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Low-T Anneal as Cure for LeTID in Mc-Si PERC Cells

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Abstract. Light and elevated temperature induced degradation (LeTID) is known to be affected by the last dark anneal that the silicon wafers or cells experience prior to illumination. Here we study how low-temperature dark anneal performed on fully processed multicrystalline silicon (mc-Si) passivated emitter and rear solar cells (PERC) influences LeTID characteristics, both the intensity of the degradation and the degradation kinetics. Our results show that a relatively long anneal at 300°C provides an efficient means to minimize LeTID while too short dark anneal at the same temperature seems to have a negative impact on the subsequent degradation under light soaking. Finally, we compare the experimental results with the model originally developed for metal precipitation and discuss the possibility of metals being involved in LeTID mechanism.

INTRODUCTION

Light and elevated temperature induced degradation (LeTID) is known to be a harmful phenomenon in crystalline silicon photovoltaics. While the mechanism is not yet fully understood, LeTID is known to be affected by thermal treatments, especially by high temperature anneals often present in so-called contact firing process [1], [2], [3], [4]. Furthermore, recent studies have reported that also anneal made at low-temperature affects the LeTID defect formation [3], [5], [6]. More specifically, it has been shown that a dark anneal (DA) alone can induce degradation and regeneration similar to LeTID and that degradation kinetics and intensity depend on the DA temperature [3], [6], [7], [8], [9], [10]. Additionally, a preliminary study has shown with the experiments made on implied-Voc samples that a long enough anneal at 240-300°C may have a beneficial effect on the LeTID defect formation under subsequent light soaking [11].

Here we study if the beneficial effect of DA reported earlier on implied-Voc samples can be extended to finished PERC cells, aiming to develop a method that could be directly applied to existing solar cells or solar cell fabrication to mitigate the harmful LeTID. We expose the PERC cells to different DA conditions and measure the subsequent degradation under typical light soaking conditions. As a reference we have implied-Voc samples having nearly identical emitter and passivation thin films than in the finished cells. The maximum temperature is limited to 300 °C in order to have a minimal impact on the junction or contact properties as the anneal times of interest are relatively long. Finally we will study if the degradation and regeneration during DA resemble metal precipitation kinetics, since earlier studies indicate that some metals may still be present in the bulk after the last high temperature step [4], [12], [13], [14], [15] although a strong evidence has been reported for hydrogen playing a crucial role as well [9], [16].

EXPERIMENTAL DETAILS

In the experiments we used so-called implied-V_{OC} samples as well as full PERC cells both processed at industrial production line. The starting wafers for both sample types were commercial 156×156 mm^2 boron-doped high-performance multicrystalline silicon wafers, the initial bulk lifetime was around 490 µs and the substrate material was known to suffer from typical LeTID. All process steps followed typical industry standards for PERC cells [11], [15]. The implied-V_{OC} were otherwise identical to the cells but no metal contacts were deposited. The last processing step was a few seconds of firing in a belt furnace with a peak temperature of 835°C for both implied-V_{OC} samples and PERC cells.

