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Effect of Different Regeneration Processes on LID Degradation Mechanisms in B-doped p-type c-Si PERC Solar Cells in Industrial Production

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Abstract. Light-induced degradation (LID) and elevated temperature-induced degradation (LeTID) mechanisms negatively affect the performance of p-type Cz-Si-based solar cells. In this study, the degradation rates under illumination were investigated for non-metallized and metallized PERC cells with different base resistivities at different temperatures. These bifacial PERC cells are produced from own-produced ingots and wafers in a vertically integrated environment. The effect of different regeneration processes, using either illuminated annealing or direct current injection used in standard production against LID, is also investigated.

Keywords: PERC, BO-LID, LeTID, injection, electrical regeneration

1. Introduction

Commercial solar cells produced today are predominantly p-type monocrystalline silicon PERC cells made from Czochralski (Cz) grown ingots and wafers. There is a significant correlation between the minority carrier bulk lifetime at the wafer stage and the cell efficiency, especially for high performance solar cells with good surface and contact passivation [1].

Until recently, boron (B) was used as dopant, however B-doped p-type solar cells suffer from Light Induced Degradation (LID), a reduction in cell efficiency after a relatively short illumination, which is attributed mostly to B-O complexes in the bulk that get activated under injection and that act as recombination centers for minority carriers/electrons [2-4]. These defects are metastable, it is possible to deactivate them with annealing, and regenerate (permanently deactivate) them with annealing under carrier injection. As such, industrial mitigation strategies exist such as direct current injection at elevated temperature.

However, in the last years the industry has been transitioning to the generally more stable gallium (Ga) dopant. In recent years, a different, light and elevated temperature induced degradation (LeTID) mechanism has been observed [5-9]. The defect mechanism is debated, but the diffusion of hydrogen from the silicon nitride passivation layers into the bulk during the high temperature fast firing step is thought to trigger a metastable defect. Both B and Ga doped PERC cells are susceptible [7-9].

2. Experimental

This study was performed in a vertically integrated factory environment, on Cz grown B-doped wafers with 0.75±0.05 Ω.cm and 1.00±0.05 Ω.cm base resistivities. These wafers have an

interstitial oxygen [O_i] content of 4.3±0.7 ppma and 9.0±1.2 ppma respectively, measured with FTIR according to ASTM F 121-80. Full G1-size bifacial PERC cells were fabricated using all standard cell process steps as indicated in Figure 1, including saw damage removal (SDR) and texture, emitter formation with sheet resistance ~150Ω/□, selective emitter (SE) formation, phosphosilicate glass (PSG) removal and rear-side polishing, plasma enhanced chemical vapor deposition (PECVD) passivation layers at the front SiNx and rear AlOx/SiNx. One group of cells were metallized after laser contact opening and the other group not, but all were subjected to the fast-firing step at (780°C) that could contribute to LID or LeTID degradation mechanisms.

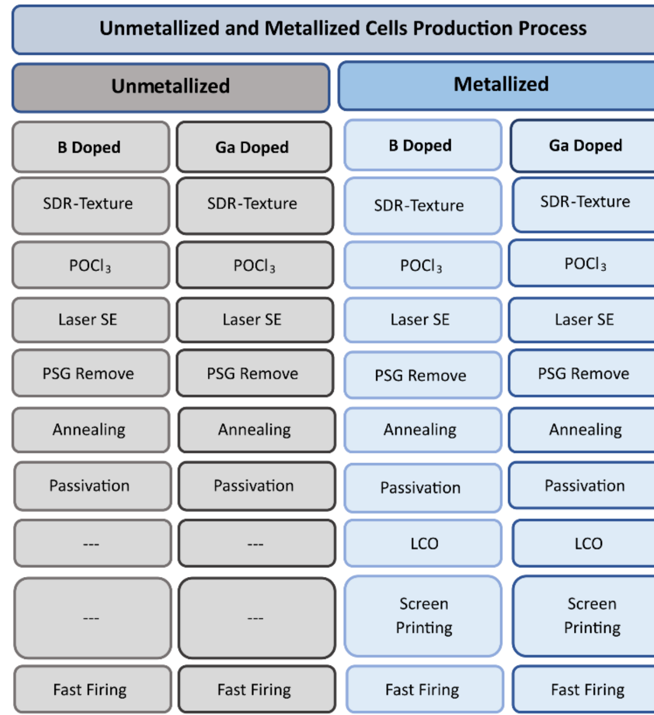

Figure 1. Process flowchart of metalized and non-metallized B/Ga-doped PERC cells.

