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Understanding Light-Induced Degradation of c-Si Solar Cells

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***Abstract* — We discuss results of our investigations toward understanding bulk and surface components of light-induced degradation (LID) in low-Fe c-Si solar cells. The bulk effects, arising from boron-oxygen defects, are determined by comparing degradation of cell parameters and their thermal recovery, with that of the minority-carrier lifetime (τ) in sister wafers. We found that the recovery of τ in wafers takes a much longer annealing time compared to that of the cell. We also show that cells having SiN:H coating experience a surface degradation (ascribed to surface recombination). The surface LID is seen as an increase in the q/2kT component of the dark saturation current (J_{02}). The surface LID does not recover fully upon annealing and is attributed to degradation of the SiN:H-Si interface. This behavior is also exhibited by mc-Si cells that have very low oxygen content and do not show any bulk degradation.**

***Index Terms* — crystalline silicon, solar cells, light-induced degradation, minority-carrier lifetime, surface, bulk, annealing.**

I. Introduction

It is now well recognized that c-Si solar cells fabricated on Czochralski (CZ) wafers exhibit light-induced degradation (LID) of the cell performance [1,2]. This effect is generally ascribed to boron-oxygen (B-O) defects in the *wafer itself* — a defect complex that is formed by prolonged exposure of CZ wafers to light (via a carrier-induced recombination mechanism) and is accompanied by a reduction in the minority-carrier lifetime in the bulk of the wafer [3]. This degradation in lifetime of the *wafer* is thought to be fully recoverable upon annealing, which causes dissociation of the B-O complex [4].

The LID in solar cells has been studied by a rather small number of research groups, using relatively small sets of samples [5,6]. Consequently, there is a large diversity in the results reported in the literature, and the details of cell degradation and recovery mechanisms are sketchy. For example: i) Reported degradation in the efficiency of cells fabricated on the wafers of about the same resistivity ranges between 0.5 and 1.5% absolute [6]; ii) It is believed that LID can be fully recovered upon annealing [1,7]; iii) The temperature/time for recovery by thermal annealing, used by many researchers, is 200°C for 30 minutes.

One issue that has not been addressed to date is that a finished solar cell has a multilayer structure, and that it is also possible to have some degradation at the interfaces upon illumination. In particular, it is known that the SiN:H/Si interface has defects and a strong positive charge accumulation that can be affected by light [8]. Hence, LID is expected to have an interface/surface component, if ionization of this charge occurs or if there is an increase in the density of interface states, D_{it}.

We have investigated LID effects of solar cells fabricated on low-Fe substrates with the intention of separating bulk and surface effects. To observe the bulk effects, we have light soaked finished solar cells and their unprocessed sister wafers. We compared degradation of solar cell parameters with that of the minority-carrier lifetime measured on sister wafers of the solar cells. In this paper, we show the typical time-dependent behavior of solar cell parameters during light soaking, and the effect of thermal annealing. The surface effect is confirmed by comparing degradation between similarly processed mono- and multicrystalline cells. We are able to distinguish between fully recoverable and non-recoverable components of dark current. These data suggest that degradation related to B-O defects is fully recoverable in a cell (about 0.4% absolute in cell efficiency), whereas surface degradation (about 0.1% of cell efficiency) is not recovered. Interestingly, a partial recovery of the surface-phenomenon-related effect occurs if the light soaking is not complete.

II. Experimental Details

We carried out the experiments in three steps:

1. Studies on monocrystalline cells to determine kinetics of LID upon light soaking and its (partial) recovery upon annealing.
2. Minority-carrier lifetime studies to determine lifetime changes associated with the bulk of the wafer/cell.
3. Light-soaking effects on low-oxygen mc-Si cells to determine interface effects and compare them with monocrystalline cells.

