

Stability of the regeneration of the boron-oxygen complex in silicon solar cells during module integration

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Abstract:

Light-induced degradation (LID) in boron-doped *p*-type Czochralski (Cz) silicon is caused by a boron-oxygen (BO) complex, which may be permanently deactivated by simultaneous illumination and heating leading to a permanent regeneration of carrier lifetime and solar cell performance. Up to now, regeneration has only been investigated on wafer and solar cell level. In this work, we investigate whether the regeneration gain on solar cell level can be transferred to module level. For this purpose, we fabricated solar cells with passivated emitter and rear on boron-doped *p*-type Cz and float zone wafers. The cells are extensively characterised regarding losses in cell performance due to LID by preparing different defect states with certain temperature and illumination treatments. The effect of the injection-dependent carrier lifetime caused by the BO complex in its active state on fill factor is investigated in detail theoretically and experimentally, developing a descriptive explanation. Finally, it is shown by integrating solar cells in the degraded and regenerated state into solar modules, that the regeneration effect can be transferred to module level and is stable upon subsequent illumination of the module.

Keywords: Cz, boron-oxygen, module, degradation, regeneration

1. Introduction

Monocrystalline silicon ingots crystallized via the Czochralski (Cz) technique [1-3] and doped with boron represent one of the most widely used sources for solar silicon wafers. Since the silicon feedstock is molten in a quartz crucible, oxygen diffuses from the crucible walls into the silicon melt and is incorporated into the silicon crystal [1-3]. Hence, boron and oxygen can form the highly recombination-active boron-oxygen (BO) defect [4, 5] in standard industrial Cz *p*-type solar silicon. In its active state, this defect limits the excess carrier lifetime in *p*-type silicon significantly and therefore the maximum conversion efficiency of *p*-type silicon solar cells [6, 7]. The characteristics of this defect and its parameterisation have been the subject of intensive research work in the past. This research revealed that the defect is metastable and can be activated upon illumination or carrier injection and fully deactivated upon annealing in the dark [8, 9], the transformation between the two defect states being fully reversible.

More recently, Herguth *et al.* [10] discovered, that the BO defect can be permanently deactivated by combined illumination and annealing, which is known as so-called regeneration. The temperatures required for regeneration vary strongly from $T = 70^\circ\text{C}$ to $T = 215^\circ\text{C}$ in literature [10, 11]. For reported regeneration of solar cells (in contrast to lifetime samples), $T = 140^\circ\text{C}$ is usually not exceeded. It is known that the regenerated state may be destroyed and the defect reactivated at elevated temperatures above $T = 170^\circ\text{C}$ in the dark [10] and for some samples (including lifetime samples) after illumination at elevated temperatures for a long time [11, 12] while the latter effect is not always observed [12]. However, no information is available on the stability of the regenerated state during thermal processes such as soldering and lamination during module assembly. As temperatures in these process steps may exceed $T = 200^\circ\text{C}$ significantly [13], they are in the critical range where regeneration may be reversed. Hence, this work aims at investigating if the regenerated state of the boron-oxygen defect which is established on solar cell level is stable upon the subsequent module assembly.

For this purpose, passivated emitter and rear (PERC [14]) solar cells have been processed at Fraunhofer ISE on industrial boron-doped *p*-type Cz silicon wafers. The effect of activation, deactivation and regeneration of the

BO defect on solar cell performance is investigated in detail taking into account the impact of changes in the injection-dependence of the minority carrier lifetime upon defect transformation on fill factor. Subsequently, one degraded and one regenerated cell are integrated into single-cell mini-modules to investigate whether the achieved gain on cell level is transferable to module level. Within all steps, a FZ solar cell is used to monitor possible process-induced effects.

2. Experimental

To evaluate the stability of the regenerated state of the boron-oxygen complex during module integration, we fabricated solar cells on industrial equipment [15]. To increase the sensitivity of solar cell performance on bulk lifetime effects, a PERC process called TOPAS (thermal oxide passivated all sides) including a selective emitter has been applied. Screen-printing has been used for metallisation; the front side contact finger pitch is $d_{\text{finger}} = 2.2$ mm and the rear side contact spacing has been adapted to base resistivity using an analytical model [16]. Process details can be found in [17, 18]. The wafer material used is industrial, boron-doped *p*-type Cz silicon with a base resistivity of $\rho_{b,\text{Cz}} = 2.3 \Omega\text{cm}$ and FZ silicon with $\rho_{b,\text{FZ}} = 0.5 \Omega\text{cm}$; the format of the wafers is pseudo-square with an edge length of $d_{\text{edge}} = 125$ mm and the wafer thickness is $d_{\text{wafer}} = 200 \mu\text{m}$ before and $d_{\text{cell}} = 160 \mu\text{m}$ after cell processing, respectively. All wafers are processed equally within the same batch. The FZ wafers are used as a reference to monitor possible process-induced effects through the subsequent treatment after cell processing which are not material-related.

Fig. 1 depicts a schematic of the experimental design; two very similar solar cells from Cz wafers (cell A and cell B) and one reference cell from a FZ wafer are (in chronological order) annealed at a temperature of $T = 250^\circ\text{C}$ for a time of $t = 20$ min in the dark resulting in the boron-oxygen defect being completely deactivated, and then degraded for $t \approx 48$ h at an illumination intensity of $E > 0.2$ suns ($1 \text{ sun} \triangleq 1 \text{ kW/m}^2$) at $T \leq 40^\circ\text{C}$ which fully activates the BO defect. After degradation, Cz cell B and the FZ reference cell are regenerated at $E = 1$ sun and $T = 140^\circ\text{C}$ for $t = 2.7$ h. The stability of the regenerated state is tested by illumination at $E > 0.2$ suns for $t \approx 5$ days at $T \leq 40^\circ\text{C}$ since light-induced re-degradation at room temperature after successful regeneration of BO has been sometimes observed on lifetime samples in literature [11]. The other Cz cell A is neither regenerated nor tested on stability but left in the degraded state.

After preparation of the degraded and the regenerated defect state in cell A and cell B, respectively, all three cells are built into mini-modules and subsequently illuminated at $E > 0.2$ suns for $t \approx 48$ h at $T \leq 40^\circ\text{C}$. The module assembly consists of manual contact soldering at $T \approx 245^\circ\text{C}$ and a lamination process of the EVA (ethylene-vinyl acetate), front side glass and rear side backsheet. The locally induced temperatures during soldering are comparable to an industrial stringer process where an entire cell is soldered at a temperature of $T \approx 225^\circ\text{C}$ within $t = 1 - 2$ s. Before contact soldering, the cells are pre-heated to $T = 120^\circ\text{C}$. The temperature profile of the lamination process consists of a ramp-up from $T_{\text{start}} = 40^\circ\text{C}$ to $T_{\text{plateau}} = 133^\circ\text{C}$ within $t_{\text{ramp}} = 8$ min, a subsequent plateau with $T_{\text{plateau}} = 133^\circ\text{C}$ for $t_{\text{plateau}} = 15.5$ min and a final ramp down to $T_{\text{end}} = 40^\circ\text{C}$ within $t_{\text{ramp}} = 7$ min. During lamination, the cells are in the dark.

In-between each experimental step, all cells respectively modules are characterised by means of I - V (current-voltage) and suns- V_{oc} [19] measurements.

