bSPATIALLY RESOLVED DEGRADATION AND REGENERATION KINETICS IN MC-SI

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ABSTRACT: The strong degradation of multicrystalline (mc) Si material upon illumination at moderate temperatures (LeTID) is an issue that might hinder the application of PERC technology to mc-Si. Interestingly, a regeneration effect can also be observed under the same conditions, starting after several hundred hours at 75°C. Studies are mainly based on time resolved investigations, and some investigations also use spatially resolved measurement techniques. Visualization of the collected data is therefore challenging, but important for a better understanding of the underlying mechanisms.
In this contribution we show that based on lifetime samples we can study the same effects as reported on solar cell level with a good spatial resolution. In ungettered samples originally good quality areas show a higher relative degradation as compared to originally poor quality areas. This behaviour changes completely for gettered samples. We also show that the regeneration process sets in earlier in good quality areas, which could be caused by the higher injection level present in these regions. The regeneration process therefore might be qualitatively similar to the known BO-related regeneration. A good point-to-point correlation of different sets of lifetime measurements allows to demonstrate the impact of local differences in material quality on degradation and regeneration behaviour.
Keywords: Multicrystalline silicon, Degradation, Lifetime

1. INTRODUCTION

Recently, a phenomenon was discovered whereby mc-Si PERC (passivated emitter and rear contact) solar cells experience degradation upon illumination at elevated temperatures (LeTID) [1-3]. The loss in solar cell efficiency can be up to 10%$_{rel}$ [3] and cannot be explained by formation of BO-correlated defects or FeB pair dissociation alone [1]. This phenomenon has the potential to completely stop the application of PERC technology to mc-Si. However, a regeneration process after degradation has been observed by Kersten *et al.* [3]. The behaviour of degradation and regeneration are influenced by light intensity and temperature, but the root cause (i.e. the underlying defect) in mc-Si PERC solar cells is still unknown. Efforts to study the parameters influencing the degradation and regeneration process mainly use solar cells or even solar modules, while investigations on lifetime samples are still rare. Lifetime samples with different surface passivations were studied by Kersten *et al.* [3] and were shown to degrade, whereas Krauss *et al.* [4] employed spatially resolved minority charge carrier lifetime maps to calculate a so-called effective defect lifetime, thereby mapping effective defects which are activated upon degradation. Still missing are good methods to make best use of the spatially and temporally resolved data from, *e.g.*, lifetime mapping techniques and to correlate the information given in these sets of data.

Lifetime samples are inherently more flexible with respect to experimental design when studying the influence of specific processing steps (*e.g.*, gettering and hydrogenation as well as high temperature steps) which might influence the degree and kinetics of LeTID and regeneration. In this contribution we concentrate on three differently processed lifetime samples and study the effects visible during illumination at moderate temperature. This allows to draw conclusions and to shed more light on the underlying mechanisms for LeTID and the following regeneration in mc-Si.

2. EXPERIMENTAL

We investigate an industrially produced mc-Si PERC solar cell and several lifetime samples to compare the degradation and regeneration process on solar cell and lifetime level. Using the solar cell allows us to link and compare the results to previous studies on the LeTID effect, while the differently processed lifetime samples are intended to identify process steps that influence the degradation and regeneration behaviour of mc-Si material.

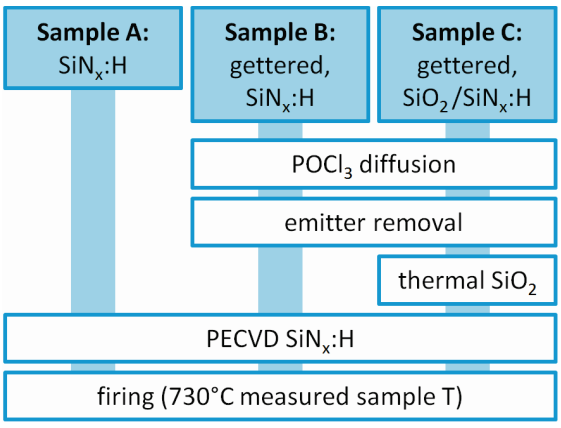

Figure 1: Process sequence of the investigated lifetime samples.

Both the wafers used for the lifetime samples (5x5 cm^2) and the investigated industrial mc-Si PERC solar cell (15.6x15.6 cm^2) originate from the same height of the same mc-Si ingot (1.5 Ωcm boron doped) and therefore have a comparable initial material quality. The lifetime samples - fabricated from sister wafers, thus having comparable grain and defect structure - were used to compare the influence of different process steps on the degradation and regeneration behaviour. A scheme of the applied process sequences is given in Fig. 1. Saw damage was removed by chemical etching. Samples B and C were gettered by a $POCl_3$ diffusion (55 Ω/□) and the emitter

was subsequently removed by chemical etching. Both sample A (ungettered) and sample B (gettered) received a surface passivation by a PECVD (plasma-enhanced chemical vapour deposition) SiN_x:H layer, while sample C was passivated by a stack of thermal SiO_2 (6 nm) and a PECVD SiN_x:H layer. Firing was done in a belt furnace with a measured peak wafer temperature of 730°C.

