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IMPACT OF TEMPERATURE AND DOPING ON LETID AND REGENERATION IN MC-SI

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ABSTRACT: Light and elevated temperature induced degradation can be observed in multicrystalline Si PERC solar cells and results in efficiency losses of up to 12%$_{rel}$. This work investigates the impact of temperature as well as doping on the degradation and regeneration behavior of lifetime samples. While ungettered Ga-doped samples did not show any regeneration effect within the duration of the experiment, increasing the treatment temperature sped up the degradation and regeneration where it could be observed. Ga-doped samples showed a slower degradation compared to B-doped samples. For higher temperatures (≥200°C) the lifetimes during regeneration exceeded the initial lifetimes before starting the illumination treatment for the gettered samples. After regeneration at higher temperature, the stability of lifetime at 75°C was tested. When tested after treatment at 150°C and before the lifetime exceeded the initial value, it stayed stable. After treatment at 250°C until the lifetime exceeded the initial lifetime, it decreased again during the stability test. However, the kinetics of this decrease was much slower than during the initial degradation.
Keywords: Degradation, Lifetime, Multicrystalline Silicon

1. INTRODUCTION

LeTID is a recently discovered effect on mc-Si PERC (passivated emitter and rear cell) solar cells [1-3]. This effect can cause efficiency losses up to ~10%$_{rel.}$ under illumination [3] and cannot be attributed to standard BO complex formation or FeB pair dissociation [1]. Therefore, it can be a showstopper for applying PERC technology to mc-Si. Also a regeneration process after degradation has been observed in [3]. The kinetics of degradation and regeneration is influenced by illumination and temperature, while the underlying mechanisms causing the degradation and regeneration of mc-Si PERC solar cells are still unknown.

This work investigates the influence of doping and temperature on the dynamics of LeTID and regeneration by varying the treatment temperature for differently processed sister wafers for lifetime studies. The motivation for the increase of temperature is to study the kinetics of degradation and regeneration and check the stability of bulk lifetime after regeneration. The outcome is of high importance for implementation of regeneration schemes for mc-PERC solar cells in industrial production where short treatment times and stability of lifetime after regeneration are essential.

2. EXPERIMENTAL

Four sets (A-D) of sister wafers (5x5cm^2, 1.3-1.4 Ωcm, comparable grain and defect structure) are used to compare the influence of different degradation conditions on B- (thickness 200 µm) and Ga-doped (150 µm) mc-Si materials. The neighbouring sample sets A and B are B-doped, sets C and D Ga-doped. Wafers originate from the middle of the ingot height and are treated equally within one sample set. All wafers are chemically etched to remove saw damage. Sample sets A (B-doped) and C (Ga-doped) receive only a surface passivation by firing of a direct plasma-enhanced chemical vapour deposition (PECVD) SiN_x:H layer. Sample sets B (B-doped) and D (Ga-doped) are gettered using an open tube $POCl_3$ diffusion process (55 Ω/□). The emitters are removed and the same surface passivation as in case of sample sets A and C was applied. This process sequence is shown in Fig. 1.

Different degradation conditions are applied to the samples. While illumination with halogen lamps (0.9±0.05 suns) is held constant, the applied temperature is varied from 25°C to 250°C. Effective minority charge carrier lifetime (τ_{eff}) is measured repetitively by the fast and self-calibrated time resolved photoluminescence imaging (TR-PLI) [4] method at room temperature, resulting in a series of spatially resolved lifetime maps for each sample over degradation time.

To determine whether the observed maxima after regeneration are stable at 75°C, samples are put on a hotplate after they were degraded and regenerated at higher temperatures such as 150°C or 250°C. Samples at these higher temperatures show a development that includes two decreases and increases in lifetime. The samples treated at 250°C are tested on lifetime stability in the final maximum whereas the stability of the first maximum was tested with samples treated at 150°C (see Fig. 2 and 3).