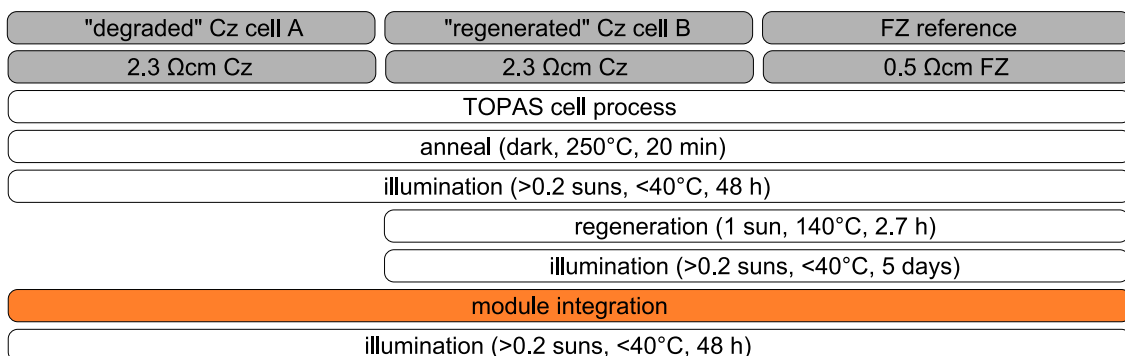


Figure 1: Sketch of the experimental design. Before module assembly, Cz cell A is brought into the degraded state, while Cz cell B and a FZ reference cell are brought into the regenerated state. In-between each step, I - V and suns- V_{oc} measurements are performed.

3. Effect of the boron-oxygen defect on solar cell performance

The degradation of minority carrier lifetime in the bulk due to activation of the BO complex can degrade all three characteristic illuminated I - V parameters: short-circuit current density J_{sc} , open-circuit voltage V_{oc} and fill factor FF . The impact of a strong injection-dependence of the Shockley-Read-Hall lifetime of a defect on fill factor has been shown e.g. by Schmidt *et al.* [20] for the BO defect using a numerical simulation and by Macdonald and Cuevas [21] using an analytical approach for multicrystalline silicon. In order to understand qualitatively the losses in V_{oc} and FF induced by the BO defect similar to Macdonald and Cuevas [21], we use a simple zero-dimensional solar cell model (that is the solar cell is considered as a point), which already illustrates the impact of changes in the injection dependence of the carrier lifetime on solar cell performance. The model is not intended as a quantitative description of the three solar cells but shall give a more instructive and descriptive explanation than numerical simulations.

For the correlation of excess carrier density Δn and voltage V representing the split of the quasi-Fermi-levels,

$$n \cdot p = (\Delta n + n_0) \cdot (\Delta n + p_0) = n_i^2 \cdot \exp\left(\frac{V}{V_t}\right) \approx \Delta n \cdot (\Delta n + N_A) \quad (1)$$

holds in p -type silicon, with n and p being the electron and hole densities, respectively, n_0 and p_0 the densities in thermal equilibrium, n_i the intrinsic carrier density, N_A the acceptor density and $V_t = kT/q$ the thermal voltage with Boltzmann constant k , temperature T and elementary charge q . For our approach, we consider recombination via defects according to Shockley-Read-Hall [22, 23] (SRH) and Auger recombination using the parameterisation of Kerr and Cuevas [24]. For the effective excess carrier lifetime,

$$\tau_{\text{eff}} = \frac{1}{\frac{1}{\tau_{\text{SRH}}} + \frac{1}{\tau_{\text{Auger}}}} = \frac{\Delta n}{R_{\text{SRH}} + R_{\text{Auger}}} = \frac{\Delta n}{R} \quad (2)$$

follows, with recombination rate R . In the simple zero-dimensional solar cell model, Δn is assumed to be constant across the bulk and all other recombination sources in a solar cell (emitter, space charge region, surfaces) are neglected. Therefore, the lifetime effects are expected to be more pronounced in the model than in a real device. The correlation between current density J and voltage V can thus be stated as

$$J(V) = \underbrace{W \cdot q \cdot R(\Delta n(V))}_{J_{\text{rec}}(V)} - J_{\text{ph}} = \underbrace{\frac{W \cdot q}{\tau_{\text{eff}}(\Delta n(V))} \cdot \left(-\frac{N_A}{2} + \sqrt{\frac{N_A^2}{4} + n_i^2 \cdot \exp\left(\frac{V}{V_t}\right)} \right)}_{J_{\text{rec}}(V)} - J_{\text{ph}}, \quad (3)$$

with W being the width of the solar cell, J_{rec} the recombination and J_{ph} the photo-generated current density.

Fig. 2a shows the effective carrier lifetime τ_{eff} as a function of Δn assuming three different defect configurations. Case 1 represents a defect with the same effective low level injection (LLI) lifetime as the BO defect but a much weaker injection-dependence, case 2 a defect with a significantly higher LLI lifetime than case 1 which roughly represents no BO defect respectively the BO defect being in an ideal annealed/regenerated state (Cz cell B / FZ cell) and case 3 the BO defect being in its active state (Cz cell A). For modelling, the assumed defect configurations in the SRH term are: (case 1) a mid-gap defect with symmetric capture cross sections and thus equal electron and hole capture time constants of $\tau_{n0} = \tau_{p0} = 45 \mu\text{s}$, (case 2) a similar mid-gap defect with reduced defect concentration and thus increased $\tau_{n0} = \tau_{p0} = 500 \mu\text{s}$ and (case 3) the Cz-specific BO defect with a deep energy level at $E_c - E_t = 0.41 \text{ eV}$ and a stronger injection dependence due to the capture asymmetry with $\tau_{p0}/\tau_{n0} = 9.5$ [25]. For the BO defect $\tau_{n0} = 44 \mu\text{s}$ is assumed. This is in accordance with the parameterisation of the effective lifetime at an injection level of $\Delta n = 0.1 p_0$ given in [26], with the doping density $N_A = [B_s] = 6.23 \times 10^{15} \text{ cm}^{-3}$ (according to $\rho_b = 2.3 \Omega\text{cm}$ for the Cz wafers used) and a typical interstitial oxygen concentration of $[O_i] = 7.5 \times 10^{17} \text{ cm}^{-3}$. For our calculations, we used the parameterisation of the entire SRH term

given in [27] which is based on [25, 26]. We assume $m = 2$ for the process-dependent parameter, which gives $\tau_{\text{BO}}(\Delta n = 0.1p_0) = 84.5 \mu\text{s}$, and to calculate the resulting J and J_{rec} , a wafer thickness of $W = 200 \mu\text{m}$.