All metalized and non-metallized PERC cells were exposed to dark annealing (DA) at 200°C for 10 min in order to de-activate BO defects. Half of the non-metallized cells were light-regenerated (LR) under ~1 sun illumination with a halogen lamp at 200°C for 10 minutes, and half of the metallized cells were current-regenerated (CR) according to a standard recipe used in production, with 8 A injection at 170 °C for 45 min. During defect activation, all cells were illuminated using a LED source (~25 $mW.cm^{-2}$, with a 400-750 nm spectrum). The samples were subjected to two sets of temperature conditions, i) at 50±2°C which is usually used to trigger BO-LID degradation [2-4], and ii) at 80±2°C, which could be considered the onset of LeTID degradation [5-9]. Effective lifetime $\tau_d(t)$ measurements of the non-metallized cells were performed by Sinton Instruments WCT-120 lifetime tester in generalized mode [9], reported at injection level 5x10^{15} cm^{-3} ($\Delta n \approx 0.3\, p_0$) and metallized cells were examined by Sinton Instruments Suns-Voc.

3. Results and Discussion

Shockley-Read-Hall (SRH) defect densities can be calculated as:

$$N_d^* = \frac{1}{\tau_d(t)} - \frac{1}{\tau_0(t)} \qquad (1)$$

In this equation, N_d^*, $\tau_d(t)$ and $\tau_0(t)$ represent effective defect concentration, lifetime of degraded state and lifetime of initial state, respectively [1,8,9].

The effective carrier lifetimes and corresponding effective defect concentrations vs. illumination duration of samples degraded at 50°C is plotted in Figure 2.

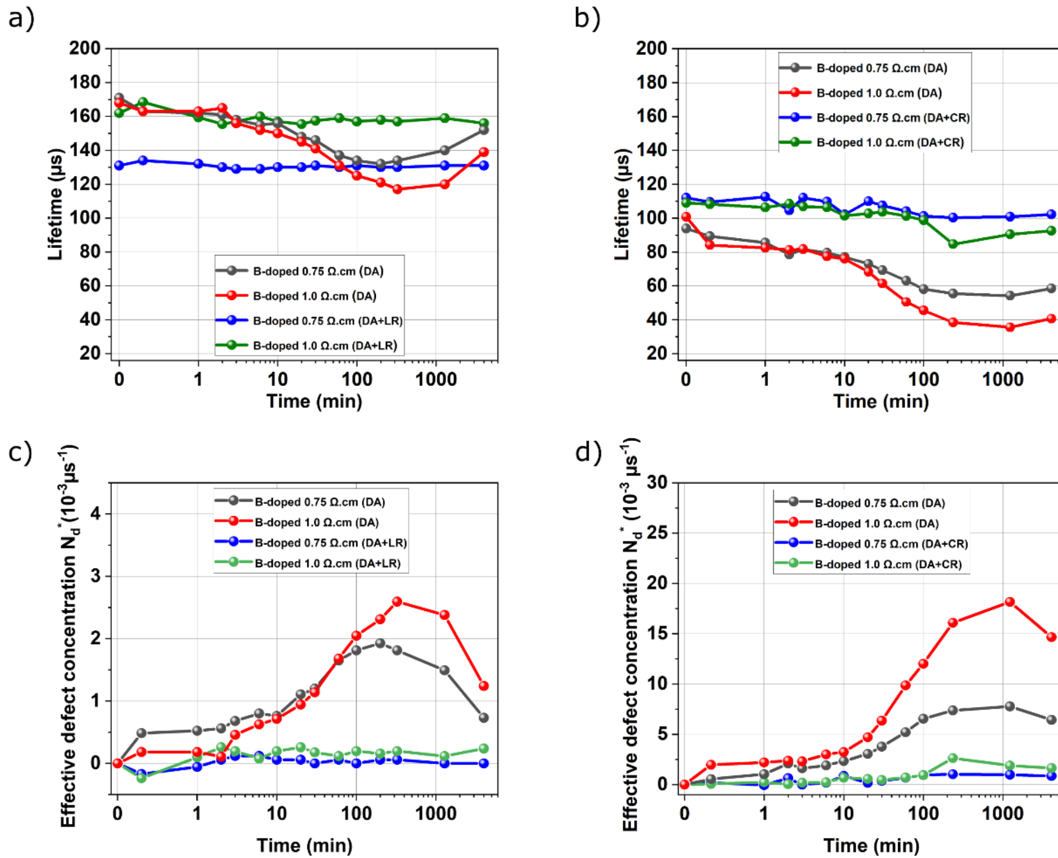

Figure 2. Effective lifetime degradation behavior of non-metalized (a) and metallized (b) B-doped PERC cells, under 0.25 mW/cm2 illumination, at 50°C. Effective defect concentration N_d^* evolution of non-metallized (c) and metallized (d) B-doped PERC cells during this degradation.