For degradation, lifetime samples as well as the solar cell are held at a temperature of approx. 75°C under illumination with halogen lamps (0.9±0.05 suns for lifetime samples, 1±0.05 sun for the solar cell). During the degradation and regeneration process the solar cell is characterized *in situ* by automated V_{oc} measurements. For lifetime samples, the effective minority charge carrier lifetime τ_{eff} is measured repeatedly by the fast and self-calibrated TR-PLI (time resolved photoluminescence imaging) method [5, 6] at room temperature, resulting in a series of spatially resolved lifetime maps for each sample over degradation time.

3. DATA ANALYSES AND RESULTS

The *in-situ* V_{oc} measurements for the solar cell are shown relative to the starting value in Fig. 2. It is obvious that this PERC solar cell is LeTID sensitive and the V_{oc} data shows a degradation of approx. $12\%_{rel}$ after 200 h followed by regeneration as also observed previously, *e.g.*, in [3]. Data acquisition for the solar cell as well as the lifetime samples continues and we assume that the solar cell will recover further.

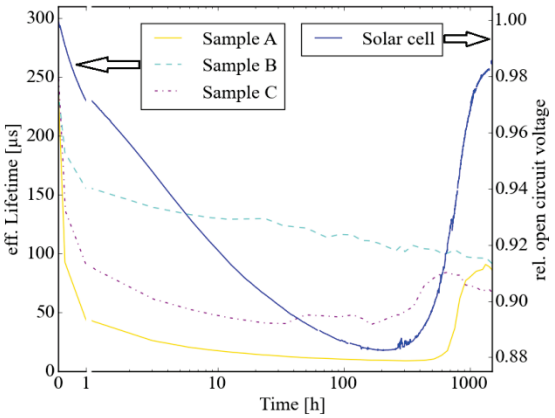

Figure 2: Left axis: harmonic average of τ_{eff} data for three differently processed mc-Si wafers (5x5 cm²). The strong influence of processing steps on the degradation and regeneration behaviour is clearly visible.
Right axis: continuously measured V_{OC} data (shown relative to starting value) of an industrial mc-Si PERC solar cell showing degradation and beginning regeneration (first 1 h: linear scale, afterwards: log scale).

Fig. 2 also shows the temporal evolution of τ_{eff} (plotted is the harmonic average of the entire effective lifetime map for each point in the time series) for the three different lifetime sister samples A, B, and C. The strong influence of processing steps on the degradation and regeneration behaviour is clearly visible. Within the first minutes a fast degradation is observed for all samples, which could be attributed to FeB- and/or BO-based degradation effects. After longer periods, significant differences are measured for samples A, B, and C regarding the strength of degradation, the range of minimum and maximum τ_{eff} in dependence of the degradation state, and the regeneration behaviour which can be clearly observed for sample A and C. Sample A (ungettered) shows the strongest degradation but also the strongest regeneration. In case of the P-gettered sample B the degradation is strongly reduced and no degradation minimum is observed up to now. In contrast to sample B, the surface passivation of sample C is realized by firing a stack of thermal SiO_2 and SiN_x:H, leading to significant differences in degradation and regeneration behaviour. Overall degradation and regeneration behaviour is closer to the ungettered sample A than to sample B. Sample C shows also a clear maximum degradation and the regeneration sets in even earlier than in case of sample A.

A comparison to the degradation behaviour of the solar cell shows that the maximum degradation level for τ_{eff} in case of lifetime samples and the V_{oc} value in case of the solar cell is reached after approximately the same range of degradation time using the same illumination level and elevated temperature. This leads to the assumption that the underlying degradation and regeneration effect can be studied either on lifetime or on solar cell level. This is an interesting finding as injection levels for a given generation should be different for lifetime samples (with very good surface passivation) and solar cells (with emitter and metalized fractions).

The material quality of mc-Si differs locally, *e.g.*, due to grain orientation, different dislocation densities or different contents and distributions of contaminations. If only the average τ_{eff} value is analyzed, local differences as visible in the TR-PLI measurements get lost.