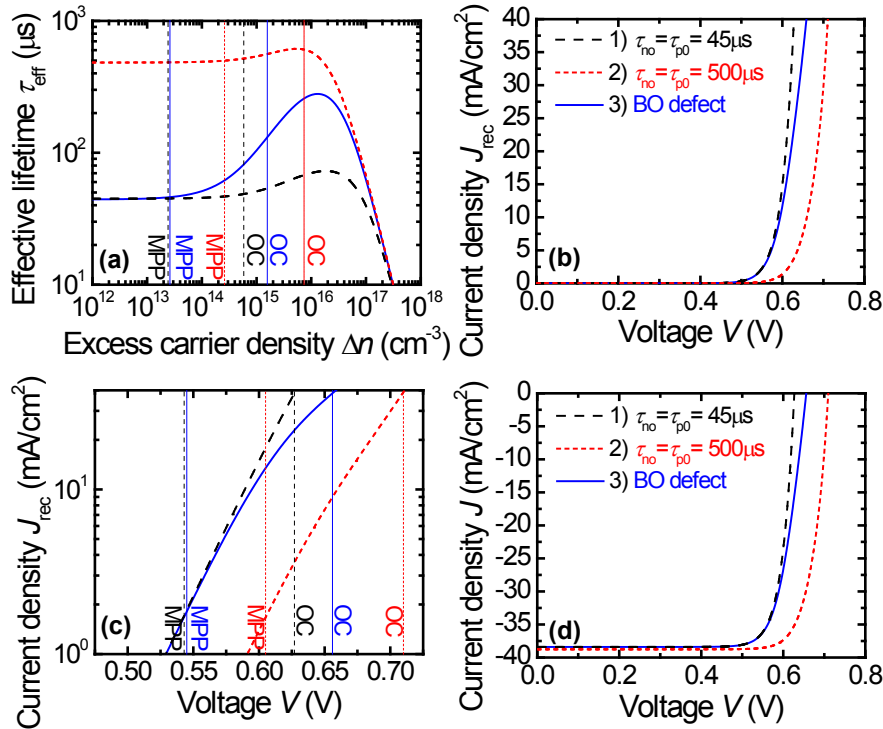


Figure 2: (a) Effective lifetime for SRH defects with (case 1) $E_t = E_i$ and $\tau_{n0} = \tau_{p0} = 45 \mu\text{s}$ (black dashed line), (case 2) $E_t = E_i$ and $\tau_{n0} = \tau_{p0} = 500 \mu\text{s}$ (red dotted line) and (case 3) the parameterisation of the BO defect according to [27] with $m = 2$, $[B_s] = 6.23 \times 10^{15} \text{cm}^{-3}$ and $[O_i] = 7.5 \times 10^{17} \text{cm}^{-3}$ based on [25, 26] (blue solid line). (b) Resulting J - V curves for the lifetimes from (a) with $J_{\text{ph}} = 0 \text{mA}/\text{cm}^2$, see Eq. (3). (c) Semi-logarithmic display of (b) in the voltage range between MPP and OC. (d) Illuminated J - V curves assuming measured J_{sc} values of the annealed state for case 2 and of the degraded state for cases 1 and 3.

Fig. 2a shows, that for $\Delta n \leq 10^{14} \text{cm}^{-3}$, cases 1 and 3 result in comparable effective lifetimes while for $\Delta n > 10^{14} \text{cm}^{-3}$, the strong injection-dependence of the BO defect leads to an increase in lifetime for case 3. Case 2 exhibits a higher lifetime across the entire relevant excess carrier density range. For $\Delta n > 2 \times 10^{16} \text{cm}^{-3}$, τ_{eff} is dominated by Auger recombination. Calculating a J - V curve for the three cases according to Eq. (3) (assuming $J_{\text{ph}} = 0 \text{mA}/\text{cm}^2$) leads to the curves depicted in Fig. 2b. Since we apply a zero-dimensional model neglecting series resistance R_s , the superposition principle [28, 29] is valid. That is, the dark J - V curve equals a suns- V_{oc} curve and by adding a value of $J_{\text{ph}} > 0 \text{mA}/\text{cm}^2$, an illuminated J - V curve can be derived. Also, the correlation $J(V=0 \text{V}) = J_{\text{sc}} = J_{\text{ph}}$ holds which is independent of Δn . In a real device, this is of course not the case for effective lifetimes as given in Fig. 2a. To consider the effect of differing LLI lifetimes between cases 1/3 and case 2 on J_{sc} , we assume $J_{\text{sc,case 1}} = J_{\text{sc,case 3}} = 38.40 \text{mA}/\text{cm}^2$ and $J_{\text{sc,case 2}} = 38.75 \text{mA}/\text{cm}^2$, which reflect the measured degraded and annealed values of the considered Cz solar cells, respectively. Fig. 2d depicts the resulting illuminated J - V curves for all three cases. The differences in V_{oc} are due to the different effective lifetimes at the operation point of open-circuit (OC), as indicated by the vertical lines in Fig. 2a. Due to the increase of the effective lifetime in case 3 compared to case 1 for $\Delta n > 10^{14} \text{cm}^{-3}$, a higher excess carrier density is reached at OC and therefore a higher V_{oc} . All relevant values are given in Table 1.

The maximum power point (MPP) of the curves given in Fig. 2d can be determined and results in a V_{MPP} , which can be converted into a corresponding $\tau_{\text{eff,MPP}}/\Delta n_{\text{MPP}}$ pair according to Eq. (1)-(2). Fig. 2a and c indicate the results. Since the effective lifetimes at the MPP in case 1 and 3 are almost identical, the values of V_{MPP} are very similar. Since $J_{\text{sc,case 1}} = J_{\text{sc,case 3}}$ is assumed due to equal LLI lifetimes, almost identical values for J_{MPP} and therefore for the efficiencies η result, as can be seen in Table 1. For case 2, higher values of V_{MPP} and η result due to the significantly higher effective lifetime and therefore excess carrier density at the MPP. When comparing case 1 and 3, J_{sc} is equal, η is almost equal and V_{oc} significantly differs. As the fill factor is defined

via $FF = (J_{MPP} \times V_{MPP}) / (J_{sc} \times V_{oc})$, case 1 results in a significantly higher FF than case 3 with $FF_{case 1} - FF_{case 3} = 3.5 \%_{abs}$. Since in case 3, which reflects the BO defect in its active state, the significant increase in effective lifetime with Δn occurs after the MPP, η cannot benefit from this increase but V_{oc} is superelevated compared to the conditions at MPP. Hence, a solar cell being represented by case 3 does not exhibit a classical “fill factor problem” with possible root causes of increased series resistance R_s or decreased parallel resistance R_p , but the fill factor is solely limited due to the intrinsic injection-dependence of the SRH lifetime of the BO defect in its active state. Since this effect is not linked to R_s , it also shows in the pseudo fill factor pFF of real solar cells as will be shown later. In-between MPP and OC point, the $J_{rec} - V$ (respectively $suns - V_{oc}$) curve of case 3 exhibits a strong kink compared to case 1. Case 2 also shows a less pronounced kink which results in a lower FF than case 1, see Table 1. As stated above, the given FF s equal the respective pFF s and η equals the respective pseudo efficiency $p\eta$.

Table 1: Short-circuit current density J_{sc} , voltage V , excess carrier density $\Delta n(V)$ and effective lifetime $\tau_{eff}(\Delta n(V))$ at the maximum power point (index MPP) and under open-circuit conditions (index OC) as well as fill factor FF and efficiency η resulting from a zero-dimensional model (simulation parameters are given in section 3). Case 1 represents a defect with $\tau_{n0} = \tau_{p0} = 45 \mu s$ and $E_t = E_i$, case 2 with $\tau_{n0} = \tau_{p0} = 500 \mu s$ and $E_t = E_i$ and case 3 the BO defect being in its active state according to [27] with $m = 2$, $[B_s] = 6.23 \times 10^{15} \text{ cm}^{-3}$ and $[O_i] = 7.5 \times 10^{17} \text{ cm}^{-3}$ based on [25, 26].

Case	J_{sc} (mA/cm ²)	V_{MPP} (mV)	$\Delta n(V_{MPP})$ (cm ⁻³)	$\tau_{eff}(\Delta n(V_{MPP}))$ (μs)	V_{oc} (mV)	$\Delta n(V_{oc})$ (cm ⁻³)	$\tau_{eff}(\Delta n(V_{oc}))$ (μs)	FF (%)	η (%)
1	38.40	543	2.41×10^{13}	45.0	627	5.82×10^{14}	48.6	82.7	19.9
2	38.75	605	2.60×10^{14}	499.6	710	7.37×10^{15}	606.2	81.6	22.4
3	38.40	545	2.61×10^{13}	46.1	656	1.57×10^{15}	131.2	79.2	19.9

4. Characterisation

4.1. Solar Cell Level

In the following section, the experimental results up to the module integration step are discussed. First, the impact of activation, deactivation and regeneration of the BO defect on illuminated $I - V$ parameters is addressed. Second, the impact on fill factor FF is investigated in more detail.

