Solar cells on low-resistivity boron-doped Czochralski-grown silicon with stabilized efficiencies of 20%

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Recently, it was shown that the boron-oxygen complex responsible for the light-induced lifetime degradation in oxygen-rich boron-doped silicon can be permanently deactivated by illumination at elevated temperatures. Since the degradation is particularly harmful in low-resistivity Czochralski silicon (Cz-Si), we apply the deactivation procedure to a high-efficiency rear interdigitated single evaporation emitter wrap-through solar cell made on 1.4 Ω cm B-doped Cz-Si. The energy conversion efficiency is thereby increased by more than 1% absolute compared to the degraded state to 20.3% on a designated area of 92 cm^2 and is furthermore shown to be stable under illumination at room temperature. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3003871]

The carrier lifetime in boron-doped Czochralski-grown silicon (Cz-Si) degrades under illumination due to the formation of a recombination-active boron-oxygen complex. This complex forms via a recombination-enhanced defect reaction involving substitutional boron (B_s) and an interstitial oxygen dimer (O_{2i}).[1] Since the open-circuit voltage, and hence the cell efficiency, strongly correlates with the bulk carrier lifetime, this degradation results in an efficiency loss of up to 10% relative in solar cells made on such material.[2,3] It has been known for some time now that the B_sO_{2i} complex can be dissociated by a short anneal (~10 min) in the dark at 200 °C.[4,5] However, subsequent illumination results in renewed lifetime degradation as both components, B_s as well as O_{2i}, are still available. By contrast, Herguth *et al.* recently reported that high and stable lifetimes can be achieved in low-resistivity B-doped Cz-Si through illumination at elevated temperatures[6,7] and that the same procedure also results in recovery of the open-circuit voltage of solar cells. More recently, we have introduced a defect reaction model, which ascribes the permanent deactivation of the boron-oxygen complex to a second defect reaction that ultimately results in the binding of the oxygen dimer in a recombination-inactive complex.[8]

In this work, we apply the deactivation treatment to high-efficiency rear interdigitated single evaporation emitter wrap-through (RISE-EWT) solar cells[9] fabricated on low-resistivity B-doped Cz-Si. The efficiency of these cells degrades by more than 1% absolute under illumination at room temperature. We demonstrate that the open-circuit voltage and the efficiency fully recover under illumination at elevated temperatures and that the recovered state is stable under illumination at room temperature.

Lifetime experiments are performed on 1.4 Ω cm B-doped Cz-Si wafers with an interstitial oxygen concentration of $[O_i]=(7.5\pm0.5)\times10^{17}$ cm^{-3}, as determined by Fourier-transform infrared spectroscopy. After an acidic damage etching and a RCA cleaning, a phosphorus diffusion is performed, resulting in a n^+ layer with a sheet resistance of ~100 Ω/sq on both sides of the wafers. This process is included because it accelerates the deactivation process by a factor of 3, as we have shown in a recent contribution.[8] Subsequently, the n^+ region is removed by a second acidic etching step after which the wafers are passivated with plasma enchanced chemical vapor deposited (PECVD) silicon nitride.[10] Effective lifetimes τ_{eff} are measured at room temperature (300 K) at a fixed injection level of $\Delta n=10^{15}$ cm^{-3} using the quasi-steady-state photoconductance (QSSPC) technique.[11] Note that due to the excellent surface passivation provided by the PECVD silicon nitride, these effective lifetimes can be identified with the bulk carrier lifetime τ_b.

In order to deactivate the boron-oxygen complex, we illuminate the lifetime samples on a hot plate with a halogen lamp. So far, results from two slightly different temperature ranges have been reported in the literature. Herguth *et al.* presented regeneration experiments performed at temperatures between 70 and 160 °C,[6,7] whereas we found that higher temperatures between 140 and 215 °C are necessary.[8] The exact reason for this discrepancy is currently investigated in our laboratory.

