Impact of Light Soaking on *p*-Type Boron- and Indium-Doped Passivated Emitter and Rear Solar Cells on Czochralski-Grown Silicon

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Solar cells fabricated on boron-doped Czochralski-grown silicon (Cz-Si) wafers are known to suffer from light-induced degradation (LID). In this work, the effect of light soaking on passivated emitter and rear (PERC) solar cells fabricated on both indium (In)-doped Cz-Si and boron (B)-doped Cz-Si wafers are investigated. Efficiencies up to 20.7% and 21.2% are obtained on In-doped and B-doped Si wafers, respectively. Though the initial conversion efficiency is lower with In-doped Si wafers, these cells show no LID after light soaking (1.0 Sun illumination at 25 °C for 85 h). In contrast, cell efficiencies dropped significantly for B-doped Si wafers, by 0.8%.

1. Introduction

Approximately 95% of crystalline silicon (*c*-Si) solar cell market share is held by *p*-type silicon substrates.[1] When exposed to sunlight, the conversion efficiency of solar cells made with *p*-type Cz-Si are prone to degrade[2] especially in the first few hours of illumination. This LID is triggered by above-bandgap illumination as well as by forward bias voltage.[3–5] LID decreases J_{sc} and V_{oc}, due to the increased minority–carrier recombination in the wafer bulk.[6] Previous work had observed that increase in boron–oxygen (B-O) complex increases the LID in B-doped Cz-Si wafers,[4,6,7] with passivated emitter and rear cells (PERC) efficiencies degrading as much as 4–6%$_{relative}$ due to the B-O defects.[8]

Schmidt et al. proposed and demonstrated that the impact of B-O related LID can be reduced by i) using *n*-type materials; ii) by choosing *p*-type material with reduced oxygen (O) and B concentrations; or iii) by substituting B with In or Ga.[4,6] The In dopant is chosen to avoid lifetime degradation during light soaking. Though In and Ga are both viable alternatives to B-dopants, the higher melting point of In (156 °C) can allow for improved doping uniformity in continuous Cz growth compared to Ga.[9] Very few reports are available on the solar cell performance of In-doped wafers and their LID response.[9–11] Cho et al. demonstrated 20.3% efficient PERC devices with no LID on Cz-grown In-doped wafers.[9]

In this study, we report on the fabrication of PERC devices on both B-doped and In-doped *p*-type Cz-Si wafers. The light soaking performance of these B-doped and In-doped devices are presented and compared.

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2. Experimental Section

2.1. Sample Preparation

All B-doped and In-doped *p*-type solar cells used in this study were fabricated on large area, 244.3 cm^2, pseudo square, monocrystalline Si wafers with bulk resistivity of 1–3 Ω cm. Both B-doped and In- doped Cz ingot were grown by Continuous Czochralski (CCz) method. B-doped wafers from two different manufacturers were used in this study, designated as B1 and B2. **Figure 1**(a) outlines the PERC fabrication process. The wafers were first saw damage etched in a KOH solution to remove ≈15 µm from each side. A SiN_x masking layer was then deposited onto the rear surface to act as an etching barrier for the subsequent alkaline texturing process. The wafers were textured using isopropyl alcohol (IPA)-free alkaline texturing solution to generate a random pyramid surface texture on the front. The wafers then went through a phosphorus diffusion in an industrial tube diffusion furnace (Quantum, Tempress, The Netherlands), resulting in a sheet resistance of 90 Ω □$^{-1}$. Following the diffusion process, 10% HF was used to remove the phosphosilicate glass (PSG) and the rear SiN_x masking layer. The wafers were then split into two different groups. For solar cells, the front surface was passivated with a PECVD SiN_x layer with a refractive index (n) of 2.05 and thickness of 70 nm. The SiN_x layers were capped with an additional 90 nm of silicon oxide (SiO_x) with $n = 1.46$ to enhance the front optics. The rear side of all the wafers were passivated using a 20 nm AlO_x, 80 nm SiO_x, and 70 nm SiN_x stack. All PECVD layers were deposited using inline microwave plasma reactor (MAiA, Meyer Burger Germany). The rear $AlO_y/SiO_x/SiN_x$ stack was then locally