4.1.1. Illuminated $I - V$ parameters

Fig. 3a depicts the illuminated $I - V$ curve of Cz cell B in the annealed, degraded and regenerated state. Qualitatively, the curves follow the behaviour of the curves for case 2 (ann./reg.) and 3 (deg.) shown in Fig. 2d. As can be seen, the activation of the BO defect by illumination degrades I_{sc} , V_{oc} and FF which all three can be recovered by regeneration. Since the degradation of I_{sc} is used as an input parameter in section 3 for the zero-dimensional model, Fig. 3b depicts the internal quantum efficiency IQE of Cz cell B in the degraded and regenerated state. Both curves only differ in the wavelength range from $\lambda \approx 750 \text{ nm}$ to $\lambda \approx 1150 \text{ nm}$ which is affected by bulk lifetime [30, 31]. This shows that the difference in I_{sc} between defect states can be attributed to material-induced bulk effects.

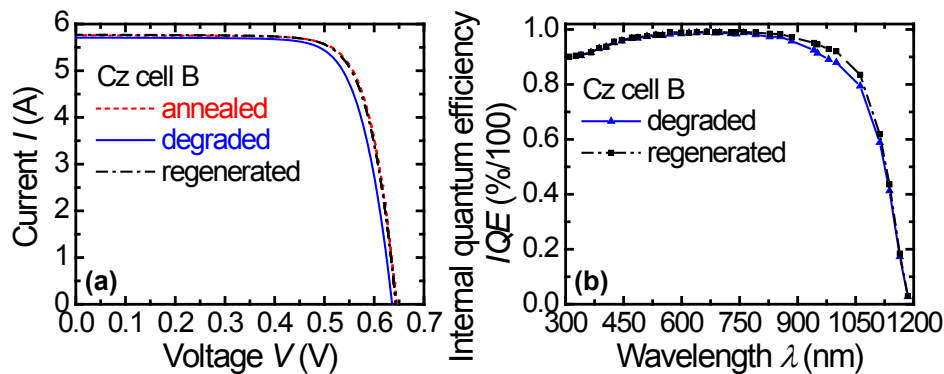


Figure 3: (a) Illuminated I - V curves of Cz cell B in the annealed, degraded and regenerated state. (b) Internal quantum efficiency IQE as a function of wavelength for the same cell in the degraded and regenerated state.

Fig. 4a shows the measurement results of the illuminated I - V parameters V_{oc} , short-circuit current I_{sc} , FF , pFF , ideal fill factor FF_0 and maximum output power P_{MPP} after each step as sketched in Fig. 1. Due to the higher base doping, the FZ reference cell exhibits a slightly lower I_{sc} and a higher V_{oc} compared to the Cz cells in the annealed state.

To highlight the impact of annealing (ANN), degradation (DEG) and regeneration (REG) on the different cell parameters, Fig. 4b depicts for each of the three cells the absolute differences compared to the values in the degraded state. Comparing for example the annealed with the degraded state, a significant reduction of the output power is observed for both Cz cells which amounts to $\Delta P_{MPP,CzA} = -0.13$ W and $\Delta P_{MPP,CzB} = -0.12$ W, respectively. The output power can be directly converted into efficiencies which are for Cz cell A $\eta_{CzA, ANN} = 19.1\%$ ($P_{MPP,CzA, ANN} = 2.84$ W) in the annealed state and $\eta_{CzA, DEG} = 18.2\%$ ($P_{MPP,CzA, DEG} = 2.71$ W) in the degraded state. Hence, the observed loss in output power of $\Delta P_{MPP,CzA} = -0.13$ W corresponds to a loss in efficiency of $\Delta\eta_{CzA} = -0.9\%$ _{abs}. Any further given power values on cell level can be converted into efficiencies accordingly. Comparing the annealed and the degraded states for the FZ cell, it can be seen that – as expected – the FZ cell is stable in all parameters.

The degradation-induced loss in the output power of the Cz cells originates from a decrease in all three cell parameters: V_{oc} , I_{sc} and FF . The voltage losses of $\Delta V_{oc,CzA} = -10.6$ mV and $\Delta V_{oc,CzB} = -8.8$ mV and current losses of $\Delta I_{sc,CzA} = \Delta I_{sc,CzB} = -0.05$ A are caused by the reduction of the bulk lifetime due to the activation of the BO complex, see section 3 and Fig. 3b. The fill factor losses of $\Delta FF_{CzA} = -1.6\%$ _{abs} and $\Delta FF_{CzB} = -1.5\%$ _{abs} predominantly result from losses in pseudo fill factor (pFF). This FF loss will be discussed in more detail in section 4.1.2.

The degradation-induced losses in the Cz cells can be recovered by regeneration while the FZ reference cell is stable in all three states. As can be seen in Fig. 4, this recovery is stable upon a second degradation cycle which is performed under the same conditions as the previous degradation but for a longer time of five days. This fourth state is thus called “stabilized”. Hence, as expected from literature, the recombination-active defect centre related to the BO complex seems to be permanently deactivated by the applied regeneration procedure with simultaneous heating and illumination, at least on solar cell level.