Under these conditions, in non-metallized and non-regenerated cells, a gradual degradation of lifetime is observed in non-regenerated samples, which reaches its maximum around $3x10^2$ min. Full recovery has not been completed during experiment duration, but can be estimated to take around 10^4 min.

The two resistivity groups follow the same kinetics, but a higher maximum degradation observed in 1.0 Ω.cm samples, which in this case can be attributed to their higher $[O_i]$ content. The same degradation trend is observed in metallized cells (with lower effective lifetimes), with a slightly slower recovery. The maximum effective defect concentrations reach $2.5x10^{-3}$ μs^{-1} in non-metallized samples, and $16x10^{-3}$ μs^{-1} in metallized cells; this difference is probably due to passivation quality and not related to BO-LID defects.

The effective lifetimes of both light illumination (LR) and (to a slightly lesser degree) industrial current injection (CR) regenerated samples remained very stable, hence both regeneration processes are effective in preventing the BO degradation of dark-annealed (DA) samples.

The effective carrier lifetimes and corresponding effective defect concentrations vs. illumination duration of samples degraded at 80°C is plotted in Figure 3.

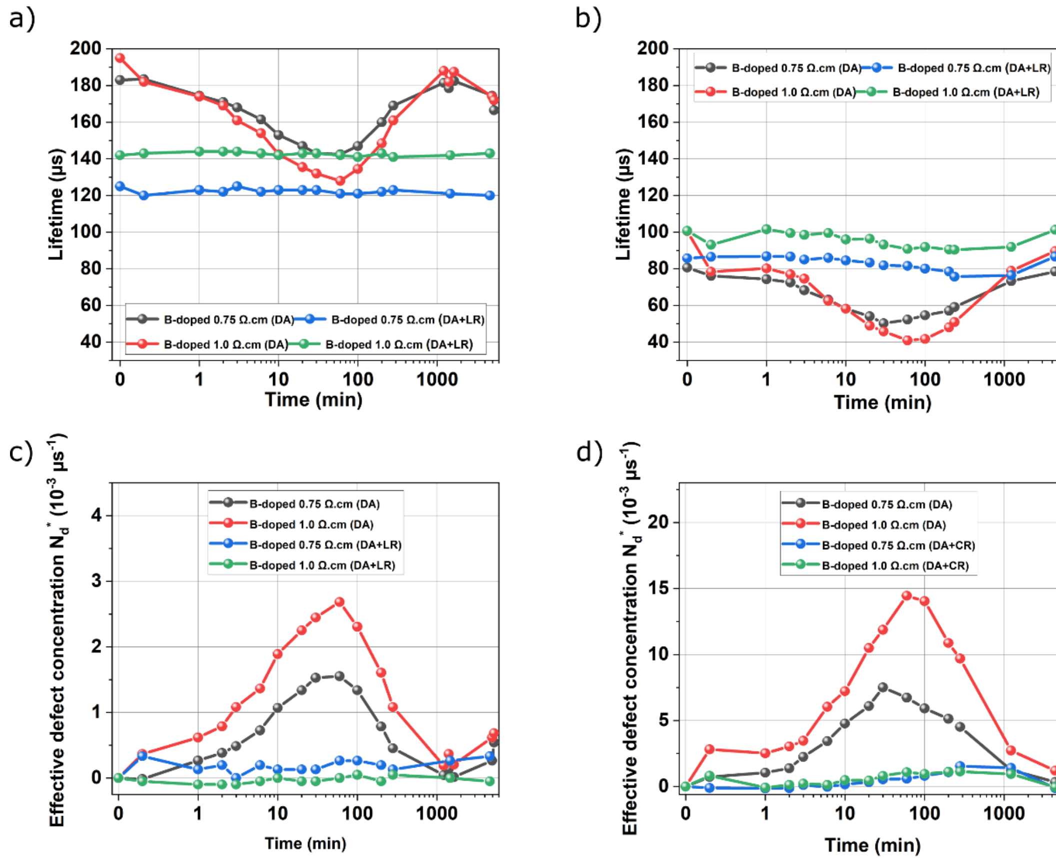

Figure 3. Effective lifetime degradation behavior of non-metalized (a) and metallized (b) B-doped PERC cells, under 0.25 mW/cm^2 illumination, at 80°C. Effective defect concentration N_d^* evolution of non-metallized (c) and metallized (d) B-doped PERC cells during this degradation.