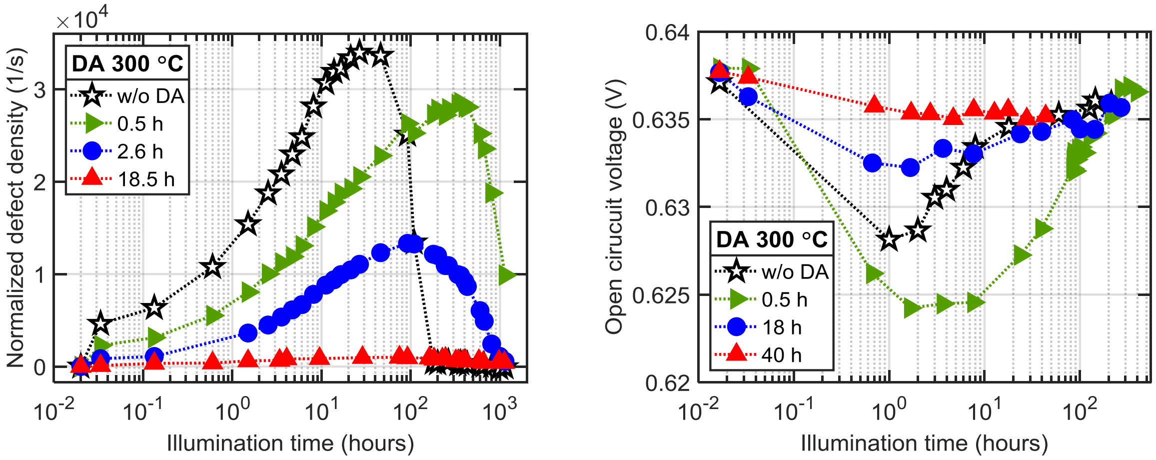
Implied-V_{OC} samples were annealed in dark at different combinations of temperature and time (200-300°C, 0.5-18.5 hours), while finished cells were annealed at 300°C for 0.5-40 hours. Some wafers/cells remained as reference i.e., they did not experience any DA after firing. The samples were then exposed to typical LeTID degradation conditions (0.6 suns at 80°C). Some samples were used for studying the kinetics of the defect formation during the DA. Cells were annealed and illuminated as whole (156×156 mm^2 in size), therefore, a special emphasis was placed to keep the light intensity and temperature homogeneous over the whole sample area.

The minority carrier lifetimes as a function of excess carrier density were measured using a quasi-steady-state photoconductance (QSS-PC) tool (Sinton Instruments WCT-120TS) at 24±1 °C. The effective minority carrier lifetimes were measured both before and after DA. The evolution of the lifetime was sequentially monitored also during the illumination. The SHR bulk recombination rate and normalized defect density that are presented later in this article were calculated using the single-defect level SRH bulk lifetime values at an excess carrier concentration of 1.1·15 cm^{-3}. Open circuit voltage, V_{OC}, of the PERC cells was measured with the cell tester Endeas Quicksun 130 CA.

RESULTS AND DISCUSSION

The results reported earlier show that the dark anneal temperature affects both the kinetics and the maximum degradation as well as regeneration behavior of LeTID [11]. In general, if the dark anneal temperature is below 300 °C LeTID was seen to be strongly enhanced, even doubled, after such anneals as compared to the reference samples. Interestingly, when the dark anneal temperature was increased to 300°C, LeTID was shown to slow down considerably and the maximum degradation was found to be smaller than in the reference sample, suggesting that 300 °C and possibly higher temperatures could be beneficial in reducing LeTID. Since the 300 °C anneal showed the most interesting characteristics, in this contribution we focus on this temperature and extended the anneal times to study the impact of anneal duration on LeTID.

Figure 1a shows the normalized defect density (NDD_t) as a function of illumination time at elevated temperature (i.e. LeTID curve) in the implied-V_{OC} samples that were exposed to 300°C dark anneal (DA) for various times prior to illumination. The reference sample without any anneal is also shown in the figure. Indeed, it is seen that both the maximum LeTID and the timescale of degradation depends heavily on the anneal time, i.e. LeTID is stronger the shorter the DA duration. Interestingly, after very long DA (18.5 hours), during subsequent illumination LeTID is almost totally suppressed.



(a) (b)

FIGURE 1. The impact of 300°C dark anneal time on LeTID in (a) implied-V_{OC} samples (b) in finished PERC cells. The reference sample without dark anneal (DA) is shown as a reference (stars). The symbols represent the measured values and the dashed lines serve as guide to the eye. The legend shows the anneal time.

In light of such promising results, we repeated the experiments with finished PERC cells and the results are reported in Fig. 1b. The impact of DA on the cells is seen to be similar to implied-V_{OC} samples, i.e. LeTID is greatly reduced the longer the duration of the DA at 300°C.

