

Evidence of Rear Surface related Degradation in Cz-Si PERC-type Solar Cells

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Abstract — A degradation phenomenon of unknown origin during illuminated annealing is observed for boron-doped PERC-type solar cells with $\text{SiO}_x/\text{SiN}_x:\text{H}$ rear surface passivation. By collating different measurement techniques and device simulations, the rear surface passivation is identified as the component responsible for the observed degradation.

Index Terms — silicon solar cell, PERC-type, degradation, surface passivation, surface related degradation.

I. INTRODUCTION

The efficiency potential of p-type PERC (passivated emitter and rear concept) solar cells surpasses that of conventional full area Al alloyed cells due to its better rear side passivation. As the additional process complexity comes down to higher costs per cell, this advantage only pays off from an economic point of view if the excess charge carrier lifetime in the bulk is sufficiently high so that rear side passivation becomes the most limiting factor.

However, Sperber et al. have shown recently [1,2] that the surface passivation quality of $\text{SiN}_x:\text{H}$ based passivation layers and stacks, including explicitly $\text{SiO}_x/\text{SiN}_x:\text{H}$ and $\text{AlO}_x/\text{SiN}_x:\text{H}$ passivation stacks commonly used in PERC-type solar cells, can be subject to severe deterioration under illumination at temperatures as low as 60°C on lifetime samples. Even though the time scale of this Surface related Degradation (SRD) reported by Sperber et al. is with hundreds to thousands of hours (1000 h correspond to approximately 42 days) of continued illumination comparably long for lab-type studies, it is on a reasonable time scale to affect solar panels in the field with a life span of 30 years or more. Sperber et al. also suspect that there is no reason to believe that this degradation phenomenon will spare solar cells.

Indeed, a long-term degradation of unknown origin was found in boron-doped Cz-Si PERC-type solar cells with $\text{SiO}_x/\text{SiN}_x:\text{H}$ rear side passivation during illuminated annealing (150°C , 1 sun). Even though these conditions seem a bit extreme compared to field conditions, the same effect was found for lower temperatures as well, however, the time scale is uncomfortably long and the used 150°C accelerate the degradation process drastically, simplifying the experiments. Fig. 1 shows the temporal evolution of V_{oc} and j_{sc} of two sister samples. The first minimum in V_{oc} and j_{sc} is related to boron-oxygen related light-induced degradation [3,4] and regeneration [5] which was to be expected for this kind of material. Then, however, both V_{oc} and j_{sc} drop for a second time, finally causing V_{oc} and j_{sc} related efficiency losses of $\sim 1\%_{\text{abs}}$. Interestingly, both V_{oc} and j_{sc} begin to recover again

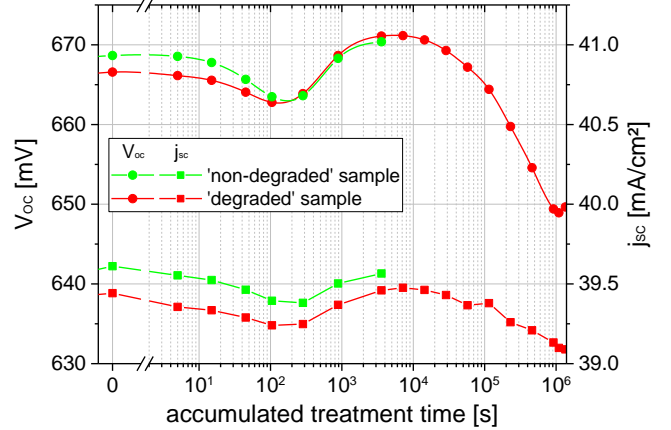


Fig. 1. V_{oc} and j_{sc} during illuminated annealing process at 150°C and 1 sun equivalent illumination.

(not visible in Fig. 1). As this second recovery happens on a time scale of months under these extreme conditions, this would probably take years or decades under field conditions.

In the following, the origin of this second drop (and subsequent recovery) of both V_{oc} and j_{sc} is investigated by a combination of different measurement techniques and device simulations.

II. EXPERIMENTAL SETUP

Two sister samples were treated at 150°C and 1 sun illumination (incandescent lamps, current-equivalent [6]). The treatment of the “non-degraded” sample (green) was stopped as it reached the intermediate maximum just before the second drop begins. The “degraded” sample (red) was treated alike until it reached the minimum after the second drop.