To investigate the bulk and the surface effects in a systematic and statistically meaningful manner, we have performed LID studies on a large number (> 25) of 156 mm x 156 mm monocrystalline solar cells. The cells were fabricated on high-quality (minority-carrier lifetime between 300 and 350 μs) wafers, which have very low Fe content to minimize B-Fe effects. The resistivity of the p-type monocrystalline wafers was 1 to 2 Ω-cm. Cells were tested and soaked under

1-sun (at 25°C) for different periods of time and tested during the light exposure. Cell measurements included: illuminated and dark current-voltage (I-V) plots, spectral response, and light-beam-induced current (LBIC) mapping. Illuminated I-V measurements were done in two modes: in one case, the I-V measurements were done during the light soaking itself using a DC testing system (XT-10); in the other case, cells were removed from the light-soaking station and tested under a (Sinton) pulse tester. Dark I-V data were analyzed by software we have developed to determine J_{01} (q/kT component), J_{02} (q/2kT component), series resistance (R_s), and shunt resistance (R_{sh}). Cells were annealed, and in some cases, they were cycled through light soaking and annealing. Annealing was done at 200°C for 30 minutes following the procedure described in Ref. [9]. All the measurements were done to promote reliable determination of the small changes in the cell parameters that occur as a result of LID. In monocrystalline Si cells, the Fe concentration is typically quite low ($<10^{12}$), whereas the oxygen content is high (in CZ). Hence, the main effect of light is expected to be related to B-O.

In the following section, we will show our results of:

1. Degradation of cell parameters as a function of time under 1-sun illumination at 25°C.
2. Changes in the illuminated and dark I-V characteristics and spectral response with light soaking and with subsequent annealing.
3. Results of dissecting dark I-V characteristics to determine J_0 components, R_s, and R_{sh}.
4. A comparison of cell degradation and recovery with degradation in the minority-carrier lifetime in wafers and their recovery upon annealing.

III. Results

To begin with, Fig. 1(a) shows the time-dependent degradation behavior of open-circuit voltage (V_{oc}) and short-circuit current density (J_{sc}) typical of our cells. Figure 2(b) shows the corresponding changes in the fill factor (FF) and cell efficiency.

For the first hour, the cell was taken out every 5 minutes and the I-V data measured with a pulse tester. The inset in Fig. 1(a) shows the changes in the cell V_{oc} and J_{sc} during the first 60 minutes. Following the first hour of soaking, the cell was exposed for one hour at a time and taken out for measurements. The inset of Fig. 1(a) suggests that there is a sort of recovery of the V_{oc} for the first one hour of light soaking of the cell. This type of recovery was not observed on J_{sc} values during the same time. Results from other cells (of this batch and others) show similar effects of partial recovery in the initial phase of light soaking. It is important to point out that this happens only if the cell is withdrawn from the light-soaking source. We feel that this is a manifestation of interface activity and that defects are either generated at the interface and/or there is charge redistribution during light soaking. The result is a higher effective surface recombination (this conclusion is also attested by the changes in spectral response

