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# Impact of carbon co-doping on the performance of crystalline silicon solar cells

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## ABSTRACT

We have investigated the impact of carbon co-doping on the performance of boron–doped Czochralski-grown silicon solar cells. It is found that carbon co-doping will deteriorate the initial performance of Aluminium-back-surface-field solar cells before light-induced degradation (LID), owing to the enhancement effect on the formation of oxygen precipitation. However, carbon co-doping can effectively suppress the formation of boron-oxygen complexes in the solar cells, which becomes more significant with an increase of the carbon concentration. Therefore, the performance of carbon co-doped silicon solar cells is better than that of conventional silicon solar cells after LID. All these results are of great significance for the practical application of carbon co-doped silicon solar cells with low LID effect in photovoltaic industry.

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## 1. Introduction

Crystalline silicon solar cell is trending towards high efficiency and low cost. However, light-induced degradation (LID) effect deteriorates the efficiency of commercial solar cells based on boron-doped crystalline silicon (c-Si) with loss up to 2–3%, due to the formation of boron and oxygen (B-O) complexes. B-O complexes, acting as effective recombination centers for carriers, form in the presence of excess carriers, particularly under sunlight illumination [1–3]. By annealing at elevated temperatures in dark, B-O complexes can be fully dissociation, but they can generate once again during the subsequent illumination at room temperature [4]. Earlier investigations have shown that the saturated concentration of B-O complexes is primarily proportional to the boron concentration and the square of oxygen concentration [5,6]. Therefore, Schmidt and Palmer et al. proposed that B-O complexes should be formed by the fast-diffusion of oxygen dimer ($O_{2i}$) towards the immobile substitutional boron ($B_s$) [7]. Later on, it has been extensively reported that the saturated B-O complex concentration increases linearly with the increase of hole concentration $p_0$ in compensated (c-Si) [8–10]. Voronkov et al. put forward a $B_iO_{2i}$ model in which the positively charged interstitial boron atoms ($B_i$) are assumed to be captured by the $O_{2i}$ to form latent centers in as-grown Si, and then the LID occurs via the transformation of latent centers into recombination centers [11]. They further updated this model with a new $B_iB_sO$ model that the $B_i$ atoms are captured by $B_sO_i$ complexes to

be the latent centers but the $O_{2i}$ are totally not involved [11]. Recently, we have presented that B-O complexes could be formed based on a short-distance diffusion of $O_{2i}$ towards $B_s$ in the latent centers [12–14].

Recently, we have reported that carbon (C) co-doping can effectively suppress the formation of B-O complexes in crystalline silicon wafers [7,15]. Furthermore, it is found by both the experiments and first-principle theoretical calculations that this suppression effect is attributed to the tensile tress in silicon lattice induced by carbon with a smaller radius and therefore tending to form more energetically favorable $C_sO_{2i}$ complexes with $O_{2i}$ [15]. Meanwhile, it has also been reported that the C doped in (c-Si) with high concentration will enhance the nucleation of high density oxygen precipitates which might strongly reduce the carrier lifetime in wafers and in turn be detrimental to the performance of solar cells [16–18]. Thus, a systematic study on the impact of C co-doping on the performance of crystalline silicon solar cells, particularly that after LID, is highly needed.

In this paper, we have investigated the performance of C co-doped crystalline silicon solar cells before and after LID, as well as that of conventional crystalline silicon solar cells. It has been demonstrated that C co-doping can effectively improve the performance of solar cells after LID. These results are of significance for the practical application of C co-doped crystalline silicon solar cells with low LID effect in photovoltaic (PV) industry.

## 2. Experimental procedure

Three 6 in., *p*-type < 100 > oriented crystalline silicon crystals were pulled under the same conditions. One is conventional silicon

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crystal for reference, labeled as Ref. The other two are C co-doped silicon crystal with different C doping levels, labeled as C1 and C2, respectively. After slicing the crystals, all the wafers were pre-annealed in Ar ambient for 30 min at 650 °C to eliminate grown-in thermal donors (TDs). Afterwards, the resistivity $\rho$ of these wafers was measured using the four-point-probe (FPP) method. The carbon concentrations and oxygen concentrations were determined by a Fourier transform infrared spectroscope (FTIR, Bruker IFS 66 V/s) with a calibration factor of $1 \times 10^{17}$ cm$^{-2}$ and $3.14 \times 10^{17}$ cm$^{-2}$, respectively. The detailed parameters of these wafers are shown in Table 1. It can be seen that the oxygen concentrations of all the samples are similar, but the carbon concentration of C2 sample is almost 3 times higher than that of C1 sample.

For carrier lifetime measurements, all the wafers were first chemically polished to remove saw damages and then subjected a double-surface passivation with plasma-enhanced chemical vapor deposited silicon nitride (SiN$_x$:H) film. The initial minority carrier lifetime ($\tau$) was measured by a quasi-steady-state photoconductance (QSSPC) instrument (Sinton WCT-120). Note that the lifetime values were determined at an injection level of $\Delta n/p_0 = 0.1$ [1,6,7].