For both samples, not only $j(V)$ characteristics were taken (Fig. 1), but also wavelength-dependent external/internal quantum efficiency data $EQE(\lambda)/IQE(\lambda)$ were collected. In addition, parts of both samples were etched back and wet-chemically re-passivated with iodine-ethanol solution [7] after they reached their final state in order to assess bulk lifetime.

III. ANALYSIS

In principle, the loss in both V_{oc} and j_{sc} may originate from a deterioration of several cell components. A more detailed analysis can be found in [8]. The two-diode model

$$j(V) = j_{01} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] + j_{02} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] + j_{sc} \quad (1)$$

can be used to estimate V_{oc} under the condition $j(V_{oc}) = 0$. Hence V_{oc} depends on the diode's saturation current densities j_{01} and j_{02} as well as on j_{sc} . The change in V_{oc} with j_{sc} is in the range of ~ 1 mV/(mA/cm²), thus the observed loss in j_{sc} of ~ 0.4 mA/cm² can by far not explain the loss in V_{oc} . A severe deterioration of j_{02} can be excluded from Suns- V_{oc} measurements showing a pseudo-fill factor which remains more or less unchanged during the observed degradation of V_{oc} and j_{sc} . By exclusion, the observed degradation should be linked to a deterioration of j_{01} which can be broken down into an emitter saturation current density j_{0e} and a base saturation current density j_{0b} : $j_{01} = j_{0e} + j_{0b}$. As discussed in [8] in more detail, a deterioration of j_{0e} can be excluded by short wavelength $QE(\lambda)$ measurements as well. The base saturation current density j_{0b} may be described by that of a finite diode [9]:

$$j_{0b} = \frac{qn_i^2 D}{N_{dop} L} \times F \quad (2)$$

especially depending on diffusion length L and a geometry factor F which deviates from unity if the diffusion length is of the order of the cell thickness w because then rear surface recombination velocity SRV becomes important.

$$F = \frac{SRV \cdot \cosh(w/L) + D/L \cdot \sinh(w/L)}{D/L \cdot \cosh(w/L) + SRV \cdot \sinh(w/L)} \quad (3)$$

Hence a degradation of j_{0b} can result from both a deterioration of diffusion length $L = (D\tau)^{1/2}$ (and thus bulk lifetime τ) and/or rear surface recombination velocity SRV .

Figure 2 shows a simulation of V_{oc} in dependence of bulk lifetime and rear surface recombination velocity assuming a j_{02} of 15 nA/cm² and a j_{0e} of 75 nA/cm². The observed non-degraded and degraded V_{oc} (highlighted contours in Fig. 2) indicate a certain relation of rear SRV and bulk lifetime required for the respective V_{oc} level. During the observed degradation of V_{oc} , either rear SRV or bulk lifetime or both parameters have to change. From the analysis of V_{oc} alone, it can neither be concluded what the initial and final values of bulk lifetime and rear SRV are nor what parameters changes.

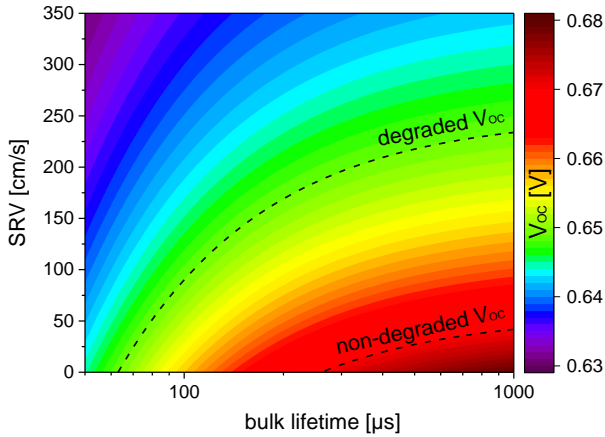


Fig. 2. Contour plot of open circuit voltage V_{oc} in dependence of bulk lifetime and rear surface recombination velocity (SRV). Contours of non-degraded (~ 670 mV) and degraded (~ 649 mV) V_{oc} are highlighted.