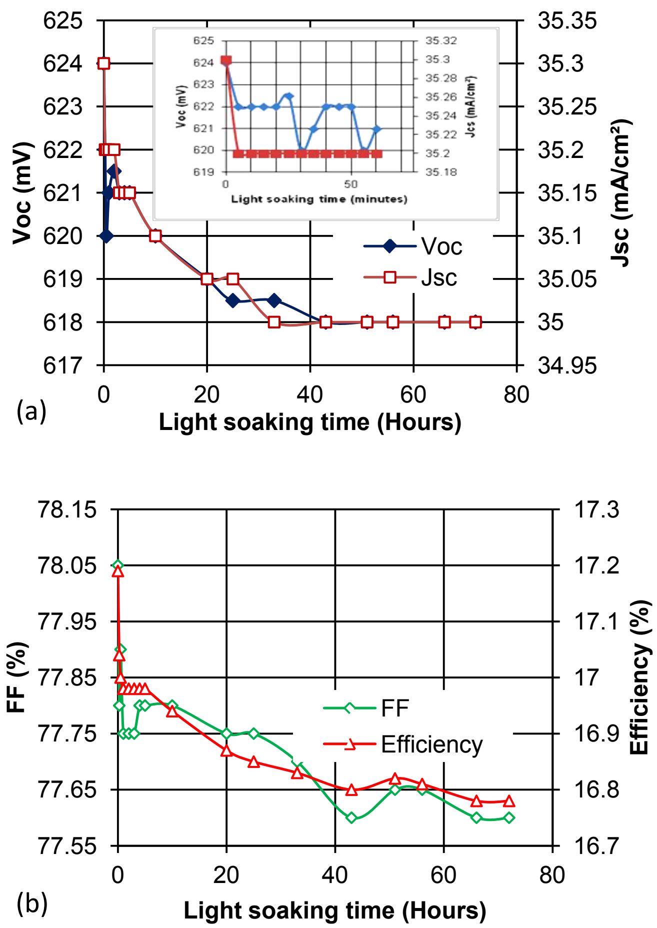

Fig. 1. (a) Variation of V_{oc} and J_{sc}, (b) FF and efficiency of one of the cells plotted as a function of light-soaking time. Inset of Fig. 1(a) shows the decrease in V_{oc} and J_{sc} for the first hour of light soaking.

seen later in Fig. 3). Figures 1(a) and 1(b) also confirm that there appears to be an initial fast decay followed by a slower decay of cell parameters, as observed by Bothe and Schmidt [10].

Figure 2(a) shows illuminated I-V plots of a typical cell before and after light soaking for 72 hours, followed by annealing. The cell parameters before/after light soaking and after annealing are shown in Table 1. It is seen that all cell parameters (V_{oc}, J_{sc}, and FF) degrade with light soaking and then recover: in this case, the V_{oc} recovered fully, whereas J_{sc} and FF recovered only partially.

Figure 2(b) shows the corresponding dark log I-V plots of the cell before and after light soaking and after annealing. It is seen that both J_{01} and J_{02} increase after light soaking. An interesting feature is that upon annealing, J_{01} decreases back to its original value, but J_{02} does *not recover***.** This is a clear indication of surface instability and is believed to be related to the SiN:H/Si interface effects. We point out that degradation of J_{01} with light soaking and its full recovery upon annealing has been observed and reported by Herguth et al. [11]. The values of J_{01}, J_{02}, R_s, and R_{sh} are also shown in Table 1.

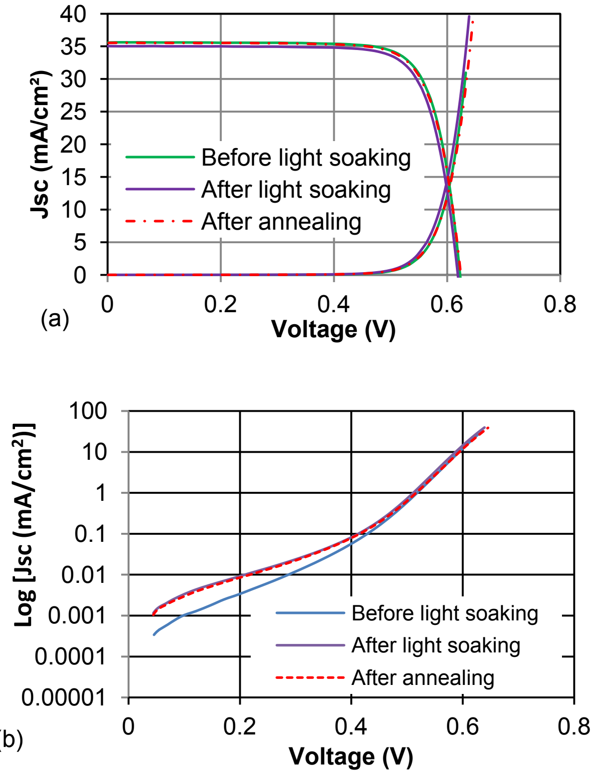

Fig. 2. (a) Light and dark I-V characteristics of a cell plotted together under different conditions. (b) Log plots of dark I-V of the same cell under different conditions.

Table 1. Cell parameters of one sc-Si cell before degradation, after degradation, and after annealing

Parameters	Before light soaking	After light soaking **(72 h, 1-sun, 25°C)**	After annealing **(200°C, 30 min)**
V_{oc} (mV)	624	619.3	624.2
J_{sc} (mA/cm^2)	35.616	35.033	35.542
FF (%)	78.58	78.16	78.13
Efficiency (%)	17.45	16.96	17.33
J_{01} (mA/cm^2)	7.88x10^{-10}	9.36x10^{-10}	7.05x10^{-10}
J_{02} (mA/cm^2)	2.49x10^{-5}	3.62x10^{-5}	3.3x10^{-5}
R_s (mΩ)	1.45	1.65	1.65
R_{sh} (kΩ)	135	32	35

The degradation at the SiN:H/Si interface and within SiN:H has been reported previously and is thought to be due to an increase in D_{it} and in the defect density within SiN:H film [12,13]. It has been shown that exposure to light will cause an increase in the interface state density D_{it} in both p- and n-type Si. This effect is also expected to cause the observed changes in the J_{02} [14].