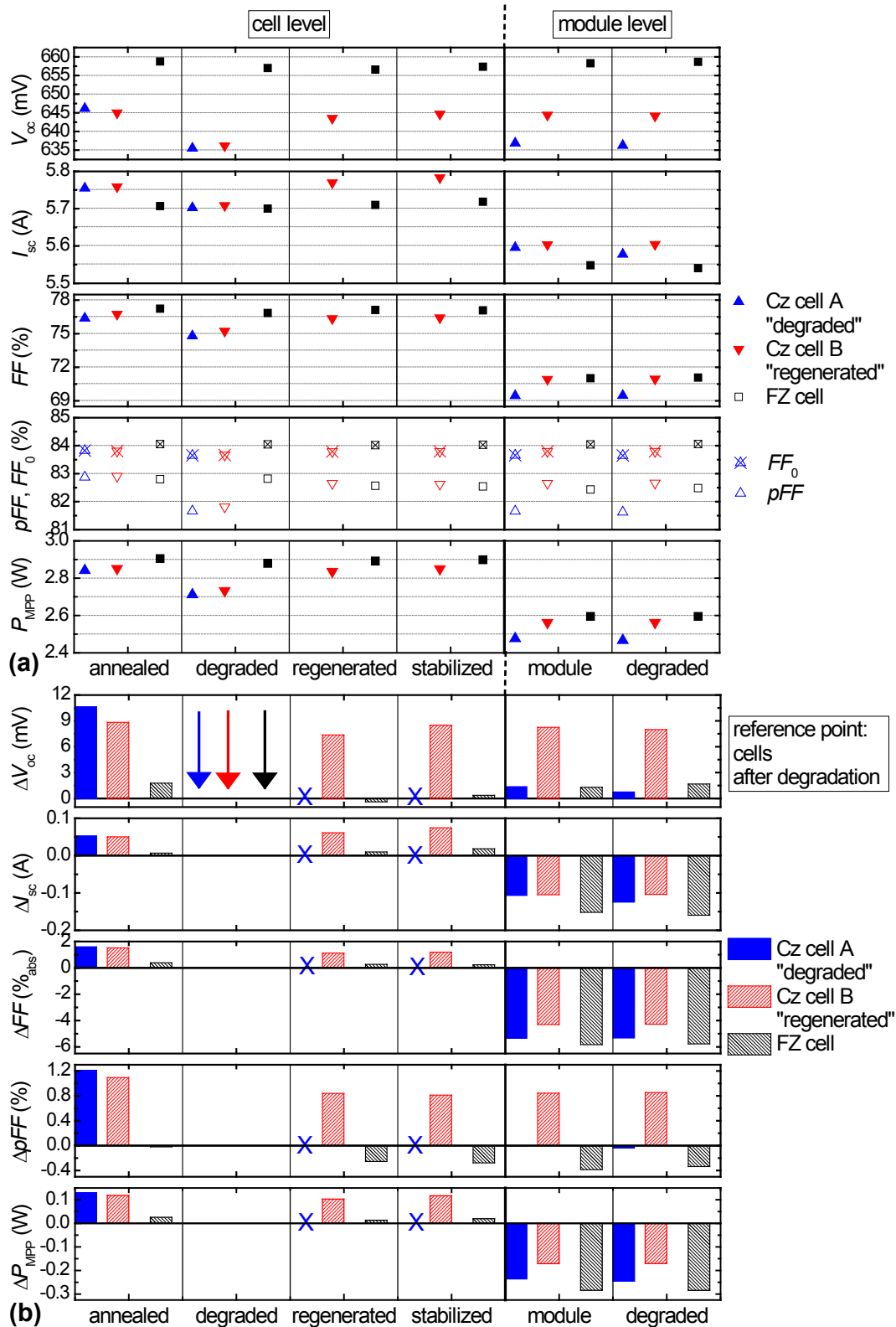


Figure 4: (a) Measured illuminated $I-V$ parameters open-circuit voltage V_{oc} , short-circuit current I_{sc} , fill factor FF , pseudo fill factor pFF , ideal fill factor FF_0 and maximum output power P_{MPP} after each conditioning step sketched in Fig. 1. (b) Absolute differences in the different conditioning steps compared to values **after degradation** (indicated by arrows) for each of the three cells.

4.1.2. In-depth characterisation of fill factor FF

In order to determine which amount of the observed FF variation in-between defect states is caused by the impact of the BO defect on lifetime, the effects on FF are investigated in detail. A limitation of the FF can be composed of multiple contributions.

(i) The trivial cause is, that a lower V_{oc} also leads to a lower FF . Applying Green's formula for the maximum fill factor FF_0 of an ideal diode with ideality factor $n = 1$ (p. 96 in [32]), a drop in V_{oc} of $\Delta V_{oc} = 646 \text{ mV} - 636 \text{ mV} = 10 \text{ mV}$, as it is observed for the Cz cells, results in a drop in FF_0 of $\Delta FF_0 = 83.73 \% - 83.55 \% = 0.18 \%_{\text{abs}}$.

(ii) A further effect degrading fill factor is series resistance R_s . When R_s is assumed to be lumped and/or small, which is the case for the cells discussed here, its effect on the pseudo fill factor can be neglected [33].

(iii) The pFF , however, can be affected by parallel resistance R_p when being too low. The measured values are $R_{p, Cz A/B} > 10 \text{ k}\Omega\text{cm}^2$, $R_{p, FZ} > 4 \text{ k}\Omega\text{cm}^2$ and, therefore, do not degrade pFF significantly.

(iv) Additional losses of the fill factor can originate from non-idealities of the diode such as injection-dependent changes in minority carrier lifetime along the course of the I - V curve. This influences the fill factor of the I - V curve under 1 sun illumination and the pFF [20, 21] in a similar manner, as derived in section 3. The root causes for injection-dependent lifetime include recombination in the space charge region, injection-dependent bulk lifetime (see section 3) and injection-dependent surface recombination velocity.

We quantify the fill factor differences due to the activation and deactivation of the BO defect by using a fill factor loss analysis according to [33] with an emphasis on the pFF . To motivate this approach, we discuss the suns- V_{oc} curves of all three cells for the three discussed defect states in the following paragraphs.

If the non-idealities of a solar cell are described with a voltage-dependent saturation current density $J_0(V)$ rather than with a second diode [2, 3] and/or a voltage-dependent local ideality factor [34], a solar cell's suns- V_{oc} characteristic can be written as

$$c \cdot E(V_{oc}) = J_0(V_{oc}) \cdot \left(\exp\left(\frac{V_{oc}}{V_t}\right) - 1 \right), \quad (4)$$

with the constant c being the conversion factor between E and J . We assume R_p being sufficiently high to not affect the characteristic which is the case for the discussed cells (see above). The proportionality of illumination intensity E and J_{sc} has been confirmed on Cz and FZ cells from the same batch by measurements in the intensity range of $E = 0.1 - 1.2$ suns. If we consider two defect states of the same cell, for example the annealed and the degraded state,

$$c \cdot E = J_0(V_{oc,ANN}) \cdot \left(\exp\left(\frac{V_{oc,ANN}}{V_t}\right) - 1 \right) = J_0(V_{oc,DEG}) \cdot \left(\exp\left(\frac{V_{oc,DEG}}{V_t}\right) - 1 \right) \quad (5)$$

holds true for every illumination intensity E . Assuming $\exp(V_{oc}/V_t) \gg 1$, an open-circuit voltage difference of

$$\Delta V_{oc} = V_{oc,ANN} - V_{oc,DEG} = V_t \cdot \ln\left(\frac{J_0(V_{oc,DEG})}{J_0(V_{oc,ANN})}\right) \quad (6)$$

can be calculated which does not directly depend on E . However, $V_{oc,DEG}$ and $V_{oc,ANN}$ are both functions of E , respectively. Hence, if J_0 shows a different injection-dependence in different defect states of the same cell, ΔV_{oc} will vary with illumination intensity E . The stronger ΔV_{oc} varies with varying E , the stronger is the difference in the injection-dependence of J_0 in-between the two states.

Fig. 5a (top) depicts the suns- V_{oc} curves of Cz cell A in the annealed and degraded state. The kink in the degraded curve is not as pronounced as in Fig. 2c but still prominent. When comparing $\Delta V_{oc}(E = 0.05 \text{ suns})$, which is close to the maximum power point of the J_{sc} -shifted suns- V_{oc} curve (pMPP), and $\Delta V_{oc}(E = 1.0 \text{ suns})$, a decrease of ΔV_{oc} from $\Delta V_{oc}(E = 0.05 \text{ suns}) = 17.2 \text{ mV}$ to $\Delta V_{oc}(E = 1.0 \text{ suns}) = 10.6 \text{ mV}$ with increasing illumination intensity E can be observed, as shown in Fig 5b. This results in a drop in pFF of $\Delta pFF = -1.2 \%_{\text{abs}}$. The ideal fill factor FF_0 drops by $\Delta FF_0 = -0.2 \%_{\text{abs}}$ due to $\Delta V_{oc}(E = 1.0 \text{ suns}) = 10.6 \text{ mV}$, compare contribution (i) discussed above. Hence, it can be concluded that the remaining pseudo fill factor loss of $\Delta pFF = -1.0 \%_{\text{abs}}$ is caused by the changes in injection-dependent SRH lifetime upon activation of the BO defect.

Fig. 5 and Table A.1 (see appendix) also show the respective plots and values for Cz cell B and the FZ reference cell considering the annealed, degraded and regenerated state. The voltage difference ΔV_{oc} between annealed and degraded state behaves similarly for Cz cells A and B causing a similar effect on pFF . For the FZ cell, the annealed and degraded curves line up very closely exhibiting values of $\Delta V_{oc} < 2$ mV across the considered illumination intensity range causing no degradation in pFF . When considering ΔV_{oc} between the annealed and regenerated state, an increase towards lower illumination intensities occurs for Cz cell B and the FZ reference cell. This increase is in the same order for both cells which indicates, that the effect is process- and not material-induced. However, this effect only accounts for a loss in pFF of $\Delta pFF \geq -0.3 \%_{abs}$ compared to the discussed $\Delta pFF = -1.0 \%_{abs}$ which results from only the changes in injection-dependent lifetime upon activation of the BO defect. This pFF difference is in good agreement with values found by Schmidt *et al.* [20, 35].