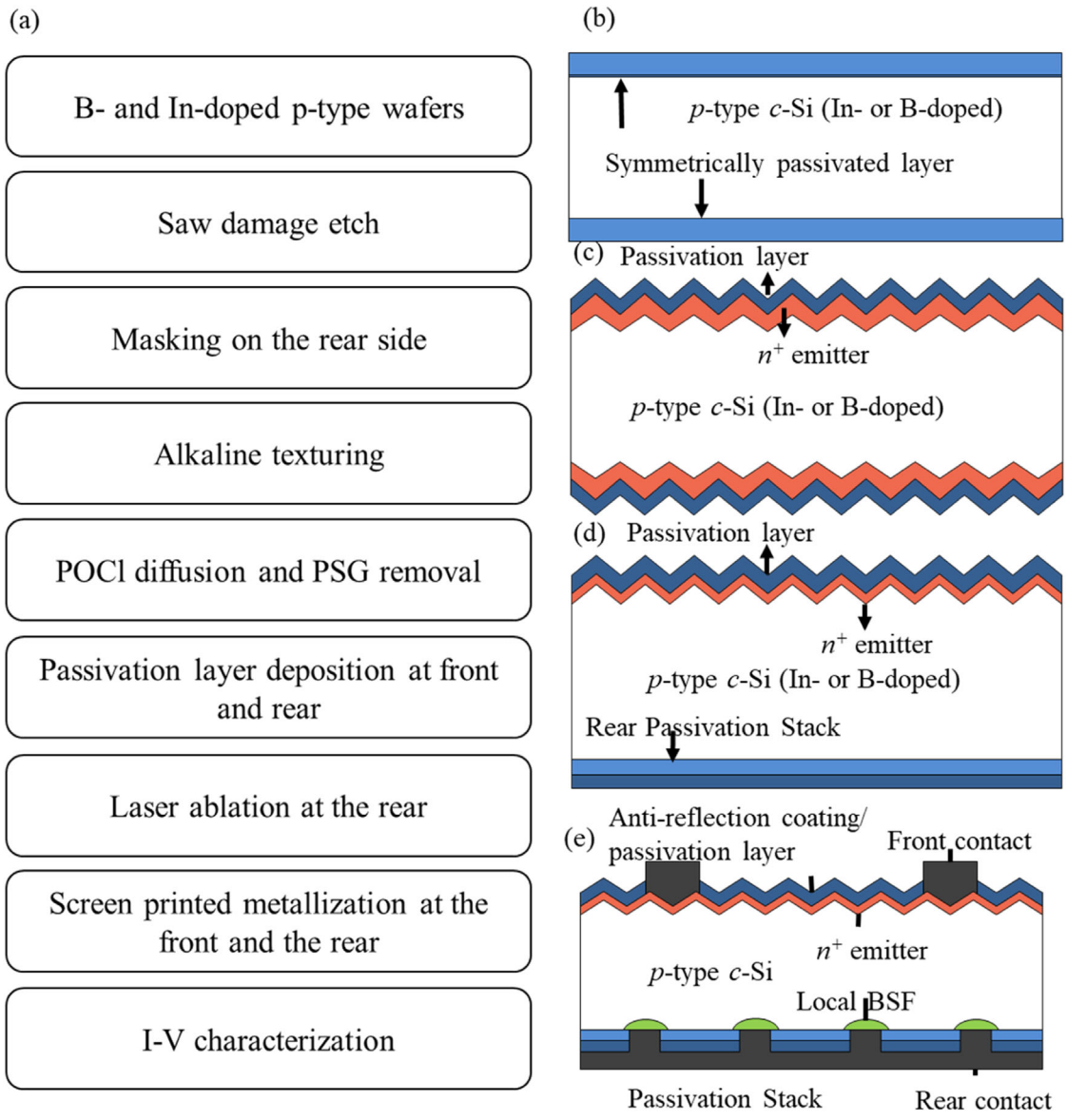

Figure 1. a) Processing sequence; b) bulk lifetime measurement; c) lifetime on textured phosphorus diffused surface; d) test structure for iV_{oc} measurements; and e) schematic of the PERC devices.

