# Investigation of LeTID Where We Can Control It – Application of FZ Silicon for Defect Studies

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**Abstract.** In this work we present results of a series of experiments to investigate the origin of the defects causing light and elevated temperature induced degradation (LeTID). It has been demonstrated that LeTID effects can be observed even in high purity monocrystalline silicon. The experiments are therefore performed on float-zone silicon and feature a variety of process schemes to test important hypotheses on LeTID and reproduce them under more defined conditions. Different surface passivation schemes based on aluminium oxide layers are combined with a designated hydrogenation treatment and subjected to different thermal processes on both p- and n-type wafers. The results on p-type wafers confirm several previous observations concerning, e.g., the influence of silicon nitride layers and the firing peak temperature. However, we do not observe a crucial influence of the specific firing temperature profile in the experiment. The investigated n-type wafers do not feature a typical LeTID behaviour but appear to be affected by the LeTID defect nonetheless. Firstly, we observe an improvement of the effective lifetime under LeTID testing conditions that is driven by an improvement of the bulk lifetime. Secondly, identical pattern are observed in lifetime images of n-type wafers directly after firing and of p-type wafers in the degraded state. These findings strongly indicate that LeTID defects can be present in the initial state of n-type wafers after firing.

# **INTRODUCTION**

Module operation conditions of illumination and elevated temperature can cause degradation of bulk charge carrier lifetimes. This effect is referred to as light and elevated temperature induced degradation (LeTID) and has been observed in silicon wafers grown by various methods, i.e. float-zone (FZ), Czochralski pulling (Cz) and directional solidification (mc) [1–6]. The origin of this defect is still under debate and further investigations are crucial to identify it. It is a key question whether the defect is introduced during sample processing and thus the same in all material types or whether a – yet unknown – interaction with grown-in defect precursors occurs. For comparable sample processing and degradation testing conditions various research groups have observed a similar and specific LeTID behaviour in the different material types. We therefore expect that the underlying defects of the degradation phenomena are the same or at least of similar nature. We regard FZ silicon wafers to be the most defined environment for defect studies because of the inherently low impurity concentrations. Therefore observation of LeTID in this material renders an involvement of e.g. metal contamination in the defect unlikely, while involvement of intrinsic defects (such as silicon interstitials or lattice vacancies) appear more conclusive. In order to test hypotheses derived from experiments in literature we use FZ silicon in this study, revealing further insight into the mechanisms behind LeTID.

## **EXPERIMENT**

FZ silicon wafers of both p- and n-type doping featuring a resistivity of 1  $\Omega$ cm, 4" diameter and a thickness of 250 µm (p-type) and 200 µm (n-type) were investigated in this study. All samples underwent an oxidation at 1050 °C and subsequent etch-back of the oxide layers before the experiment to deactivate potentially pre-existing defects in the FZ wafers [7]. After wet chemical cleaning, a part of the samples was subjected to an annealing under hydrogen plasma at 500 °C to introduce additional hydrogen to the wafer bulk. All wafers were passivated by Al<sub>2</sub>O<sub>3</sub> layers of 10 nm thickness deposited via atomic layer deposition (ALD) in an Oxford Instruments OpAL reactor at 180 °C on both wafer sides. Some samples received a 100 nm thick a-SiNx capping layer on top of the Al<sub>2</sub>O<sub>3</sub> deposited in an industrial PECVD reactor. To study the effect of different temperature profiles on LeTID the passivated samples were either subjected to "fast firing" in an industrial belt firing furnace (FFO) or "slower" profiles in a rapid thermal processing (RTP) furnace. For an optimum comparability with previous studies the used temperature profiles were optimized to agree with the profiles shown in [8] with measured peak sample temperatures of 800 °C (RTP) and 785 °C (FFO). It has been shown in [8] that these firing profiles cause pronounced (FFO) or negligible (RTP) LeTID in mc silicon samples with a similar surface passivation stack as the one used in this study. The process sequences are also illustrated in the legend of Fig. 1.

LeTID testing was performed under conditions used in many studies from literature to support comparability: the samples were subjected to 1 sun equivalent halogen lamp illumination (spectrum roughly corresponding to 3200 K black body radiation) while positioned on a hotplate, resulting in a sample temperature range of 75-80 °C. Throughout the experiment, effective carrier lifetimes  $\tau_{eff}$  were measured with a WCT-120 Sinton Instruments Lifetime Tester<sup>TM</sup> in transient mode evaluated at a minority charge carrier density (MCD) of  $2 \cdot 10^{14}$  cm<sup>-3</sup>. This MCD was chosen to ensure reasonable sensitivity to the degradation in our experiment due to the strong injection dependency of  $\tau_{eff}$  introduced by LeTID defects. It should be noted that the extracted effective lifetimes can only qualitatively be compared to evaluations in literature that were performed at other injection densities. Photoluminescence imaging (PLI) was performed at most time steps and at various intensities to track lateral effects and the amount of surface damage caused by the repeated sample handling.