Figure 3 shows spectral response plots before and after light soaking. It is seen that although the response in most of the wavelength range is reduced, the reduction in response at the shortest wavelength is relatively large. This supports the interface effect described above.

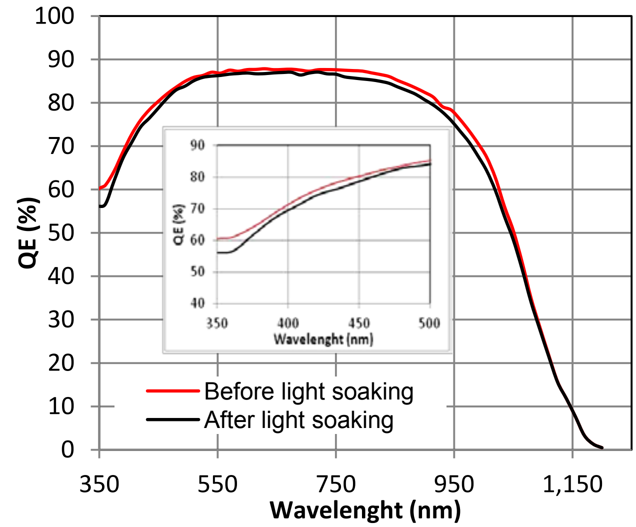

Fig. 3. Quantum efficiency of one of the cells before and after light soaking. Inset shows magnified short wavelength region.

The above results clearly suggest that light soaking also has a surface effect, which we believe is a result of increase in D_{it} at the SiN:H/Si interface. Because multicrystalline Si solar cells also use SiN:H as an antireflection coating, a similar behavior of mc-Si solar cells under light soaking is expected.

IV. Minority-Carrier Degradation vs. Degradation in the Cell Performance

It is instructive to examine if the LID in the cells is fully controlled by the degradation in τ. To accomplish this, we measured changes in the minority-carrier lifetime with light soaking of the similar wafers (prepared by the same crystal/wafer technology) corresponding to various cells. The wafers were prepared by a procedure described in Ref. [15] and their lifetime measured by quasi steady-state photoconductive decay (QSS-PCD) (in "generalized mode") using iodine-ethanol passivation. After performing lifetime measurement, the wafers were then cleaned by the same procedure and soaked for different periods of time under 1-sun at 25°C. Following the light soaking, lifetime of each wafer was measured again. Figure 4 shows the effect of light soaking on the lifetime.

From Fig. 4, one can see that the behavior of the time dependence of τ degradation is about the same as for a cell (made on the adjacent wafer), as seen in Fig. 1. The lifetime decays rapidly in the first hour, followed by a slower decrease.

Interestingly, the decay shows a partial recovery behavior similar to that in Fig. 1(a).

Figure 4 also shows the effect of 30-min anneal (at 200°C) on the lifetime of each of the wafers that were light soaked. It is seen that the recovery is quite incomplete. Our measurements (not shown here) indicate that it takes more than 4 hours to fully recover the lifetime.

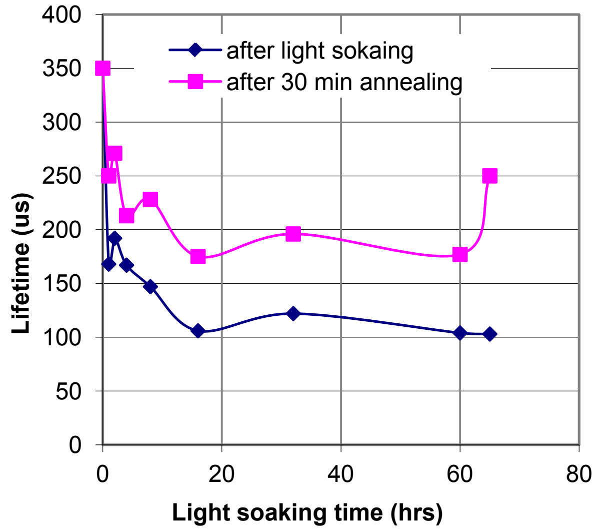

Fig. 4. Measured changes in the minority-carrier lifetime as a function of light soaking on a sc-Si wafer.