The deactivation process has been shown to be thermally activated with an activation energy of 0.7 eV,[6–8] resulting in a faster recovery of the carrier lifetime at higher temperatures. However, the temperature also has an impact on the stability of the recovered lifetime. At temperatures significantly higher than 200 °C, e.g., 230 °C, we find that the deactivated state is no longer completely stable. This is shown by the black diamonds in Fig. 1. The effective lifetime increases during illumination at a light intensity of 1 sun (i.e., 100 mW/cm^2) on the hot plate. However, once the sample is removed from the hot plate (as indicated by the black dashed line) and illuminated at room temperature, the lifetime notably decreases again, in this case by 30 μs from 100 to 70 μs. The lifetime of samples which were illuminated at 200 °C (open red circles) and 185 °C (open red triangles), on the other hand, is constant under illumination at room temperature (i.e., points after the red dotted line), as can be seen in Figs. 1 and 2. The slight losses of 10 and 5 μs, respectively, observed after removal from the hot plate are still within the uncertainty range of 10% of the QSSPC setup but might also be weakened forms of the degradation observed in the sample illuminated at 230 °C. We explain the observed instability of the regenerated lifetime within the

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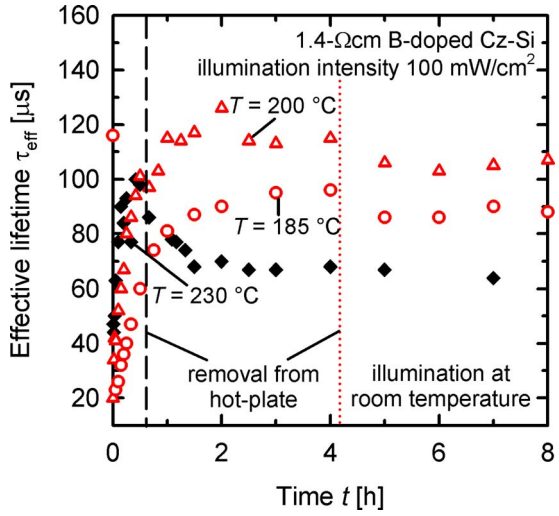

FIG. 1. (Color online) Lifetime evolution of three P-diffused 1.4 Ω cm B-doped Cz-Si wafers which are illuminated at 1 sun at 185 °C (open red circles), 200 °C (open red triangles), and 230 °C (filled black diamonds), respectively. The dashed black line marks the point in time where the 230 °C sample is removed from the hot plate, whereas the other two samples were removed at the dotted red line.

framework of our recently introduced defect reaction model.[8] At higher annealing temperatures the complex which binds the detrimental oxygen dimer is dissociated, increasing the dimer concentration again. Accordingly, under illumination at room temperature, the fast-diffusing oxygen dimer is available to form the highly recombination-active boron-oxygen complex responsible for the light-induced degradation.

Figure 2 shows the time dependence of the effective carrier lifetime under illumination with 0.1 sun light intensity of three different types of silicon samples with comparable resistivities (1–2 Ω cm) and surfaces passivated by PECVD silicon nitride. The down triangles show that float-zone silicon (FZ-Si) with extremely low oxygen content ($[O_i] < 10^{16}$ cm^{-3}) suffers no lifetime degradation under illumination. In addition, this measurement verifies our assumption that the silicon nitride surface passivation does not change during illumination. The filled circles in Fig. 2 show how the