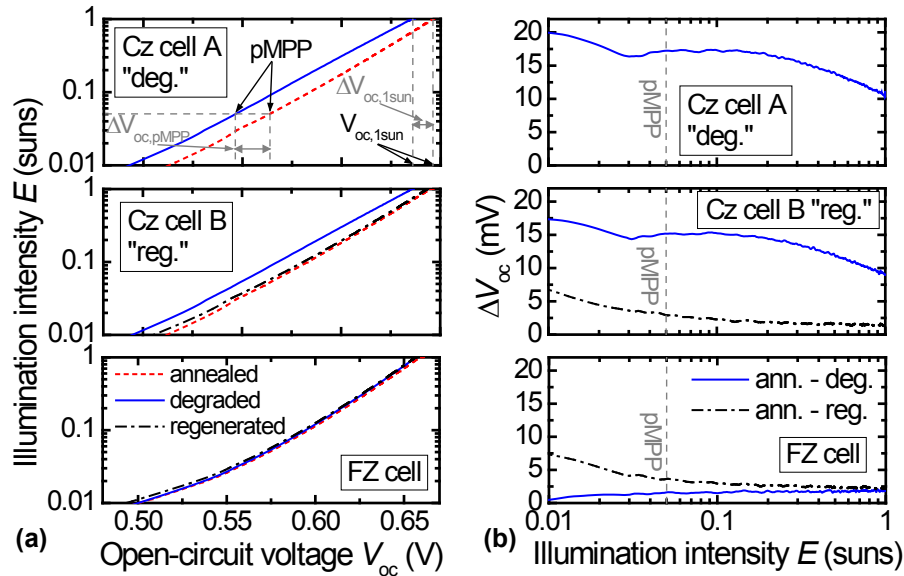


Figure 5: (a) Measured suns- V_{oc} curves of all three considered cells for the three different defect states. (b) Difference in open-circuit voltages V_{oc} in-between different defect states for the three cells as a function of illumination intensity E .

Fig. 4 summarizes the results of the fill factor analysis (additional values are given in Table A.1). The fill factor degradation from the annealed to the degraded state for the Cz cells is mainly caused by a degradation in pFF due to the strong injection-dependence of the SRH lifetime of the activated BO complex, as discussed in section 3. By regeneration, the original fill factor value can almost be recovered and is stable upon subsequent illumination for five days. As this behaviour is characteristic to the metastable BO defect, we exclude other injection-dependent mechanisms, such as injection-dependent surface recombination velocity, as cause for the fill factor degradation. The FF of the FZ cell does not change to a large extent in-between all preparation steps conducted on cell level which proves that there are no major process-induced effects on FF .

In summary, characterising the different states on cell level reveals that, for Cz cell B, all illuminated $I-V$ parameters (V_{oc} , I_{sc} and FF) can be almost completely recovered by the regeneration step and are stable upon subsequent illumination for five days while the reference FZ cell does not degrade.

4.2. Module level

With the solar cells being conditioned in different states, the next steps in the experimental design, see Fig. 1, are module integration and subsequent illumination to investigate whether the achieved gain by regeneration of the boron-oxygen defect on cell level is transferable to module level. For the $I-V$ and suns- V_{oc} measurements on module level, different shading patterns have been applied to control the effect of total internal reflection under the module glass. All given measurement values have been recorded with a shading pattern representing the symmetry element in a standard industrial module, that is a square pattern with an opening of $A = 127 \times 127 \text{ mm}^2$ simulating the distance of cells in a module to be $d = 2 \text{ mm}$.

To interpret the results, Fig. 4 and 6 have to be considered coherently. Fig. 6 shows the differences in V_{oc} , I_{sc} , FF , pFF and P_{MPP} compared to the values of each cell in a reference state before module integration. That is, for Cz cell A the degraded state, for Cz cell B the stabilized state after successful regeneration and for the FZ cell the state after the same treatment as for Cz cell B.

The deviation in V_{oc} before and after module integration is $\Delta V_{oc} < 1.5$ mV for all cells which shows that there is no significant degradation. As illustrated in Fig. 4b, the gain in V_{oc} of $\Delta V_{oc} \approx 8$ mV due to regeneration of the BO defect compared to the degraded values can be transferred to module level. This is also true after subsequent illumination of the modules for $t > 48$ h. For a rough, theoretical estimate of possible temperature-induced effects during the moduling process on V_{oc} , Herguth's [10] data on the temperature-dependent decay constants on cell level for the destabilization of the regenerated state in the dark are used. However, the experimental data provided by Herguth are not in the range of the applied temperatures during the moduling process. Hence, his data need to be extrapolated to higher and lower temperatures. For V_{oc} , Herguth determined the activation energy of the destabilization to be $E_a \approx 1$ eV. By manually parameterising and extrapolating Herguth's Arrhenius plot from [10], decay constants of $c_{decay}(T_{soldering} = 225^\circ\text{C}) = 1.1 \times 10^{-1} \text{ min}^{-1}$ and $c_{decay}(T_{lamination} = 133^\circ\text{C}) = 7.2 \times 10^{-4} \text{ min}^{-1}$ result. Assuming worst case conditions for the applied moduling process (see section 2), that is $t(T = 225^\circ\text{C}) = 2$ s and $t(T = 133^\circ\text{C}) = 30$ min, a loss of less than 3 %_{rel} in V_{oc} gain is calculated. Although in general extrapolated data need to be considered with care, our experimental data support Herguth's findings.

Considering FF , both Cz cells exhibit the same degradation due to the module integration, as shown in Fig. 6. As the pFF is preserved during module integration, the loss in FF can be fully attributed to additional series resistance losses in the cell interconnectors and feed lines. Due to the layout of the mini-module, the additional series resistance per cell is slightly higher than for standard industrial modules with $n \geq 60$ cells. Fig. 4b illustrates, that the gain in FF and pFF due to regeneration can be transferred to module level and is stable upon subsequent illumination of the module.

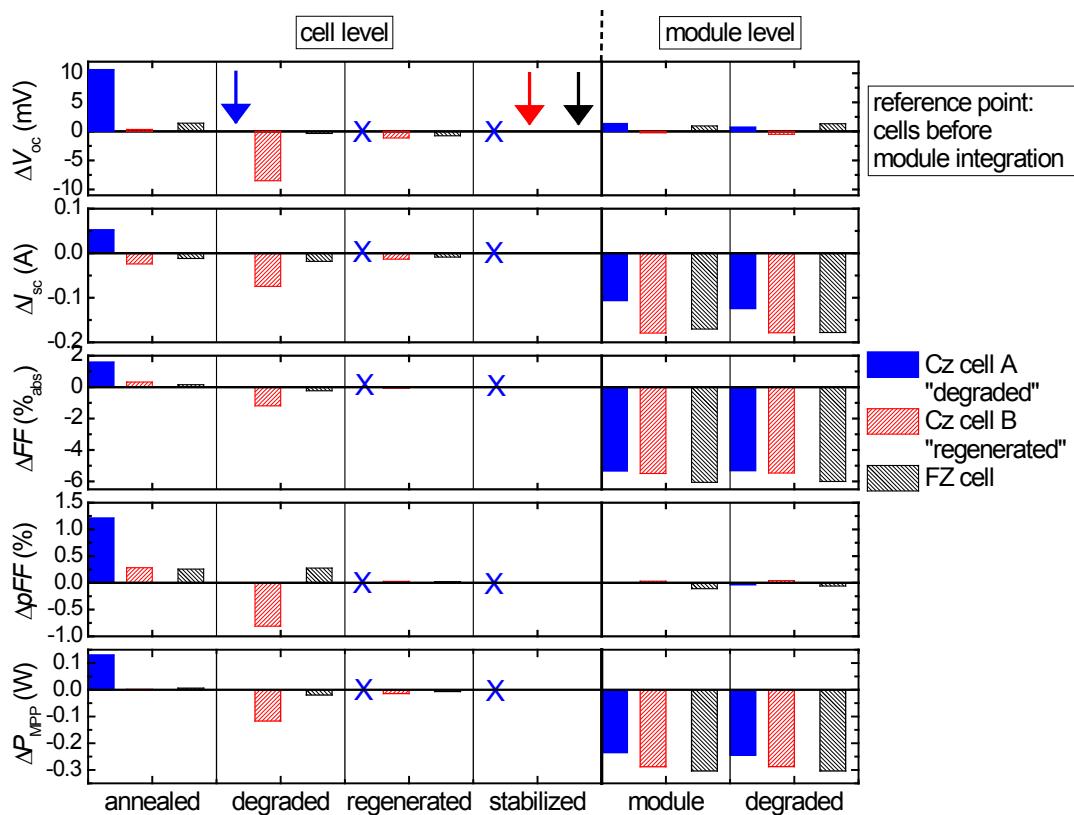


Figure 6: Absolute difference in open-circuit voltage V_{oc} , short-circuit current I_{sc} , fill factor FF , pseudo fill factor pFF and maximum output power P_{MPP} compared to values of each cell **before module integration** (indicated by arrows). Note, that Fig. 6 shows the same data as Fig. 4b but calculated with respect to a different reference point for each cell.