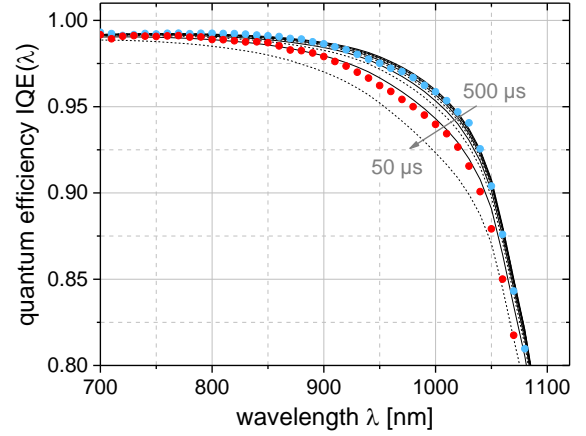


Fig. 3. Long wavelength $IQE(\lambda)$ vs. wavelength λ at the intermediate maximum (blue data) and in the second minimum (red data). In addition, simulation results are shown assuming a deterioration of bulk lifetime.

In order to pin the origin of the V_{oc} and j_{sc} losses, $IQE(\lambda)$ curves measured at the intermediate maximum and in the minimum of the second drop were compared.

Fig. 3 shows the measurement of the long wavelength $IQE(\lambda)$ in the non-degraded and degraded state together with the simulation results, in which bulk lifetime was varied from 50 to 500 μs (in steps of 50 μs). There is a difference between the IQE measured at the intermediate maximum (blue) and in the second minimum (red) in the range above 900 nm. It appears as if the measured data resemble the simulated 100 μs (better ~ 80 μs) curve which suggests a degradation of V_{oc} in Fig. 2 along a horizontal cut with SRV smaller than 50 cm/s.

However, bulk lifetime and rear SRV are so closely correlated in the geometry factor F (Eq. 3) that the same effect can be reproduced by a variation of rear SRV as well. Fig. 4 shows the same measured $IQE(\lambda)$ data as in Fig. 3, but this time together with simulation results with varying rear SRV from 25 to 300 cm/s instead of bulk lifetime (bulk lifetime fixed to 500 μs). As can be seen, a deterioration of rear SRV to ~ 200 cm/s could reproduce the observed change as well.

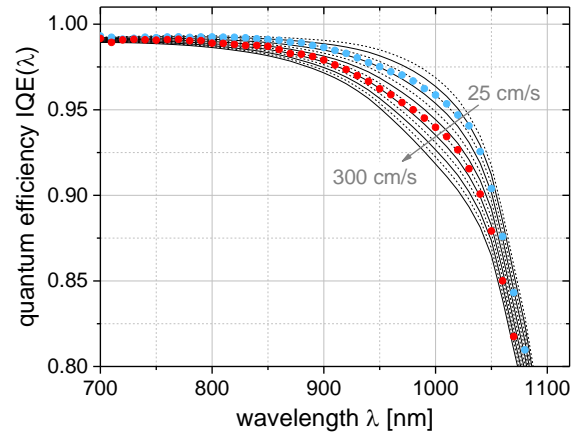


Fig. 4. Long wavelength $IQE(\lambda)$ vs. wavelength λ at the intermediate maximum (blue data) and in the second minimum (red data). In addition, simulation results are shown assuming a deterioration of rear surface recombination velocity (SRV).

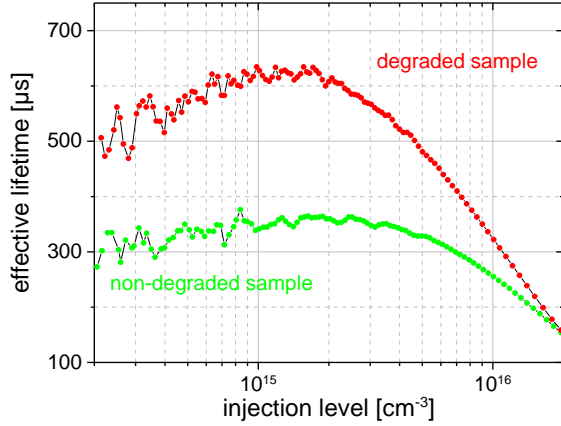


Fig. 5. Effective lifetime measured by a photoconductance decay technique after wet-chemical re-passivation of a sub-sample of the samples shown in Fig. 1 in their final stage.

Hence, taking only $j(V)$ and $IQE(\lambda)$ data into account, one cannot reliably distinguish between a degradation of bulk lifetime and a deterioration of rear SRV .