ablated using a nanosecond green laser (Innolas, Germany) with a central wavelength of 532 nm and pulse duration of 38 ns. Following rear dielectric ablation, aluminum (Al) paste from Toyo Aluminium (Japan) was screen-printed onto the entire rear surface. The front grid consisted of 35 μm wide finger openings with 105 fingers and 5 busbars, and was printed using silver (Ag) paste (PV20, DuPont). The cells were then fired in an industrial fast-firing furnace (Sinterra, BTU, USA).

2.2. Characterization Methods

The phosphorus-diffused emitter sheet resistance was measured using a 4-point probe (SR2000N, AIT Instruments, South Korea). The bulk lifetime and implied V_{oc} (iV_{oc}) of non-metallized and non-laser processed wafers were measured using a Sinton photoconductance tool using quasi-steady-state photoconductance (QSSPC) technique.[12] To measure the bulk lifetime, the saw damage of the wafers were removed and symmetrically

Table 1. Resistivity, oxygen concentration, and bulk lifetime of B-doped and In-doped wafers.

Wafer type	Thickness [μm]	Wafer resistivity [ohm cm]	Oxygen interstitial [atoms cm^{-3}]
B1	190	3.05	1×10^{18}
B2	180	1.45	1×10^{18}
In	190	2.6	7.5×10^{17}

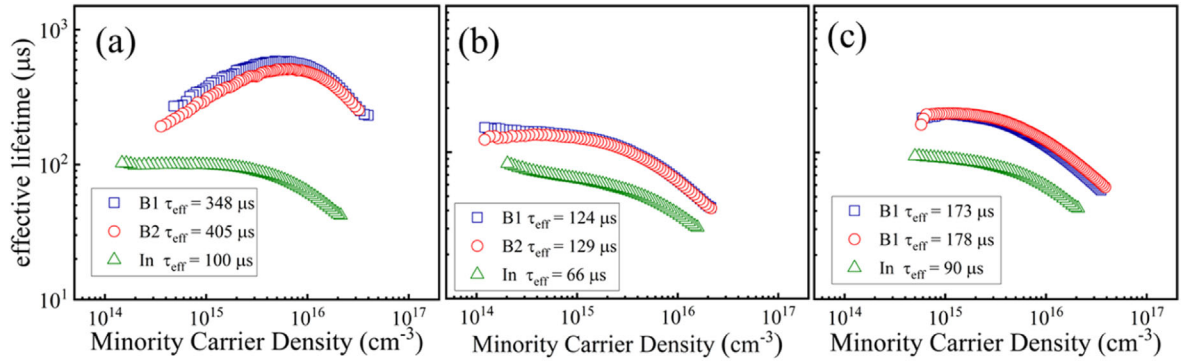

Figure 2. Measured effective lifetime as a function of minority carrier density a) symmetrically passivated on a saw damage etch wafers for bulk lifetime b) symmetrically passivated on textured phosphorus diffused surface c) lifetime of unmetallized cell precursor.

Table 2. Lifetime and iV_{oc} of unmetallized cell precursors at 1.0 Sun.