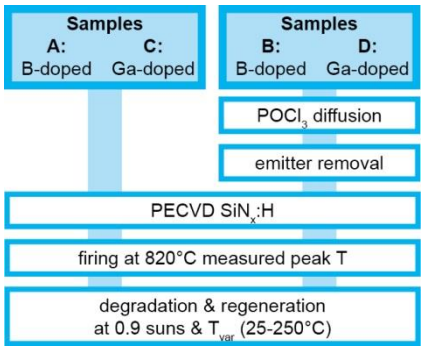

Figure 1: Process sequence of the investigated lifetime samples.

3. RESULTS AND DISCUSSION

3.1 Harmonic average lifetime values

The behaviour of lifetime samples degraded at 75°C and 1 sun was examined in multiple studies and was published before (*e.g.* [3, 5]) Degradation at this temperature is often used in literature, therefore the choice of this temperature is helpful for comparison of results from different experiments, and was proposed as standard for degradation experiments [3]. Nevertheless, it is tempting to speed up the process of degradation and regeneration by increasing the temperature.

This can be seen in Fig. 2, where the development of τ_{eff} over time is shown for B-doped P-gettered samples. As for all plots, the first 0.02 h (slightly over 1 min) are plotted linearly to show the behavior at the start of the treatment. After the break in the x-axis the plot is shown in logarithmic scale to better represent the whole timespan of the examination.

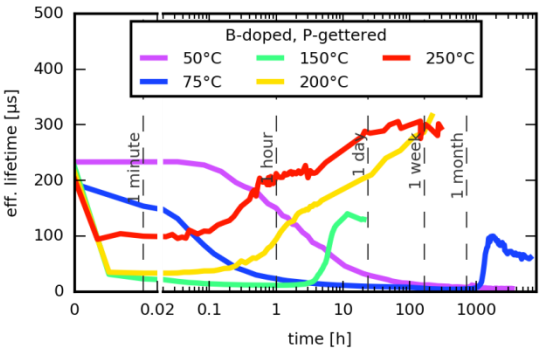

Figure 2: Overview of the harmonic averages of τ_{eff} for each point in time for different degradation temperatures. The samples are B-doped and P-gettered.

As expected, degradation is faster and regeneration sets in earlier with increasing temperature. This also means that the minimum in τ_{eff} is reached faster with increasing temperature. As the regeneration reaction sets in earlier with increasing temperature, it starts to overlap with the degradation leading to less pronounced minima for higher temperatures. As a result, the minimum of τ_{eff} at 200°C and 250°C is less pronounced compared to the minimum for 75°C and 150°C. These minima at 75°C and 150°C have a comparable τ_{eff}, which can be explained by the assumption that regeneration does not overlap too much with degradation. At lower temperature, the degradation reaction is almost completed before significant regeneration kicks in.

To quantify the increasing dynamics of degradation and regeneration, the time of treatment after which the regeneration visibly sets in can be used.

For the B-doped sample treated at 200°C (Fig. 2), the developing of a slight shoulder can be seen at approximately 2 h. Afterwards, τ_{eff} increases further to values even above the initial τ_{eff} before the treatment. The same can be observed for the sample treated at 250°C. Here the shoulder can be seen at ~1 h before the initial lifetime is exceeded.

The harmonic averages of τ_{eff} over time for P-gettered Ga-doped samples can be seen in Fig. 3. Degradation and regeneration of the samples treated at 75°C and 150°C are similar but slower than for the B-doped samples shown in Fig. 2. For the sample degraded at 200°C, the maximum visible at around 1 h is reached much faster than for the 150°C sample. After that a second minimum can be observed at ~10 h. Following this minimum, τ_{eff} exceeds the initial lifetimes, as for the B-doped samples. So the shoulders seen in the Ga-doped sample at 250°C and in the B-doped samples at 200°C and 250°C are probably this first maximum which overlaps with a second decrease and increase. This is why the maximum can only be detected as a shoulder. Again, all these kinetics are accelerated by the increase in temperature.

If the temperature on the other hand is too low, the second maximum does not occur within the examined time of, *e.g.*, ~5,000 h at 75°C.

