared to the subsequent high temperature phase at 75 °C which leads to the conclusion that the BO defect and FeB pair dissociation do not play a significant role in our experiments. This conclusion is supported by experiments on solar cells that have been processed by the same silicon material with a modified cell process which did not show any significant light induced degradation [16].

The first high temperature degradation cycle leads to an efficiency degradation of about $10\%_{rel}$ while the second degradation resulted in an efficiency reduction of $8\%_{rel}$. After the first degradation and annealing phase, the initial efficiency could not be completely restored during annealing but a relative efficiency of about 95% was achieved similarly to our first experiment shown in Fig. 1. The corresponding data of the open circuit voltage V_{oc} is shown in Fig. 2 (left). This confirms the results of our first experiment and supports the conclusion that the state after annealing is different from the initial state before any degradation cycle.

Furthermore, it can be observed that the second degradation cycle is faster than the first one. This effect can be quantified by analyzing the decay rates of the normalized effective defect concentration. This effective defect concentration was calculated as described in Ref. [9] using the expression $N(t)\equiv e^{-qV_{OC}(t)/k_BT}-e^{-qV_{OC}(t=0)/k_BT}$. The time dependence of the normalized defect concentrations is shown in Fig. 2 (right). Assuming an exponential decay $N(t)=N_\infty\left(1-\exp\left[-R_{gen}t\right]\right)$, the defect generation rates R_{gen} can be determined. They are in the range of 0.0014–0.002 min^{-1} for the first and second degradation,