Wafer type	Lifetime [μs]	iV_{oc} [mV]
B1	173	676
B2	178	679
In	90	669

passivated with high quality thin aluminum oxide (AlO_x) layer by atomic layer deposition. Assuming that the surface recombination values are negligible due to thin ALD AlOx layer passivation, the measured effective lifetime values can be approximated to the wafer bulk lifetime. **Table 1** represents the bulk lifetime values of the B-doped and In-doped samples. One-sun current–voltage (*I–V*) measurements of the finished solar cells were measured using an LED flash tester (SINUS 200, Wavelabs, Germany). The spectral response was measured in the wavelength range between 300 and 1200 nm using a large area spectral response analyzer (SR156, EnliTech, Taiwan) at ≈25 °C.

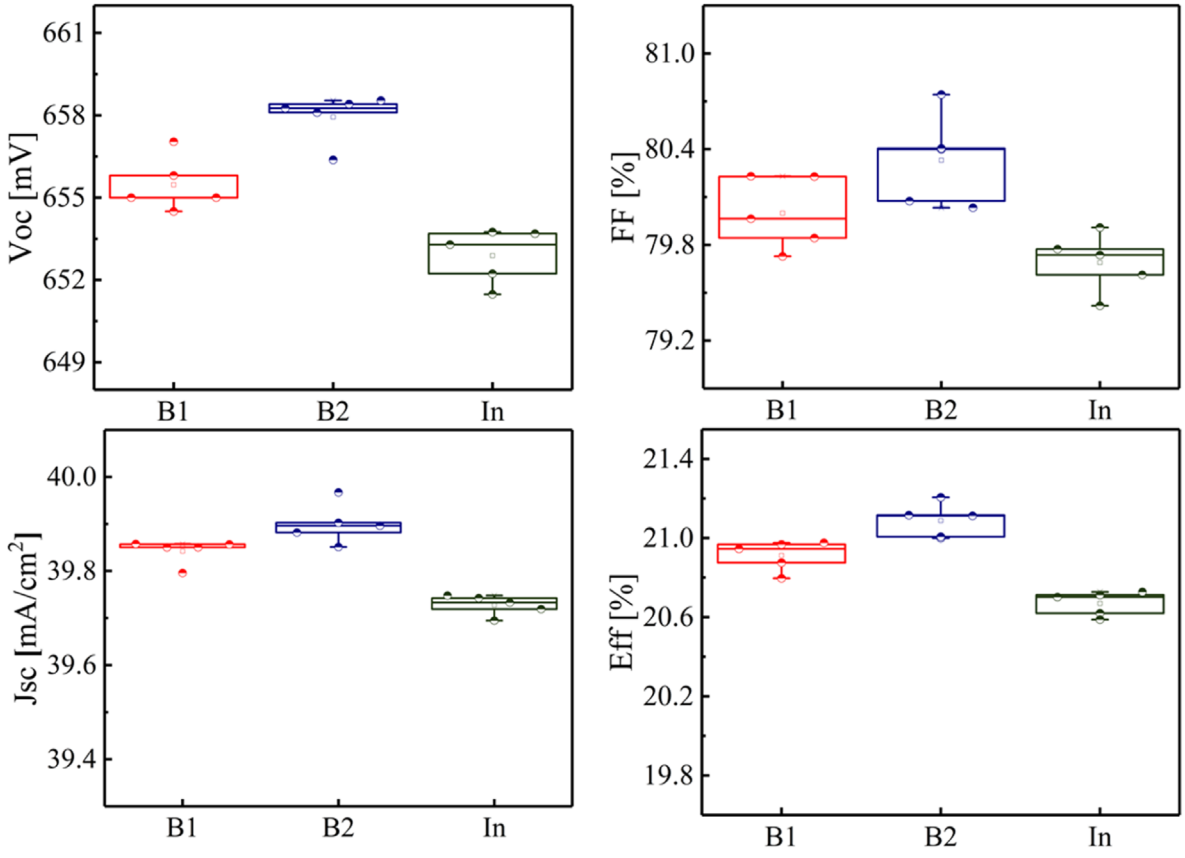

Figure 3. *I–V* characteristics of the PERC devices on B-doped and In-doped wafers.