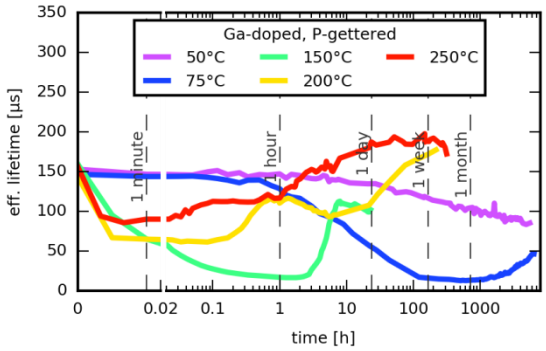

Figure 3: Overview of the harmonic averages of τ_{eff} for each point in time for different degradation temperatures. Tests for stability are not shown here. The samples are Ga-doped and P-gettered.

3.2 Spatially resolved lifetime values

Often only averages of τ_{eff} are used to discuss the effects on a mc-Si sample. This has the disadvantage that information on local lifetime distribution is not taken into account. Therefore, further analyses of the degradation and regeneration behavior will be discussed based on rainbow plots like shown in Fig. 4. Each single line in Fig. 4 represents one of 2,500 small areas on the lifetime sample. The applied color coding, based on the initial τ_{eff} values of the sample at the beginning of degradation shows that for the relative τ_{eff} distribution is kept within the sample during the experiment. So the areas with highest initial τ_{eff} remain the areas with highest τ_{eff} throughout the experiment. This was also observed before (*e.g.* [5, 6]).

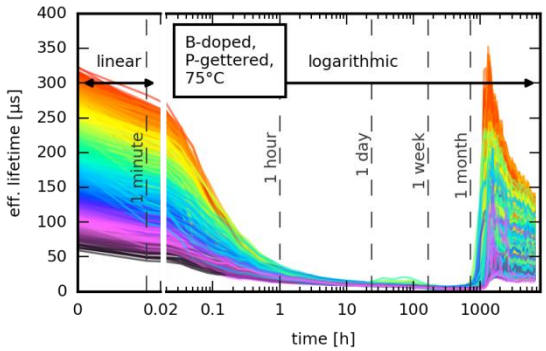

Figure 4: Development of τ_{eff} during treatment at 75°C and 1 sun for a P-gettered, B-doped sample.

To better compare the results for increased temperatures, first the τ_{eff} data of a P-gettered B-doped sample degraded at 75°C is shown in Fig. 4. The ungettered, B-doped samples show a similar development but on a lower τ_{eff} level.

The ungettered Ga-doped samples show a different behaviour. They degrade but do not regenerate within the investigated time span of roughly 5,000 h (at 75°C). But they also do not regenerate within the investigated time span when treated at higher temperatures (*e.g.* within 3,000 h at 225°C).When treating the samples at 75°C, the maximum of τ_{eff} after degradation and regeneration is reached after roughly 1,000 h (~42 d). Due to these long timescales at 75°C, an increase in temperature is quite tempting as it speeds up the kinetics.

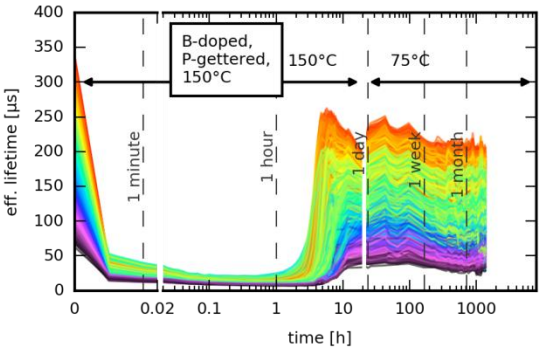

Figure 5: A sister sample (gettered and B-doped) of the one shown in Fig. 4 during treatment at 150°C and 1 sun and a following test for stability at 75°C.

By using equally processed sister samples, the influence of temperature during treatment is the dominating parameter when comparing the results. As can be seen in Fig. 5 (150°C), the whole process of degradation and regeneration accelerates. The lifetimes measured at maximum degradation are nevertheless comparable to the lifetimes at maximum degradation for the sample degraded at 75°C (*cf.* Fig. 2). The following test for stability at 75°C and 1 sun shows that the sample stays approximately at this τ_{eff} level for the rest of the examined time span of over 1,300 h.