Solar cells were fabricated from the 156 mm × 156 mm conventional and C co-doped crystalline silicon wafers with a thickness of 200 μm on the same production line at the Hareon Solar Company by a standard Al-back-surface-field (Al-BSF) process, including alkaline texture, phosphorus diffusion, Si$_3$N$_4$ film deposition, screen-printing and contact firing. For each kind of sample, 10 solar cells are fabricated. Note that the Si$_3$N$_4$ film has a refractive index of 2.05, with a thickness of 70 nm, which can act as a good anti-reflection film for the sunlight absorption of solar cell. The illuminated current-voltage characteristics of the solar cells were performed under the standard conditions (one sun, AM 1.5 Global spectrum, 25 ± 1 °C), using a Berger Flasher Pss 10 solar simulator. The illumination intensity was calibrated using a reference cell obtained from Fraunhofer ISE, Germany. After illumination under a halogen lamp with intensity of 100 mW/cm$^2$ at room temperature for 150 h, the cell efficiencies were investigated again. The internal quantum efficiencies (IQE) of the solar cells were derived from the cell spectral responses and the spectral reflectance. The minority carrier diffusion lengths ($L_{diff}$) of the solar cells were obtained from the light beam induced current (LBIC) measurement [19].

## 3. Results and discussion

Fig. 1 shows the initial average minority carrier lifetime of the wafers prior to any light soaking. One can see that with an increase of the C concentrations ([C]s), the initial minority carrier lifetime decreases, which indicates much more recombination centers in the bulk of C co-doped c-Si. As reported in the previous studies [20–22], carbon has an enhancement effect on the formation of oxygen precipitation in c-Si via two mechanisms. On the one hand, carbon bonds with oxygen and then forms [C$_i$-O$_i$]C(3) centers at temperatures lower than 800 °C, acting as effective heterogeneous seeding sites for oxygen precipitation. On the other hand, carbon atoms play catalytic roles at temperatures higher than 850 °C.

**Table 1**
Detailed parameters of the reference and C co-doped silicon wafers.

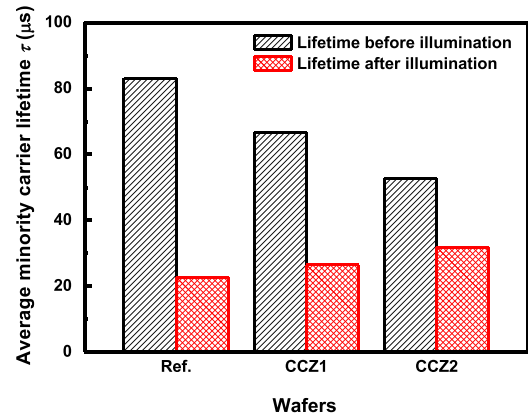| Sample | Resistivity (Ω cm) | C concentration (cm$^{-3}$) | O concentration (cm$^{-3}$) |
|---|---|---|---|
| Ref. | 1.40 | NA | $1.0 \times 10^{18}$ |
| C1 | 1.40 | $9.9 \times 10^{16}$ | $1.0 \times 10^{18}$ |
| C2 | 1.39 | $3.4 \times 10^{17}$ | $1.0 \times 10^{18}$ |



**Fig. 1.** Average minority carrier lifetime of the reference and C co-doped silicon wafers before and after illumination at room temperature for 150 h.
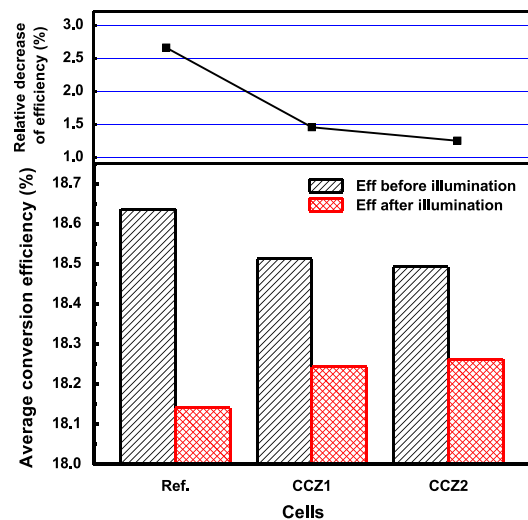


**Fig. 2.** Average conversion efficiency of the reference and C co-doped silicon solar cells before and after illumination at room temperature for 150 h, as well as its relative decrease.

Meanwhile, oxygen precipitates can cause deep energy levels in band gap of silicon, which have strong electrical recombination activity for carriers [17,23–25]. Therefore, the reduction of initial $\tau$ in C co-doped silicon wafers should be attributed to the generation of high density oxygen precipitates. This implies that carbon co-doping may deteriorate the performance of solar cells before LID.

Fig. 2 shows the average conversion efficiency of the corresponding solar cells before and after illumination at room temperature for 150 h. It should be mentioned here that the conversion efficiencies don't change any more with additional light soaking. Thus, the 150 h illumination at room temperature has proved to be long enough to saturate solar cells degradation completely. As we predicted above, the conversion efficiency of the solar cells before LID decreases with the increase of [C]s, due to more oxygen precipitates recombination centers. However, after light soaking, the conversion efficiency of the C co-doped silicon solar cells decreases less significantly than that of the reference cell. The relative decrease in these solar cells is also shown in Fig. 2 (top). Our previous work has demonstrated that C co-doping in (c-Si) can effectively suppress the formation of B-O complexes, owing to the formation of more energetically favorable CO$_{2i}$ complexes [15]. As a consequence, the conversion efficiency of these solar cells after LID increases with the increase of [C]s is shown for the first time. These results suggest that carbon co-doping is beneficial