After initial *I–V* characterization, representative cells from each group were placed in a light soaking system (B-70, Solaronix, Switzerland). The cells were kept at 25 °C and illuminated using a halogen light source at 1.0 Sun light intensity. The cells were kept under illumination for ≈85 h and were removed at specific time intervals for *I–V* measurements.

3. Results and Discussion

Three different test structures (see Figure 1) were fabricated to determine bulk lifetime, emitter saturation current density J_{0e} and iV_{oc} of the B- and In-doped wafers. These structure will help us to improve the fundamental understanding of the difference in B- and In-doped wafers used in this study. The bulk lifetime was directly measured using the test structure as shown in Figure 1(b). **Figure 2** depicts the lifetime values obtained during different processing steps. Bulk lifetime of 348 and 405 µs were obtained for B-doped samples B1 and B2, respectively, where as the In-doped wafers resulted in a bulk lifetime of 100 µs. Carrier lifetime of 124 and 129 µs were obtained for B-doped samples B1 and B2 respectively, on the phosphorus diffused surface (see Figure 1c) where as the In-doped wafers resulted in a lifetime of 66 µs. On the unmetallized cell precursor (see Figure 1d), carrier lifetime of 173, 179, and 90 µs were obtained for the B1, B2, and In-doped samples, respectively.

Table 2 shows the lifetime and iV_{oc} values measured using unmetallized cell precursors as well as the oxygen concentrations measured by Fourier transform infrared spectroscopy for B- and In-doped samples (taken from the wafer specifications sheet). Note that the B2 wafers showed higher iV_{oc} compared with similar resistivity B1 wafers. Compared to both B-doped wafers, the iV_{oc} of the In-doped wafers was ≈5 and ≈20 mV less for B1 and B2 wafers, respectively. This reduction in the iV_{oc} of In-doped wafers is due to the lower wafer bulk lifetime of In doped wafers when compared to B doped wafers used in this study (Refer Table 2).

Figure 3 shows the results of the 1.0 Sun light *I–V* measurements of PERC solar cells fabricated on the B- and In-doped wafers. Among B-doped PERC devices, B2 gave the best efficiency of 21.2% compared with 21.0% from B1 wafers, whereas the In-doped cells resulted in the best efficiency of 20.7%. The difference in the pre-LID efficiencies of the In-doped wafers is mainly due to a lower V_{oc} (≈7 mV) and lower fill factor (*FF*) when compared with the B-doped wafers. This notable difference in efficiency is because PERC cells are more sensitive to bulk lifetimes. Compared with B-doped wafers, In-doped devices typically result in lower bulk lifetimes[10] as there is more inactive dopants that acts as recombination centers.To quantify the influence of resistive and recombination losses on the *FF*, a detailed *FF* loss analysis was carried out (see **Figure 4**).