Concerning I_{sc} , Fig. 4b shows that the I_{sc} advantage due to regeneration of the BO defect can be transferred to module level when comparing Cz cell B to the FZ reference. However, compared to Cz cell A, which is in the degraded state before module integration, the gain in I_{sc} due to regeneration on cell level cannot be completely transferred to module level, as can be seen in Fig. 4b. The effect of differing I_{sc} losses in-between modules becomes more pronounced when considering the absolute difference of I_{sc} compared to its values before module integration (see Fig. 6). Cz cell B and the FZ cell lose $\Delta I_{sc,moduling} = -179$ mA and -178 mA, respectively, due to module encapsulation while Cz cell A, surprisingly, only loses $\Delta I_{sc,moduling} = -125$ mA. The difference in I_{sc} degradation upon module encapsulation between Cz cell A and B amounts to $\Delta I_{sc,moduling, Cz A} - \Delta I_{sc,moduling, Cz B} = -125$ mA $- (-179$ mA) $= 54$ mA. Both, V_{oc} and pFF , remain constant during module assembly, which indicates that Cz cell A is still in its degraded state. There are three main effects that could cause different absolute losses in I_{sc} during moduling: (i) differences in optical coupling of the individual cells when comparing air and module encapsulation, (ii) different parasitic absorption of the glass and EVA of the different modules, (iii) different effective shading caused by the soldered cell interconnectors. Different shading and backsheet scattering due to different alignment of the shading pattern during $I-V$ measurements can be excluded as repeated measurements show.

All three effects should influence the external quantum efficiencies (EQE) of the considered cells and modules. As shown in Fig. 3, the effect of activation and deactivation of the BO defect affects quantum efficiency for wavelengths of $\lambda > 750$ nm. To focus on effects related to the moduling process only, wavelengths up to $\lambda = 750$ nm are considered in the following discussion. Fig. 7a depicts the measured EQE of the three considered cells in their state before module encapsulation and Fig. 7b a cut-out. It can be seen that, in the depicted wavelength range, the EQE of Cz cells A (being degraded) and B (being regenerated) are almost identical. Fig 7c depicts the EQE of the three cells after module encapsulation and Fig. 7d a cut-out. It can be seen that the module encapsulation is non-transparent for wavelengths $\lambda < 355$ nm. To estimate the effect of differing EQE on cell and module level on I_{sc} , we calculate a cumulated $I_{sc,cumulated}$ giving the integrated spectral contribution up to a wavelength λ via

$$I_{sc,cumulated}(\lambda) = \int_{\lambda=300nm}^{\lambda} S(\lambda') \cdot EQE(\lambda') \cdot \frac{q \cdot \lambda'}{h \cdot c} \cdot d\lambda', \quad (7)$$

with $S(\lambda)$ being the energy density of the irradiated spectrum, h Planck's constant and c the speed of light. Fig. 7e shows the difference in $I_{sc,cumulated}$ between cell and module level for each cell using the measured spectrum of the flasher used for $I-V$ measurements within the industrial cell tester at Fraunhofer ISE, see right hand axis in Fig. 7e. The cumulated cell-to-module I_{sc} difference exhibits a maximum at $\lambda \approx 385$ nm due to the parasitic absorption in the module encapsulation. For higher wavelengths, the difference decreases; this decrease in $\Delta I_{sc,cumulated}$ is more pronounced for Cz cell A than for the other two cells. Up to $\lambda = 750$ nm, this accounts for $\Delta I_{sc}(\lambda = 750 \text{ nm}) \approx 35 - 38$ mA. When using the AM1.5G spectrum [36] to calculate $I_{sc,cumulated}$, a difference of $\Delta I_{sc}(\lambda = 750 \text{ nm}) \approx 35 - 39$ mA results which is almost identical to the values resulting from using the measured flasher spectrum. This indicates a good quality of the applied flash lamp. Hence, calculating a cumulated cell-to-module I_{sc} difference up to $\lambda = 750$ nm explains almost three quarters of the measured difference in I_{sc} .

The parasitic absorption of the module encapsulation system leads to a maximum in $\Delta I_{sc,cumulated}$ at $\lambda \approx 385$ nm, see Fig. 7e. The absolute magnitude of the maximum of Cz cell A compared to the other two cells is slightly lower but only accounts for $\Delta I_{sc} \approx 3 - 4$ mA which shows that differences in the parasitic absorption of the module encapsulation system are unlikely as the root cause for the current difference. When comparing the spectral reflectance of the entire encapsulated cell with the spectral reflectance of a position in-between busbars of the cells, the additional shading contribution of the cell interconnectors can be assessed. Since this parameter does not differ significantly in-between the three cells, also parasitic shading due to cell interconnectors is implausible as the root cause. That leaves differences in optical coupling due to slightly differing indices of refraction, thicknesses of the anti-reflective coating and/or differing back-reflection from the glass due to differing metallisation finger shapes as remaining, possible explanations. This thesis is also supported by a slight difference in the measured spectral reflectance of the three cells on cell and module level, see Fig. 7f. This is also visible in the EQE in Fig. 7b and d. The last quarter of the observed deviation is suspected to originate from better optical coupling in the wavelength range of $750 \text{ nm} < \lambda < 1200 \text{ nm}$.