FIGURE 1. Lifetime progression of various FZ samples under LeTID testing conditions (75 °C, 1 sun equivalent illumination).

#### RESULTS

Figure 1 shows examples for the evolution of  $\tau_{eff}$  during LeTID testing on a variety of differently processed samples, as indicated in the figure legend. In accordance to literature we observe that samples passivated with just

 $Al_2O_3$  provide reasonable initial  $\tau_{eff}$  even after firing for both p- and n-type. In previous studies we have observed that samples with the same passivation layers showed higher  $\tau_{eff}$  when they were subjected to an annealing in forming gas instead of a firing step, indicating a suboptimal passivation performance of the samples shown here. The fired samples exhibit a good stability over time during LeTID testing. It should be noted that the  $\tau_{eff}$  are still higher than observed in most LeTID studies performed on mc or Cz silicon and that thus the mostly unchanged  $\tau_{eff}$  indicates the absence of the degradation in these samples. PLI of samples passivated with just  $Al_2O_3$  does not show noticeable structures but reveals a growing number of features related to sample handling, c.f. Fig.2.

P-type samples featuring a-SiN<sub>x</sub> layers feature mediocre  $\tau_{eff}$  after firing and a significant degradation when subjected to LeTID testing. This is in good agreement with literature results suggesting that the presence of a-SiN<sub>x</sub> layers during firing support the occurrence of LeTID, e.g. [9,10]. After the degradation we observe a quick  $\tau_{eff}$  recovery that exceeds the initial value. Contrary to the results of *Eberle* et al. [8] for mc silicon we observe that significant LeTID also occurs when p-type FZ silicon wafers featuring a-SiN<sub>x</sub> layers are subjected to RTP firing processes (i.e. slower temperature ramps than for industrial FFO processes, results not shown in Fig. 1).

Contrary to the p-type samples, we observe the lowest lifetime in n-type wafers featuring  $a-SiN_x$  layers in the initial state after firing. Lifetimes increase with time under LeTID testing conditions.

We can confirm the strong influence of the firing step observed in mc (e.g. [8,11]) to recur in FZ: PLI on FFO fired p-type samples in the degraded lifetime state exhibit a zig zag pattern (see Fig.2) that reflects the slight temperature variations caused by contact to the furnace belt during FFO firing. The pattern appears upon activation of the bulk defects and disappears with their subsequent deactivation. In n-type wafers this pattern is observed in the initial state and disappears during the subsequent lifetime recovery under LeTID testing conditions.



FIGURE 2. Photoluminescence images recorded at different time steps along the degradation under laser illumination intensity of 1 sun equivalent, the frame colour refers to the symbol colours in Fig. 1 (blue: n-type, orange and red: p-type). The image brightness indicates the PL intensity, which is adjusted individually for each sample.

# DISCUSSION AND CONCLUSION

It was already mentioned in the previous section that our experiments on p-type reproduce several findings from literature gathered on mc and Cz silicon. This section therefore focuses on the results that do not directly agree with expectations and especially on the results on the n-type wafers.

We did not observe a qualitative change in the occurrence or magnitude of LeTID when samples underwent the remote hydrogen plasma treatment on neither p- nor n-type. This finding would contradict the suggested role of hydrogen in LeTID if the hydrogen content in the wafer bulk was significantly increased by the process. However, we have performed numerical estimations of the process based on considerations of *Voronkov* et al. [12] and have found that only minute concentrations of additional hydrogen might have been introduced during the specific process we have performed. We plan to repeat the experiment with an optimized temperature profile in the future.

Interestingly, the  $\tau_{eff}$  progression of the fired n-type samples with  $a-SiN_x$  in our experiment is fundamentally different than reported in literature. There are not many reports of LeTID studies in n-type silicon and if so they usually report rather slight lifetime degradation, e.g. [5,13]. We find a progressing improvement of  $\tau_{eff}$  during LeTID testing (see Fig.1). We have observed this behaviour on similar samples in a previous study but did not discuss it in detail [14]. We believe this significant increase in  $\tau_{eff}$  is caused by the deactivation of bulk defects that are already present after firing. These defects might well be the same that cause LeTID in p-type silicon. We have three indications for this hypothesis:

- I) The FFO fired n-type samples feature the furnace belt structure observed in p-type samples in degraded state, as indicated in Fig.3 by red marks. The pattern disappears during the improvement of the sample, as can be seen in Fig.2.
- II) Most LeTID affected p-type samples we have investigated recover to a higher  $\tau_{eff}$  level than they had in initial state, indicating the presence of active defects directly after firing. It appears reasonable that n-type samples would be similarly affected after the same processes.
- III) We observe a faint and fine striation pattern on the n-type samples in initial state (see blue indications in Fig. 3) that resembles the pattern reported in our previous study on LeTID in FZ silicon [3]. Similar patterns occur in our degraded p-type wafers and are likely related to the distribution of a defect precursor species involved in LeTID whose concentration is sensitive to slight process oscillations during crystal growth.