Thus, the recovery of lifetime takes a significantly longer annealing time than 30 minutes reported (by other references) for solar cells. Although we believe that the full recovery of the cell should take the same time as the recovery of the lifetime, one could reconcile this fact by the following argument. Because the lifetime of the wafers is large (> 100 µs even after degradation) and that the cell efficiency is only 17.5%, it is possible that there is an *apparent* recovery of the cell parameters. Indeed, a solar cell simulation shows that a lifetime of 150 µs is quite sufficient to yield the cell parameter shown in Fig. 1.

V. Study of LID in mc-Si Solar Cells

Multicrystalline silicon has a low concentration of oxygen (typically ~10^{17} cm^{-3}) and is not expected to display significant B-O defect formation. Hence, solar cells made from cast material are not expected to have LID. Yet, some researchers have reported degradation in the cell performance upon exposure to light [16,17].

We have tested many (>20) mc-Si solar cells to investigate if the mechanism of observed LID is also related to the surface effect that we have observed in CZ cells. Figures 5(a) and (b) show the measured variations in cell parameters with light soaking under 1-sun at 25°C. The cell parameters before and after light soaking are given in Table 2. It can be seen that there is a very small change in the cell parameters. However, it is interesting to note that Figs. 5(a) and (b) have recovery features similar to that of Figs. 1 and 2.

Table 2. Cell parameters of one mc-Si cell before degradation, after degradation, and after annealing

Parameters	Before light soaking	After light soaking (**86 hours, 1-sun, 25°C**)	After annealing (**200°C, 30 min**)
V_{oc} (mV)	616.4	616.5	616.3
J_{sc} (mA/cm^2)	33.846	33.603	33.530
FF (%)	78.20	78.08	78.18
Efficiency (%)	16.31	16.18	16.16
J_{01} (mA/cm^2)	12.0 x10^{-10}	10.5x10^{-10}	9.8x10^{-10}
J_{02} (mA/cm^2)	1.61x10^{-5}	2.88x10^{-5}	3.41x10^{-5}
R_s (mΩ)	2.3771	2.2335	2.0179
R_{sh} (kΩ)	50	35	55

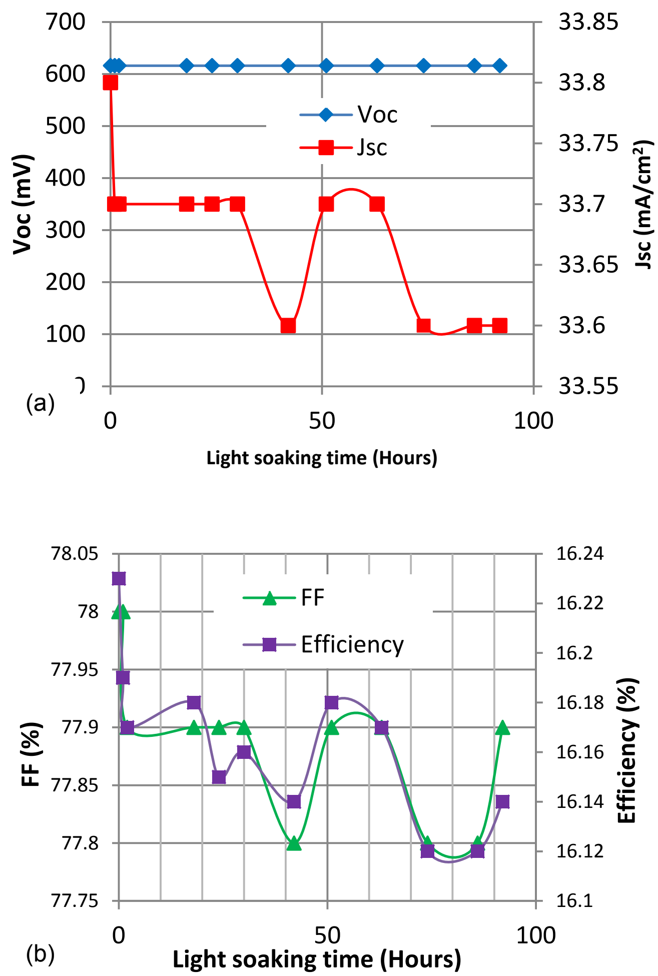

Fig. 5. Measured variations in the (a)V_{oc} and J_{sc} (b) FF and cell efficiency in a mc-Si solar cell as a function of light soaking.