The effective lifetime degradations observe similar trends to the degradation at 50°C, but with a faster reaction rate, as expected from the higher temperature. In non-metallized cells, the maximum degradation is reached around 60 min, and full recovery around 1000 min; the evolution in metallized cells take slightly longer. The maximum effective defect concentrations are identical to those observed for the 50°C process, which is expected from cells originating from the same wafer batch and indicate the activation of the same BO-LID mechanism [10].

As for the 50°C degradation study, the effective lifetimes of both light illumination (LR) and (to a slightly lesser degree) industrial current injection (CR) regenerated samples remained stable, hence both regeneration processes are effective in preventing the BO degradation of dark-annealed (DA) samples.

A similar degradation study at 80°C was also performed on Ga-doped non-metallized cells with 0.5, 0.75 and 1 Ω.cm resistivities, with otherwise identical preparation. However, these cells showed no appreciable onset of LeTID degradation even after 5x10^2 min.

Figure 4 provides a comparison of light-regeneration and current-regeneration mechanisms, for the 50°C and 80°C degradations. It can be clearly seen that the degradation is not completely suppressed by the current-regeneration procedure, and there is a slight residual defect concentration remaining in both degradation temperatures, as opposed to the very stable effective lifetime observed in light-regenerated samples. This also hints at the possibility of optimizing the industrial regeneration recipe of 8 A injection at 170 °C for 45 minutes [11].

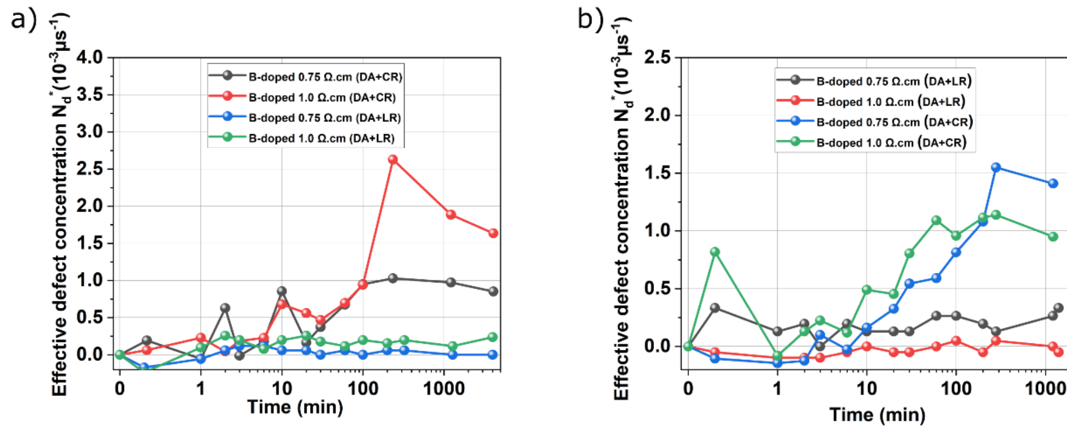

Figure 4. Effective defect concentrations for light-regenerated (LR) and current-regenerated (CR) samples, degraded at 50°C (a) and 80°C (b).

4. Conclusion

In this study, the effective lifetimes under illumination of non-metallized and metallized PERC cells is examined at two different temperatures, depending on the dopant type, resistivity, and the use of light or current regeneration processes.

No appreciable change was observed in the lifetimes of Ga-doped PERC cells in 80°C temperatures, up to the longest timescales considered, which should nonetheless be enough to trigger the onset of LeTID degradation [5,7,9]. Further studies at higher temperatures and in dark is planned to investigate LeTID in Ga-doped PERC cells.

As expected, the BO-LID degradation kinetics of B-doped PERC cells depend on the degradation temperature, but the maximum effective defect densities depend only on resistivities and oxygen content.

The light regeneration and industrially applicable current-injection regeneration processes are applied to corresponding PERC cells and their effect in preventing LID degradation is compared. Current-injection regeneration is found to be less effective than light-regeneration, which could be remedied by process parameter improvements.

Data availability statement

The data supporting the results of this contribution can be shared by the authors upon request.

Author contributions

Kübra Çelen: investigation, writing of original draft; Alihan Kumtepe: investigation, visualization; Mete Günöven: methodology, supervision, writing - review & editing.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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