Based on the experimental results reported above, it is evident that the DA affects the defects that are responsible for LeTID, and it is therefore important to understand the phenomena occurring during the DA. To obtain further insight into this, we studied the evolution of the recombination rate during the DA, at the same temperatures used in the experiments i.e. 200°C, 240°C and 300°C. The general trend observed in Fig. 2 is that the recombination rate increases strongly in the beginning of DA and then decreases back to the initial value – or even below. A similar behavior was reported also in earlier studies in implied-V_{OC} samples at temperature of 175°C [3], [9] at temperature of 232°C [8] at temperatures of 160-300°C and in V_{OC} of finished cells at temperature of 250°C [7]. Such behavior resembles the actual LeTID characteristics and indeed, it has been confirmed recently that the defects generated during DA are the same that are generated during LeTID [3]. From the LeTID point of view, it would be beneficial to have as low defect density as possible prior to illumination. Thus, Fig. 2 suggests that the longer the DA anneal time and the higher the temperature, the closer to optimal the initial conditions are.

There are currently many speculations about the root cause of the LeTID defect and how to explain the similar DA recombination activity. The majority of both theories and experiments support the presence of hydrogen as one crucial component and rules out the role of metal contamination [9], [16], while other studies support the involvement of fast diffusing metals [14], [17]. In this work we study the latter approach, i.e. the possibility of formation and dissolution of recombination active metal precipitates and the simultaneous segregation of the mobile metals to the surface or the emitter. Modeling the metal precipitation and dissolution, as well as segregation and diffusion at different temperatures, is relatively straightforward based on the models found in literature [18]. In addition to modeling the impurity redistributions, we also simulate the recombination rate during the dark anneals reported above to see if they correlate with the experiments. Figure 2 shows that the simulations show a similar trend with the experiments without even adjusting interfacial energy between precipitate and silicon matrix. To summarize, the change in the bulk recombination rate in our samples could be explained with fast metal precipitation and slow dissolution. Similar phenomenon could be also present under LeTID conditions, although the dissolution (i.e. regeneration) would be very slow due to low metal solubility close to room temperature.

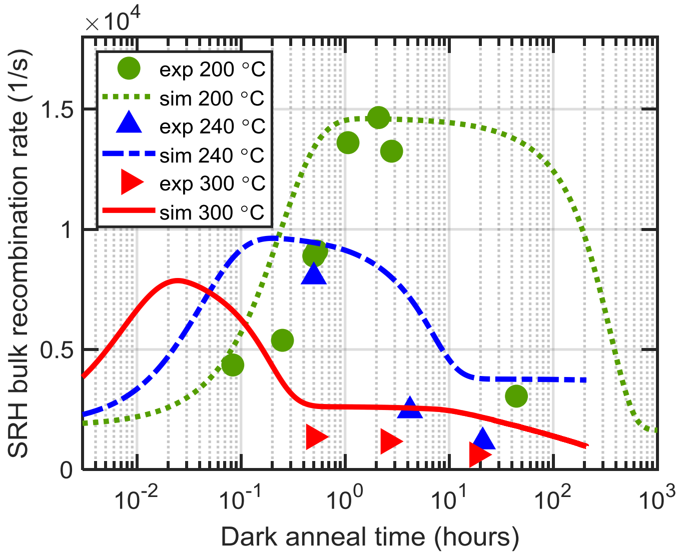


FIGURE 2. Shockley-Read-Hall bulk recombination rate during dark anneal at different temperatures (T=200°C, T=240°C and T=300°C). The symbols show the experimental recombination values while the lines represent the simulated curves.

CONCLUSIONS

We have shown that a dark anneal at low-temperature (~ 200-300°C) carried out prior to light soaking can have a large impact on LeTID both in finished PERC cells as well as in implied-Voc samples. The impact can be either negative or positive, depending on the temperature and time of the dark anneal. In case of a short anneal the impact is mostly negative and DA results in increased degradation under subsequent light soaking. For instance, a dark anneal for 30 min at 300°C slowed down greatly the LeTID degradation and regeneration rate in addition to increasing the intensity of the degradation. When the anneal time is long enough, the dark anneal was shown to suppress LeTID, and eventually after tens of hours, LeTID was almost totally eliminated in PERC cells. The results are similar both in PERC and implied-Voc samples although slightly longer anneal was required for the PERC to suppress LeTID. A comparison of the experiments to the simulations suggest that metals may be involved in LeTID mechanism as the experimental behavior follows similar trends than metal precipitation and dissolution combined with subsequent diffusion towards surfaces.

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