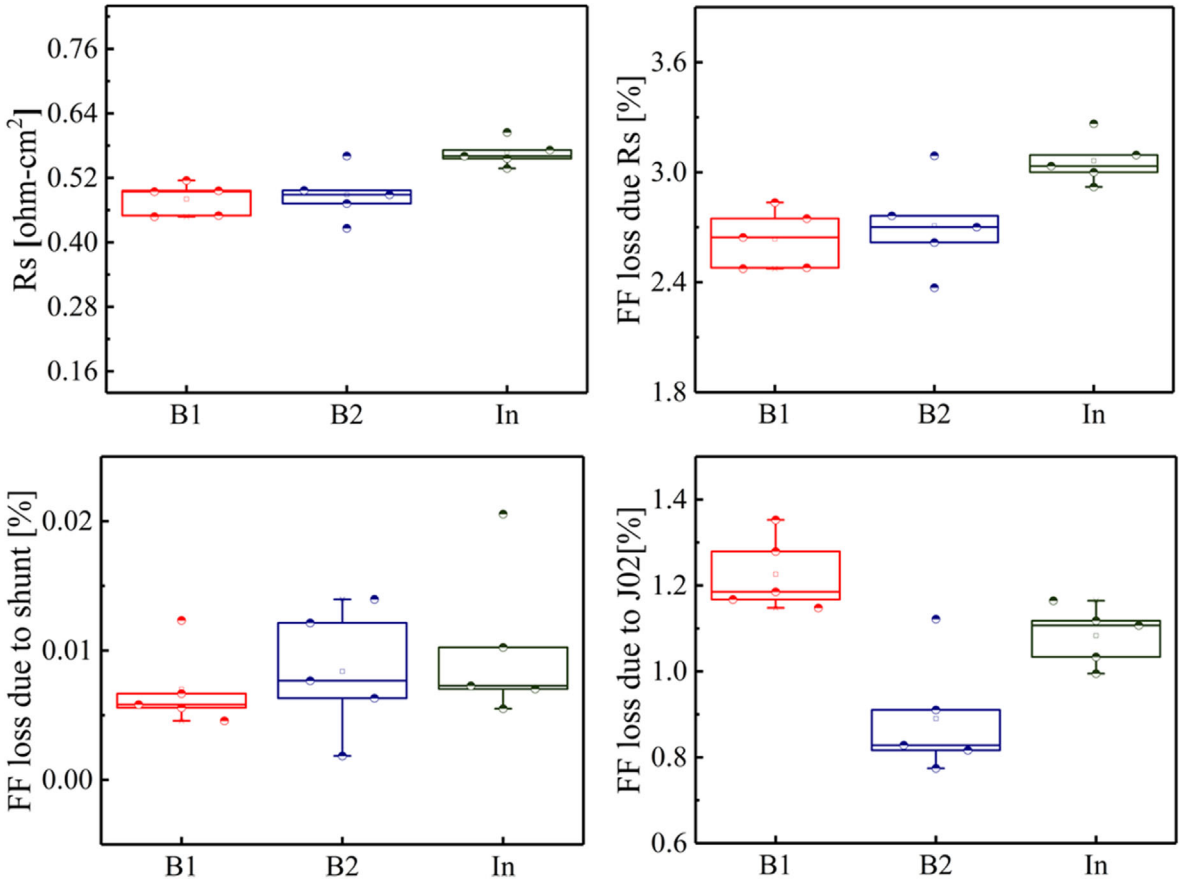

Figure 4. *FF* loss analysis of the PERC devices on B-doped and In-doped wafers.

Table 3. Measured J_{oe} and V_{oc} comparison of B-doped and In-doped wafers.

Wafer type	J_{0b} [fA cm^{-2}]	J_{0e} [fA cm^{-2}]	Calculated iV_{oc} [mV]	Measured iV_{oc} [mV]	Measured V_{oc} [mV]
B1	135	65	676	672	655
B2	125	68	679	674	659
In	186	66	669	666	653

Though the Rs is high for B2 and In, however, the FF loss due to J_{02} is low.

Numerical simulation was carried out to investigate the reason for the observed V_{oc} and efficiency gap between the B-doped and In-doped cells. The structure in Figure 1(b) gives bulk lifetime, and structure in Figure 1(c) gives J_{0e} value of the phosphorus diffused emitter surfacce. The measured J_{0e} values were around ≈66 fA cm^{-2} for both B- and In-doped samples as the emitters were formed simultaneously. The J_{0b} value was ≈125 and ≈186 fA cm^{-2} for the B- and In-doped samples. Using the J_{0b} and J_{0e} values as shown in **Table 3**, and J_{sc} of 39.8 mA cm^{-2}, iV_{oc} for the B- and In-doped cells was calculated using the Equation (1)

$$iV_{oc} = \frac{KT}{q}\ln\left(\frac{J_{sc}}{J_{0e}+J_{0b}}+1\right) \quad (1)$$

The measured and calculated iV_{oc} values of ≤4 mV (Table 3) for both B- and In-doped cells agreed very well. However, there is ≈15 mV drop in V_{oc} after the screen printed metallization compared with the calculated iV_{oc} values of B- and In-doped devices. These drop in V_{oc} values after screen printed metallization are comparable to values reported in the literature.[13]