Figures 6(a) and (b) show the illuminated and dark I-V plots before and after light soaking, and after annealing. The degradation in efficiency is only 0.1%. Again, it is seen that the J_{02} component of the dark current does not recover upon annealing. Table 2 also includes J_{01}, J_{02}, R_s, and R_{sh} values.

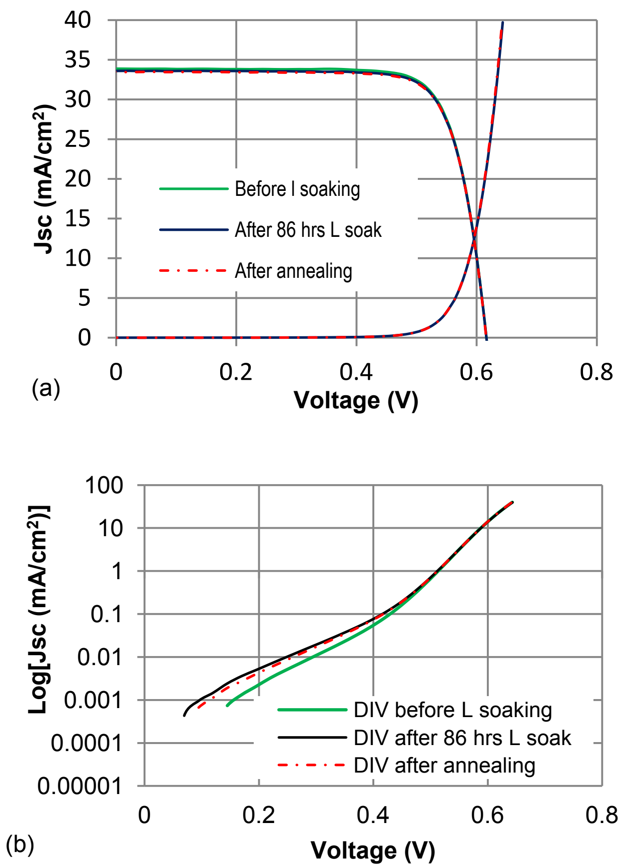

Fig. 6. (a) Illuminated and dark I-V plots before and after light soaking, and after annealing. (b) Changes in the log plot of the dark I-V characteristics of the same mc-Si solar cell as a function of light soaking.

VI. Conclusions

We have carried out detailed analyses of LID of c-Si and mc-Si solar cells to further understand the bulk and surface components. Results to date have shown that degradation mechanisms are bulk and surface related. The bulk effect is primarily B-O related and follows a behavior similar to that of the changes in the minority-carrier lifetime. The annealing results in almost full recovery. The surface effect appears to be related to SiN:H/Si interface. Although their manifestation is very little in the illuminated cell characteristics, it can be easily seen in the J_{02} component of the dark plot. Likewise, it appears as a slightly lower short-wavelength response in the spectral response after light soaking.

The other salient characteristics of LID that we have seen are the following:

1. As is already known, there is an initial rapid decay of all cell parameters (within a few minutes), followed by a slower degradation. In general, all cell parameters experience a reduction.
2. Under 1-sun at 25°C, it takes about 72 hours for complete light-induced degradation.
3. The total effect of LID is about 0.5% absolute (we have not observed > 0.5% degradation).
4. In the initial course of light soaking, there is evidence of partial recovery of cell parameters if the cell is taken out of illumination for I-V measurement.

We are carrying out measurements to directly determine changes in D_{it} at the SiN:H/Si surface of the cell as a result of light soaking and annealing. We will present these results along with LBIC studies (which can detect smaller spatial changes) in forthcoming publications.

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