When trying to accelerate the process even further by increasing temperature to 250°C (Fig. 6), samples reach the (less deep) minimum in τ_{eff} and a first maximum (or shoulder, respectively) earlier, but they also start increasing towards a second maximum directly afterwards. This is why the first maximum at around 1 h cannot be seen clearly when examining data from samples treated at 250°C (*cf.* Fig. 2). Nevertheless, the first maximum can still be seen as a shoulder in the increasing lifetime towards a second maximum that is reached after roughly 200 h.

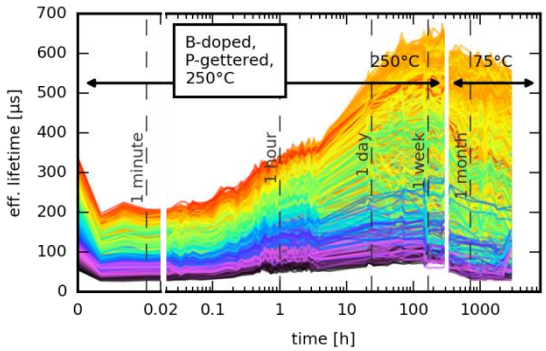

Figure 6: Another sister sample (gettered and B-doped) of the ones shown in Fig. 4 and 5 during treatment at 250°C and 1 sun and a following test for stability at 75°C (starting at ~300 h).

At the time this maximum is reached, the measured lifetimes are at least equal but mostly considerably higher than the initial τ_{eff} values.

The samples were then also tested for stability at 75°C to get further insight in the underlying mechanisms. This second maximum seems not to be stable. The B-doped (P-gettered and ungettered) samples show a slight decrease in τ_{eff} directly after lowering the temperature and afterwards a slight degradation. The P-gettered Ga-doped sample shows a steady decline in lifetime when checking for stability of the second maximum but no immediate decrease in lifetime after changing the temperature.

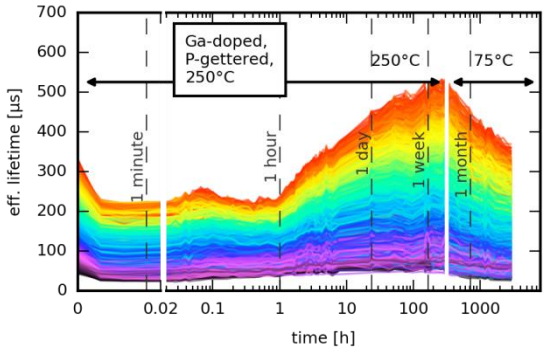

Figure 7: Gettered Ga-doped sample during treatment at 250°C and 1 sun followed by a stability test at 75°C (starting at ~300 h).

This decline can be seen in Fig. 7 starting at around 300 h for the gettered Ga-doped sample. Another aspect that can be seen in the data of the Ga-doped sample is that the increase after the first minimum and the decline after the first maximum do not overlap as much as with comparable B-doped samples. Therefore, the first maximum is more clearly visible compared to the B-doped sample (Fig. 6), where it can only be seen as shoulder (around 1 h).

One question arising from the fact that at higher temperatures two declines and increases are observed is to determine whether those effects originate from the bulk or the surface of the sample. According to investigations presented in [5, 7], the first minimum is due to bulk effects, whereas the second one arises from surface effects (temporarily degrading surface passivation overlapping with beginning regeneration). These results

were gained examining Cz and FZ samples, but they match very well the timescales and behaviour of the mc-Si samples shown here.

4 SUMMARY

The influence of different temperatures on LeTID and regeneration could be shown using spatially resolved data from TR-PLI.

The higher the used temperature, the faster the samples degrade and regenerate. This roughly follows the law of Arrhenius for the examined temperatures of 75°C, 150°C, 200°C and 250°C, as described in [6].

For samples treated at 150°C, a similar minimum lifetime compared to 75°C sister samples could be determined. For higher temperatures, the minimum is less pronounced due to competing regeneration and/or annealing effects.

A second increase could be seen when treating samples with temperatures of ~200°C or higher. This second maximum reaches lifetimes higher than the initial lifetimes of the sample but did not seem to be stable at a following treatment at 75°C 1 sun.

The first maximum was also tested for stability using samples that were degraded and regenerated at 150°C. This first maximum is more stable for the examined time of ~1,300 h.

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