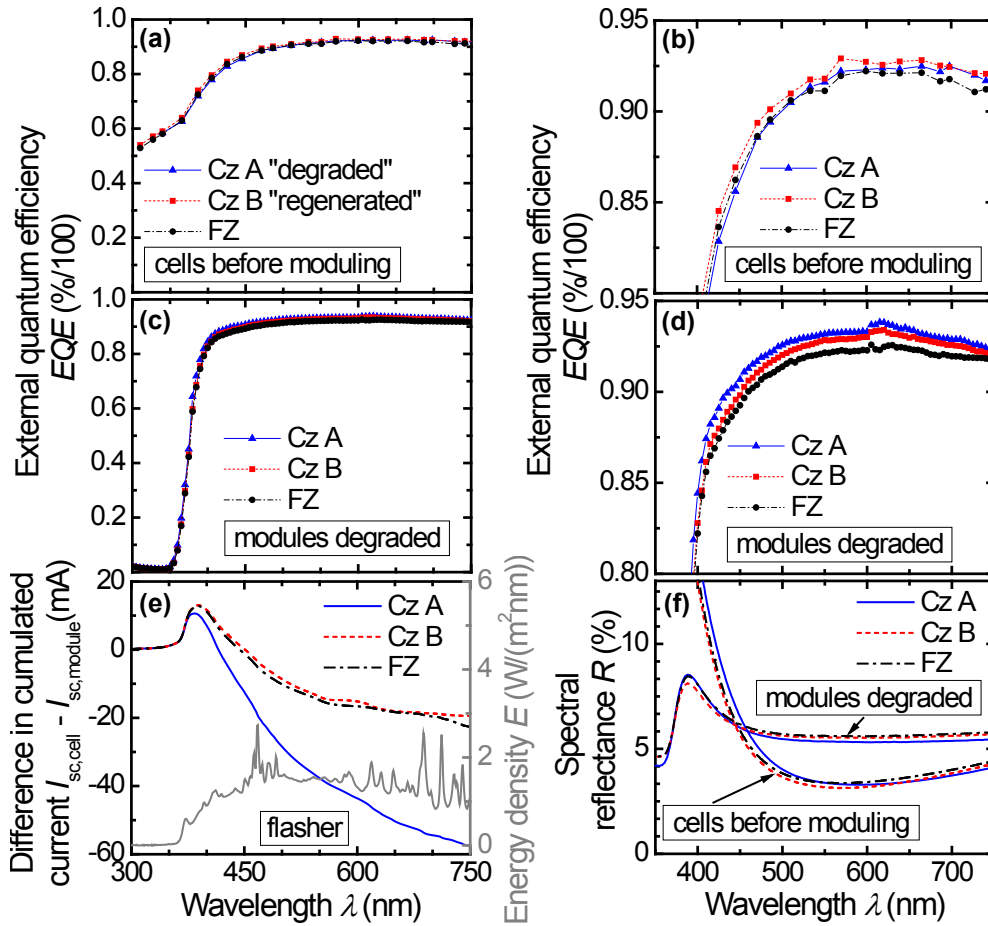


Figure 7: (a) Measured external quantum efficiency EQE of the three discussed cells before module integration. (b) Cut-out of Fig. 7a. (c) EQE of the cells when being encapsulated. (d) Cut-out of Fig. 7c. (e) Difference in cumulated I_{sc} values between cell and module level calculated according to Eq. (7) using the measured spectrum of the applied flasher during I - V testing. (f) Spectral reflectance before and after module integration.

In summary, the relative gain in V_{oc} and FF due to regeneration can be transferred to module level while the module encapsulation-induced loss in I_{sc} is slightly smaller for Cz cell A compared to the other two cells. However, a significant gain in P_{MPP} can still be transferred to module level, as can be seen in Fig. 4a. The difference between Cz cell B (being regenerated) and Cz cell A (being degraded) before module integration amounts to $\Delta P_{MPP} = 139$ mW. On module level, the difference between both cells still amounts to $\Delta P_{MPP} = 96$ mW. Comparing Cz cell B with the FZ cell in the same manner, values of $\Delta P_{MPP} = -49$ mW before and $\Delta P_{MPP} = -32$ mW after module integration result. Hence, it can be concluded, that a gain due to regeneration of the BO defect on cell level can be transferred to module level.

5. Summary and conclusion

Regenerating the BO defect in passivated emitter and rear solar cells fabricated on industrial boron-doped p -type Cz wafers with a base resistivity of $\rho_b = 2.3$ Ω cm leads to an increase in all illuminated I - V parameters resulting in an efficiency gain of $\Delta \eta_{cell} = 0.8 - 0.9$ %_{abs}. In accordance with previous studies, it is shown that the difference in FF is mainly due to the injection-dependent SRH lifetime of the BO defect in its active state accounting for a regeneration-induced fill factor gain of $\Delta FF_{cell} > 1.0$ %_{abs}. This effect shows also in the pFF which can be determined from suns- V_{oc} measurements. The experimentally observed effects can be described qualitatively by simulating the impact of activation and deactivation of the BO defect on solar cell parameters.

We have shown that the benefit achieved by regeneration on solar cell level can be transferred to module level when applying industrially used processing steps such as soldering and lamination, and is stable upon subsequent illumination. The I - V parameters of Cz cell B (which is in the regenerated state before moduling) suffer from the same amount of module encapsulation-induced losses as the FZ reference cell. Hence, no Cz-specific degradation of the “regenerated” Cz cell B during module encapsulation is observed. Except for short-circuit current, the same effect is observed for Cz cell A which is in the degraded state before moduling. The difference in I_{sc} in-between Cz cell A and B on module level is most likely due to differences in optical coupling.

These results indicate, that regeneration of the BO defect on cell level might be a possible solution to overcome efficiency limitations of solar cells and modules fabricated from boron-doped p -type Cz silicon wafers.

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Appendix

Table A.1: Differences in ideal fill factor FF_0 , pseudo fill factor pFF , fill factor FF and open-circuit voltages V_{oc} for illumination intensities of $E = 0.05$ suns (representing the pMPP) and $E = 1.0$ suns, in relation to the annealed state for all three considered cells.

state	Difference to annealed state	Cz cell A („degraded“)	Cz cell B („regenerated“)	FZ reference
degraded	ΔFF_0	-0.2 ‰ _{abs}	-0.1 ‰ _{abs}	0.0 ‰ _{abs}
	ΔpFF	-1.2 ‰ _{abs}	-1.1 ‰ _{abs}	0.0 ‰ _{abs}
	ΔFF	-1.6 ‰ _{abs}	-1.5 ‰ _{abs}	-0.4 ‰ _{abs}
	$\Delta V_{oc}(E = 0.05 \text{ suns})$	-17.2 mV	-15.2 mV	-1.6 mV
	$\Delta V_{oc}(E = 1.0 \text{ suns})$	-10.6 mV	-8.8 mV	-1.8 mV
regenerated	ΔFF_0	-	0.0 ‰ _{abs}	0.0 ‰ _{abs}
	ΔpFF	-	-0.3 ‰ _{abs}	-0.2 ‰ _{abs}
	ΔFF	-	-0.4 ‰ _{abs}	-0.1 ‰ _{abs}
	$\Delta V_{oc}(E = 0.05 \text{ suns})$	-	-2.9 mV	-3.6 mV
	$\Delta V_{oc}(E = 1.0 \text{ suns})$	-	-1.5 mV	-2.2 mV
stabilized	ΔFF_0	-	0.0 ‰ _{abs}	0.0 ‰ _{abs}
	ΔpFF	-	-0.3 ‰ _{abs}	-0.3 ‰ _{abs}
	ΔFF	-	-0.3 ‰ _{abs}	-0.2 ‰ _{abs}
	$\Delta V_{oc}(E = 0.05 \text{ suns})$	-	-3.2 mV	-3.3 mV
	$\Delta V_{oc}(E = 1.0 \text{ suns})$	-	-0.3 mV	-1.4 mV
module	ΔFF_0	-0.2 ‰ _{abs}	0.0 ‰ _{abs}	0.0 ‰ _{abs}
	ΔpFF	-1.2 ‰ _{abs}	-0.3 ‰ _{abs}	-0.4 ‰ _{abs}
	ΔFF	-6.9 ‰ _{abs}	-5.8 ‰ _{abs}	-6.2 ‰ _{abs}
	$\Delta V_{oc}(E = 0.05 \text{ suns})$	-16.4 mV	-2.3 mV	-3.4 mV
	$\Delta V_{oc}(E = 1.0 \text{ suns})$	-9.3 mV	-0.6 mV	-0.5 mV
module, degraded	ΔFF_0	-0.2 ‰ _{abs}	0.0 ‰ _{abs}	0.0 ‰ _{abs}
	ΔpFF	-1.2 ‰ _{abs}	-0.2 ‰ _{abs}	-0.3 ‰ _{abs}
	ΔFF	-6.9 ‰ _{abs}	-5.8 ‰ _{abs}	-6.2 ‰ _{abs}
	$\Delta V_{oc}(E = 0.05 \text{ suns})$	-17.2 mV	-2.4 mV	-2.7 mV
	$\Delta V_{oc}(E = 1.0 \text{ suns})$	-9.9 mV	-0.8 mV	-0.1 mV

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