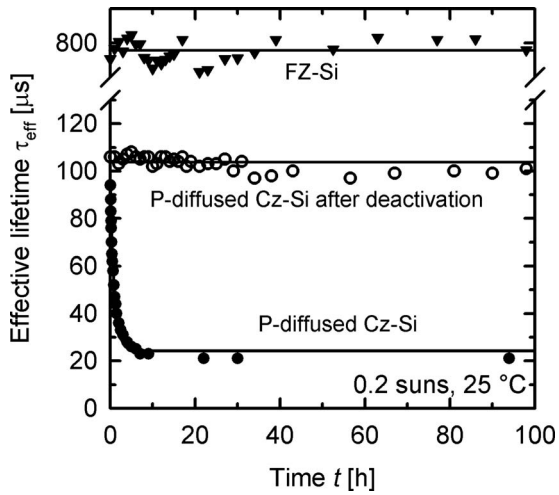

FIG. 2. Comparison of the time dependence of the effective lifetime τ_{eff} in oxygen-lean FZ-Si (down triangles), P-diffused Cz-Si (filled circles), and P-diffused Cz-Si which underwent the deactivation procedure (open circles).

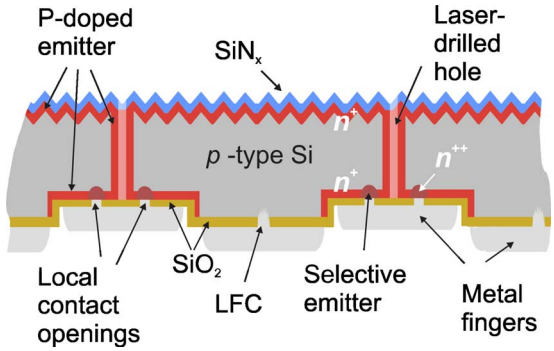

FIG. 3. (Color online) Schematic structure of a RISE-EWT solar cell (Ref. 4).

effective lifetime of a common P-diffused Cz-Si sample degrades within less than 10 h to a very low lifetime of only ~20 μs at an injection density of $\Delta n = 10^{15}$ cm^{-3}. By contrast, the effective lifetime of a comparable sample which underwent the deactivation treatment at 200 °C (open circles) is constant at 105 μs for more than 100 h.

In order to achieve both a fast and a stable recovery of the open-circuit voltage and thus the energy conversion efficiency, we apply the deactivation procedure to RISE-EWT solar cells fabricated on low-resistivity B-doped Cz-Si at 200 °C. A schematic of the RISE-EWT cell structure is shown in Fig. 3. Base and emitter fingers are interdigitated and on different height levels on the rear side of the cell. The n^+ emitter on the front is connected to the emitter on the back via laser-drilled holes (EWT structure[12]). The base region is contacted by laser-fired contacts (LFCs),[13] which are formed through laser firing of aluminum through a silicon oxide layer. Fabrication steps include RCA cleaning, oxidation, front-surface texturing, laser structuring of the rear, laser drilling of holes, phosphorus diffusion, front-surface passivation, a single metallization step of the entire rear with self-aligning contact separation,[9] and formation of the LFCs. Details of the solar cell process have been published elsewhere.[14] The base material of the cells investigated in this study is the same as that used for the lifetime measurements. Current-voltage characteristics are measured under standard testing conditions (25 °C, AM1.5 spectrum, 1 sun), which are set using a calibrated RISE-EWT solar cell with a similar spectral response. The total cell area is 100 cm^2; however, due to a nonoptimized busbar design the measurements presented here refer to a designated area of 92 cm^2. Measurements of the total cell area yield the same open-circuit voltage and short-circuit current density while the fill factor suffers a loss of 2% absolute.

RISE-EWT solar cells made on FZ-Si have demonstrated energy conversion efficiencies of up to 21.4% on a designated area of 92 cm^2.[14] On low-resistivity (1–2 Ω cm) boron-doped Cz-Si, we typically achieve efficiencies of (20.0 ± 0.5)% before light-induced degradation and (19.0 ± 0.5)% after complete degradation on the same illuminated cell area. Figure 4 shows the evolution of (a) the open-circuit voltage and (b) the efficiency of an exemplary RISE-EWT cell. The initial efficiency before light-induced degradation is 20.2%. After 8 h of illumination at room temperature using a halogen lamp at 0.2 sun, this value decreases to 19.2%. The open-circuit voltage after degradation is 645 mV and the short-circuit current density is