3.1. Influence of Light Soaking on B- and In-Doped Cells

In this section, we compare the post-light soaking performance of the B- and In-doped cells after they were exposed to 1.0 Sun illumination. **Figure 5** shows the time dependent behavior of the normalized *I–V* characteristics of representative samples. *I–V* data were measured at specific time intervals. There was no significant degradation in the efficiency of the In-doped cell after the light soaking test for a period of 85 h. In contrast, the cell

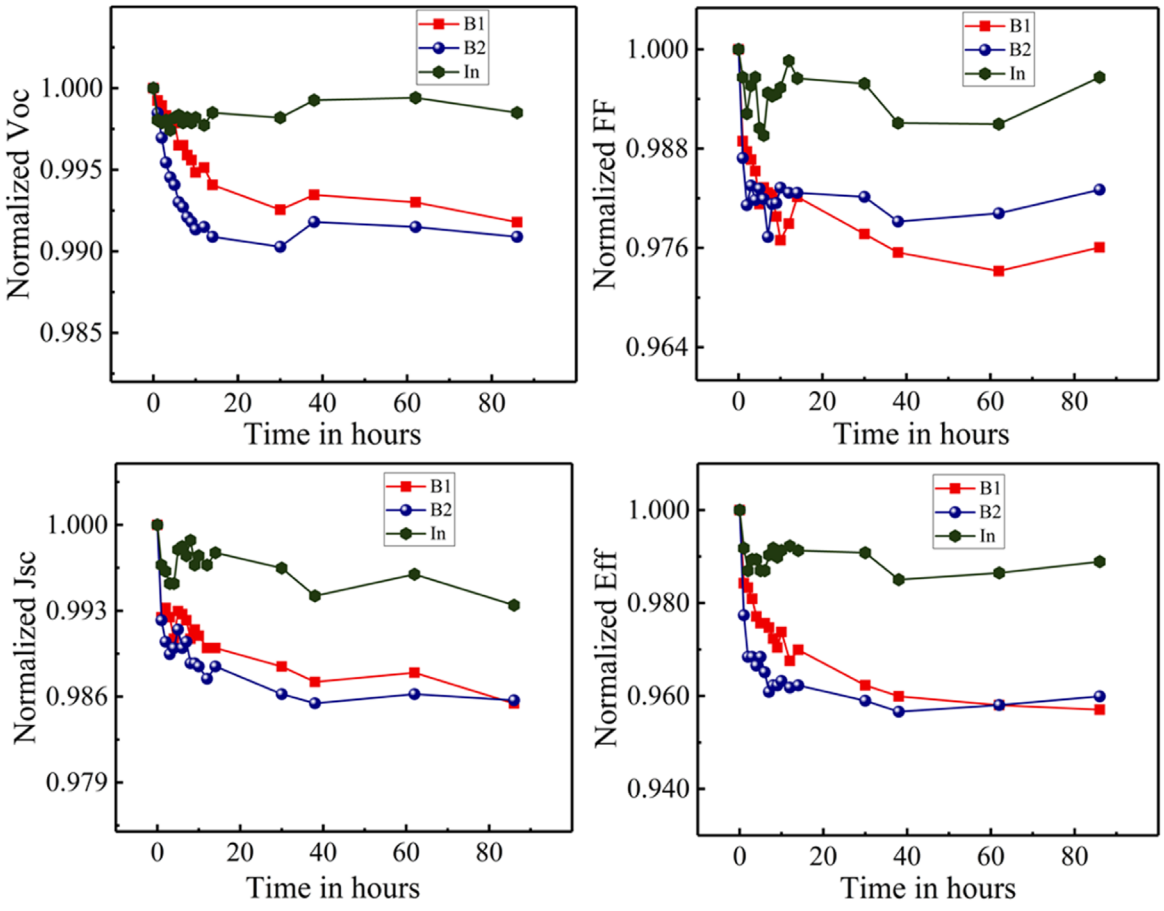

Figure 5. Measured LID behavior of PERC devices with B-doped and In-doped wafers. All curves are normalized to their initial respective *I–V* values.