In order to clarify whether bulk lifetime degraded or not, parts of the green and red sample in Fig. 1 were etched back, cleaned and wet-chemically re-passivated. Effective lifetime was measured by a photoconductance decay technique [10] directly after re-passivation. Fig. 5 shows the results from one sub-sample each. As can be seen, bulk lifetime is not that limited as one might have expected from Fig. 3. The device simulations suggested a degraded bulk lifetime of $\sim 80 \mu\text{s}$ in order to consistently explain the observed losses. Contrary, measured effective lifetime (a lower limit of bulk lifetime as surface passivation limits the effective lifetime as well) exceeds with more than $300 \mu\text{s}$ the expected $\sim 80 \mu\text{s}$ by far. Thus degradation of bulk lifetime can be excluded as origin of the second drop in Fig. 1.

A closer look at Fig. 5 reveals that the effective lifetimes measured on the degraded sub-sample exceed even $600 \mu\text{s}$. This makes perfect sense as the development of the non-degraded sample in Fig. 1 (green) was stopped at the intermediate maximum resulting from the upward trend of the regeneration of boron-oxygen related light-induced degradation and the downward trend of the second drop. Most likely, regeneration of boron-oxygen related degradation was not complete and bulk lifetime would have continued to increase. In contrast, the degraded sample from Fig. 1 (red) probably had enough time so that bulk lifetime recovered completely from boron-oxygen related degradation and the red lifetime data in Fig. 5 show the background limitation of the material.

As all results point towards a deterioration of rear SRV , as suspected by Sperber et al. [1,2], a comparative experiment with a Cz-Si lifetime sample passivated by a $\text{SiO}_x/\text{SiN}_x:\text{H}$ stack was done. The same treatment conditions as for the solar cells in Fig. 1 were chosen, meaning 150°C and 1 sun illumination. The result of this experiment is shown in Fig. 6. The lifetime sample shows two degradation phenomena. The first one is also related to boron-oxygen related degradation.

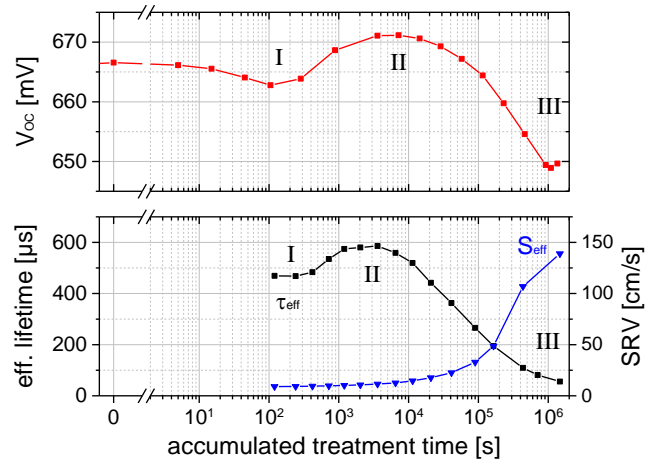


Fig. 6. Comparison of the V_{oc} data from Fig. 1 (top) and lifetime data from a Cz-Si lifetime sample with $\text{SiO}_x/\text{SiN}_x:\text{H}$ passivation stack (bottom).

The second drop in lifetime is related to a degradation of surface passivation quality as can be seen from the increase in SRV . Even though the passivation stacks of the solar cells and the lifetime samples might not be identical due to different deposition parameters and probably different firing conditions and even though the injection level during illuminated annealing might be different, the time scale and extent of the second drop of both sample types resemble each other.

IV. CONCLUSIONS

It can be concluded that the origin of the second drop in V_{oc} and j_{sc} in Fig. 1 is related to a degradation of surface passivation quality on the rear side of the PERC-type solar cell with a $\text{SiO}_x/\text{SiN}_x:\text{H}$ stack and that the results of Sperber et al. [1,2] on lifetime level are indeed transferable to PERC-type solar cells.

Hence, this proves that PERC-type solar cells can be prone to an additional degradation effect, besides the known effects of boron-oxygen related light-induced degradation (BO-LID) [3,4] and light and elevated temperature induced degradation (LeTID) [11,12]. This Surface Related Degradation (SRD) probably occurs on an extremely long time scale and thus eludes detection by typical short-term degradation tests. Such a degradation could be a serious issue for the production of PERC-type solar cells.

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