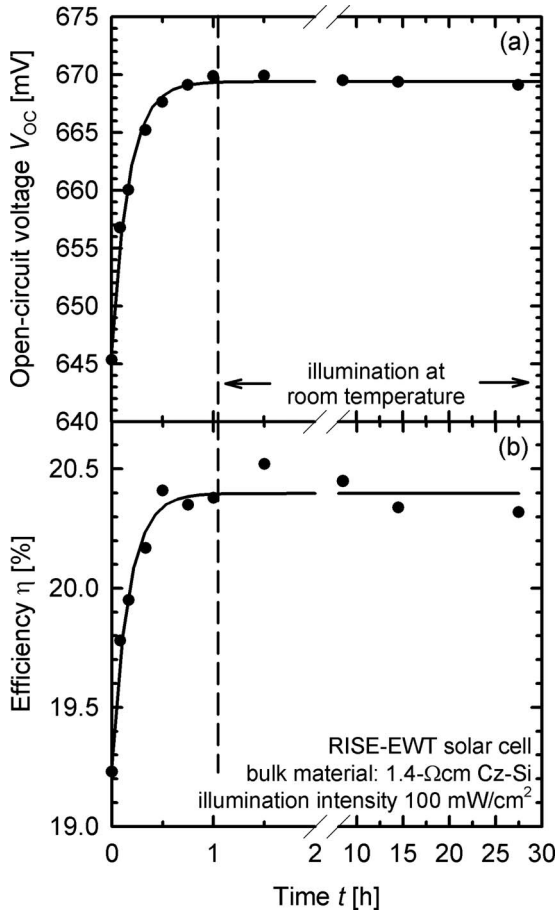

FIG. 4. Time dependence of (a) the open-circuit voltage V_{OC}, and (b) the efficiency η of a high-efficiency RISE-EWT solar cell made on 1.4 Ω cm B-doped Cz-Si which is illuminated at 1 sun at 200 °C. After removal from the hot plate, no efficiency degradation is discernible after several hours of illumination at room temperature.

40.4 mA/cm^2. Note that the short-circuit current density shows only a negligible degradation because for EWT-type cells the short-circuit current density is less sensitive to reduced base diffusion lengths, and thus to reduced bulk lifetimes, than for standard cells.[15] In order to deactivate the B_sO_{2i} complex the solar cell is illuminated at 200 °C with a halogen lamp at a light intensity of 1 sun. As can be seen in Fig. 4, V_{OC} increases to nearly 670 mV after 60 min. J_{SC} remains the same within the uncertainty range (40.9 mA/cm^2), resulting in an energy conversion efficiency of 20.3%. After 20 h of illumination at room temperature the *IV* characteristic is taken again, showing no significant loss in either V_{OC} or η. No further efficiency loss due to the formation of B_sO_{2i} complexes is thus expected. The time constant of the deactivation process determined from the measurements shown in Fig. 4 amounts to 9.98 min, which agrees well with the value of 9.02 min measured on lifetime samples under the same conditions. In addition, we use data previously published by Hermann *et al.*[14] to analyze the improvement in the bulk carrier lifetime as implied by the improvement in the open-circuit voltage. These calculations yield an increase in τ_b from ~100 to ~400 μs as V_{OC} increases from 645 to 669 mV. Hence, we conclude that the deactivation process has been demonstrated on the device level.

The efficiency of RISE-EWT solar cells fabricated on low-resistivity (1.4 Ω cm) boron-doped Cz-Si is shown to increase by more than 1% absolute compared to the degraded state after illuminating the cell at 1 sun intensity and annealing it simultaneously at 200 °C for 1 h. After applying this deactivation treatment, we reach stable efficiencies above 20%. This is the highest stabilized efficiency reported for a solar cell made on low-resistivity boron-doped Cz-Si so far.

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