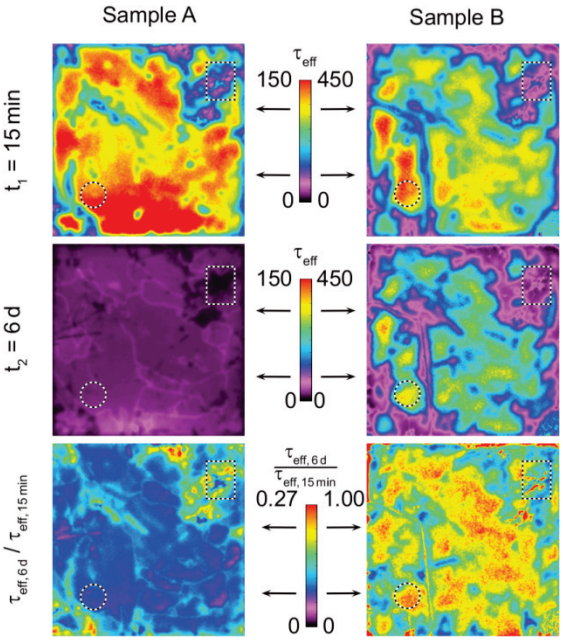

Figure 3: TR-PLI measurement of differently processed sister wafers A (ungettered) and B (gettered) after 15 min and 6 d at 75°C and under illumination (1 sun), as well as calculated maps of relative lifetime changes ($\tau_{eff,6d}$ /$\tau_{eff,15min}$), clearly indicating the different strength of degradation. Note the different scaling for sample A and B!

To demonstrate the spatially resolved information of the TR-PLI maps, Fig. 3 shows lifetime images of sample A and B at the beginning of the degradation and at the point where maximum degradation occurs for sample A, as well as calculated maps of relative lifetime changes ($\tau_{eff,degraded}/\tau_{eff,initial}$).

In case of sample A the whole wafer area degrades strongly and leads to a lifetime reduction of at least 70%. The relative lifetime change is lower in regions of lower initial lifetime as indicated by a striped box in Fig. 3 (approx. 80%) than in areas of higher initial material quality as indicated by a striped circle in Fig. 3 (approx. 90%).

If these two indicated areas of higher (circle) and lower (box) initial lifetimes are compared to the corresponding wafer regions of the gettered sample B, a different behaviour is observed. The overall degradation of the gettered sample B is much lower as already discussed for the harmonic average τ_{eff} (Fig. 2). Areas of high initial lifetime now show only a relatively weak degradation of approx. 0-15%, while areas of lower initial lifetime degrade by approx 50%.

A more detailed correlation of degradation behaviour in different sample areas and local defect structure is currently underway.

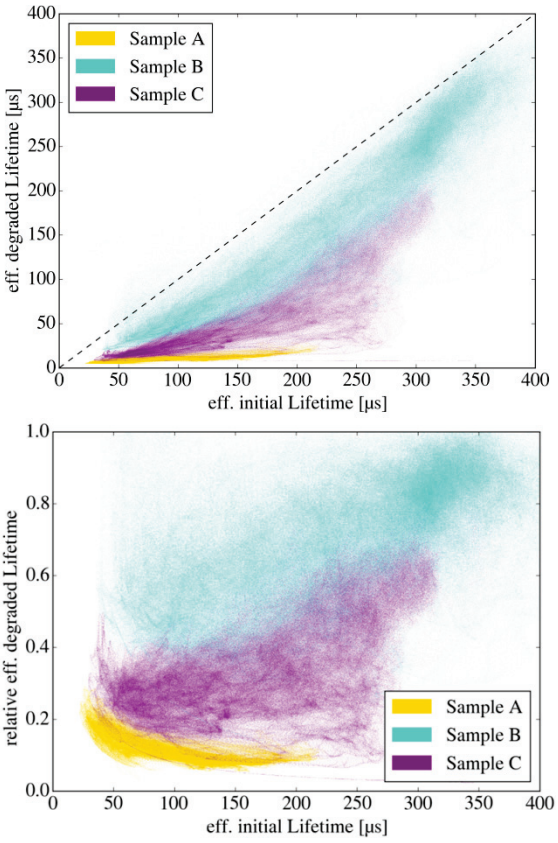

Figure 4: τ_{eff} at maximum degradation and relative τ_{eff} compared to the initial τ_{eff} for each single data point of TR-PLI maps of the different processed sister wafers A, B, and C. The strongly different influences of the applied process steps can be observed.

In Fig. 4 degraded τ_{eff} (top) as well as relative degraded τ_{eff} relative to initial τ_{eff} (bottom) for each single data point of the TR-PLI map is plotted over initial τ_{eff} for each of the differently processed sister samples A, B, and C. As also discussed for Fig. 2, sample A shows the strongest degradation over the whole sample area, while the strength of degradation is significantly reduced for all areas of the gettered sample B. An additional high temperature step (thermal oxidation after P-gettering) like in case of sample C passivated by firing of a stack of thermal SiO_2 and SiN_x:H leads to a stronger degradation over the whole sample compared to the also P-gettered sample B without thermal oxidation. The interpretation in context of Fig. 3, that the relative impact of degradation is stronger in areas of higher initial τ_{eff} in case of sample A and much lower in case of sample B, holds also true analyzing the whole sample as shown in Fig. 4 (bottom) and not only chosen sample areas as discussed for Fig. 3.