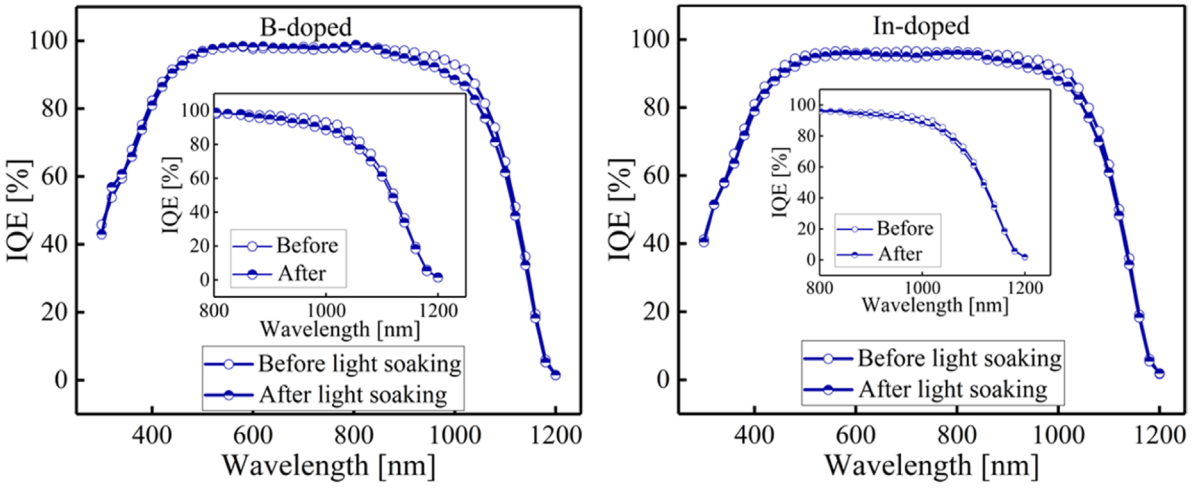

Figure 6. Internal quantum efficiency of B-doped and In-doped cells after 85 h light soaking. Inset shows magnified longer wavelength region.

efficiency dropped sharply and significantly for the B-doped cells (0.8%$_{abs}$). This degradation in the efficiency is likely attributed to a degradation in bulk lifetime caused by B-O related defects, especially since the same effect was not observed in the In-doped cells.

The IQE of representative B- and In-doped PERC cells after light soaking are shown in **Figure 6**. The longer wavelength IQE of B-doped wafers reduced significantly after light soaking. The poor long wavelength response after light soaking can be attributed to the bulk lifetime degradation resulting in the B-O complexes, which increase bulk recombination and reduces solar cell efficiency of the B-doped wafers. However, in the case of In-doped wafers, there was no significant degradation in the long wavelength response.

4. Conclusion

This work presents a systematic investigation of the effect of light soaking on In- and B-doped Cz-Si wafer solar cells. 20.7% efficient, large-area, screen-printed, In-doped PERC cells were fabricated, with negligible reduction in cell efficiency after 85 h of light soaking at 1.0 Sun illumination. Although B-doped wafers initially resulted in a cell efficiency of 21.2%, their efficiency values dropped by 0.8%$_{abs}$ after 85 h of light soaking. Compared to B-doped wafers, the starting, non-light soaked efficiency of In-doped wafers was lower by ≈0.4%$_{abs}$ and can be attributed to comparatively low bulk lifetimes. However, the In-doped cells demonstrated a much more stable device efficiency after extended light exposure.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

crystalline silicon, In-doped Si wafers, light-induced degradation, PERC solar cells, solar cells

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