Findings I) and II) would agree with the reasonable assumption that the used Al<sub>2</sub>O<sub>3</sub> passivation layer is damaged during firing and slowly recovers. However, a  $J_0$  evaluation of the measurements showed mostly stable surface recombination throughout the experiment and conjunction with finding III) indicates that the observed  $\tau_{eff}$  progression is indeed caused by the reduction of recombination via bulk defects.



FIGURE 3. Photoluminescence image taken at 0.5 sun equivalents of an n-type FZ wafer with an  $Al_2O_3/a$ -SiN<sub>x</sub> passivation stack directly after firing. Two distinct features are visible on the wafer (indicated in blue and red).

To illustrate the different behaviour of the p- and n-type samples Fig.4 shows a comparison of the relative recombination rate change in two samples during the LeTID testing. The inverse of  $\tau_{eff}$  is a direct measure for the total recombination rate in the sample and we subtract the initial rate and normalise the result to assess the relative change over time. This quantity bears resemblance with normalized defect concentrations used by other authors. Similar to plotting the normalized defect concentration, the quantitative expressiveness of referring to the initial state is limited when lifetime *improves* during the process. However, Fig.4 demonstrates nicely what sometimes gets lost in lifetime and in normalized defect representation: both samples reach a significantly better state after the extended LeTID testing. The overall recombination rate reduced by more than 50% in both samples compared with the initial state. This overall improvement indicates that more defects – or more general: recombination active sites – were deactivated during LeTID treatment than were activated, implying that active defects were present in initial state, i.e. after firing but before being subjected to illumination at elevated temperature.



FIGURE 4. Temporal progression of the relative recombination change of one p- and one n-type FZ silicon wafer passivated with an  $Al_2O_3/a$ -SiN<sub>x</sub> passivation stack during LeTID testing after firing. The p-type sample (red) goes through the typical degradation-regeneration cycle expected for a sample prone to LeTID. Both wafers show an overall improvement upon extended testing indicating that defects were active in the initial state and then deactivated during LeTID testing.

The absence of a detectable degradation in the n-type samples is remarkable. This is in contrast to the observation for p-type FZ silicon samples, where defects are being activated and subsequently deactivated in a typical LeTID manifestation. We have identified three different explanations for this observation:

1.) It indicates that no inactive defect precursors are left after firing in our n-type samples (i.e. all of them are in active configuration). Then, the higher initial lifetime of the n-type samples would indicate the defects to be less recombination active in n-type silicon than in p-type silicon. This would be in agreement with the observation that LeTID studies on n-type material have often reported rather insignificant lifetime changes.

2.) The LeTID testing conditions do not facilitate the activation of inactive defect precursors in our n-type FZ silicon samples. This could be due to kinetic effects and/or a consequence of Fermi level position, indicating involvement of species whose charge state is different in n- and p-type samples. A manifest explanation is the involvement of hydrogen in the LeTID defect reaction – which would be in line with several other observations and hypotheses in recent years, e.g. [13]. It would also provide a line of reasoning to explain the differences between our observations and experiments of e.g. *Chen* et al. on samples with diffused regions or LeTID activation via dark annealing [5,6,13,13].

3.) The observed lifetime changes of our p- and n-type samples are caused by different defects than those causing LeTID in mc and Cz silicon. Given the series of similarities between our observations on FZ silicon that are especially pronounced on p-type wafers we do not regard this a likely explanation but still need to consider it. For more discussion see our previous contribution to this topic [2].

All three explanations open interesting pathways for future research and can hopefully be elucidated by experiments. The same is true for the observed ring pattern and the uncommon recovery kinetic. Thus we can summarise that the LeTID experiments on FZ silicon have independently confirmed several observations from mc and Cz silicon under more defined conditions. Due to the high purity of the material we have made interesting observations that might have been missed or discarded on less pure material – e.g. due to a superposition with effects of e.g. oxide precipitates, or iron or other metal contaminations and – of course – boron oxygen defects.

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