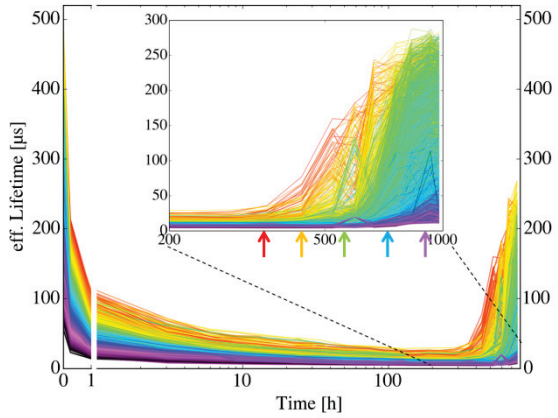

Figure 5: τ_{eff} of the ungettered sample A (first 1 h: linear scale, afterwards: log scale). Each line in the graph represents an area of 150x150 µm² in the spatially resolved TR-PLI lifetime measurements and each colour is chosen according to this areas lifetime value at the beginning of degradation. The inset highlights the different regeneration behaviour. The regeneration process starts significantly earlier in areas with higher initial τ_{eff} (red lines) than in areas of lower initial τ_{eff}, as indicated by the differently coloured arrows.

Fig. 5 shows the behaviour of τ_{eff} for sample A. Each single line represents a small area on the lifetime samples as described in the image caption. The whole ungettered sample A shows a very strong and fast degradation, as already discussed for other analysis methods above. The areas of higher initial τ_{eff} suffer more from the applied degradation conditions, and relative degradation in these areas is stronger than in sample areas with lower initial τ_{eff}. That even areas of initially high τ_{eff} exhibit such strong degradation could be explained by assuming an approximately homogenous formation of defects over the wafer area (see [7] and [8] for more details).

The effective lifetime distribution of sample A initially is very wide (approx. 20–350 µs), but shrinks down to a very narrow distribution (approx. 5–30 µs) at maximum degradation level. The maximum degradation level is reached approximately at the same illumination time for the whole sample, independently of the initial τ_{eff}. After about 300 h of illumination a regeneration process sets in, with regeneration in areas with higher initial τ_{eff} (red lines) starting significantly earlier than in areas of lower initial τ_{eff}. This behaviour is indicated in

Fig. 5 by coloured arrows representing the starting point of regeneration for different initial lifetimes. That the starting points for observable regeneration should be so different is remarkable, especially considering the very narrow τ_{eff} distribution at maximum degradation level. These differences in regeneration behaviour lead to the assumption that regeneration is not just a reversal of the first degradation reaction and that the underlying mechanism is more complex. It is not yet known whether τ_{eff} will recover its initial value. However, we currently assume that a decrease of the surface passivation quality during the degradation process of several hundred hours limits the maximum level of regeneration in case of sample A. The experiment is still running to complete the data set.

In case of sample C it is also observed that the regeneration starts earlier in sample areas of higher initial lifetime (not shown).

This indicates that the injection level might play a role in regeneration kinetics, as under homogeneous illumination injection is higher in regions of higher lifetime. This was also reported for investigations on solar cell level [3] and resembles qualitatively the behaviour also known for regeneration of BO-related defects [9].

4. SUMMARY AND OUTLOOK

Spatially resolved LeTID and regeneration was studied in mc-Si material. It could be shown that the behaviour of average τ_{eff} values in lifetime samples qualitatively resembles the behaviour of an industrial PERC solar cell processed from mc-Si of comparable quality.

Ungettered mc-Si material shows a severe degradation effect, followed by a distinct regeneration phase. In an ungettered sample, relative degradation is higher in initially good quality areas. This trend changes for gettered samples, although on a much higher lifetime level. In gettered samples relative degradation is stronger in areas of poor initial quality (most probably areas of higher density of extended defects like grain boundaries, dislocations, precipitates).

Point-to-point (or area-to-area) correlations of lifetime maps gained from TR-PLI allow for a detailed analysis of factors influencing degradation and regeneration kinetics which is not possible when only analyzing average lifetime or solar cell parameter values.

The timescale for LeTID and regeneration is rather long, and the described experiments are still running to check especially for the following regeneration behaviour.

5. ACKNOWLEDGEMENTS

Part of this work was funded by the German BMWi under contract numbers 0325581 and 0325763B. The content of the publication is the responsibility of the authors. The authors would like to thank Axel Herguth, Lisa Mahlstaedt and Barbara Rettenmaier for their assistance with this study.

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