Annihilation of LETID effect in mono and multicrystalline boron doped silicon solar cells by illumination

A. MOHAMMED KRARROUBI[1,2,*], D. BOUHAFS[1], I. Y. ZENTAR[3], R. SI-KADDOUR[1], H. AMROUCH[1]
[1]*Research Center in Semiconductor Technology for the Energetic (CRTSE), 16048, Algiers, Algeria*
[2]*Unité de Recherche en Energie Renouvelables en Milieu Saharien URERMS, Centre de Développement des Energies Renouvelables, CDER, 01000, Adrar, Algeria*
[3]*Coating Materials and Environment Laboratory, University of M'hamed Bougara Boumerdes 35000, (UMMB), Algeria*

This study investigates the effect of Light andElevated Temperature Induced Degradation (LETID) and the subsequent regeneration on the electrical performance of silicon solar cells. The research focused on boron-doped Czochralski silicon (Cz-Si) with a TiO_2 coating and multicrystalline silicon (Mc-Si) with a SiNx: H antireflection coating (ARC) layer.The regeneration process entailed illuminating the cells at temperatures 130 °C and 190 °C for a duration of 30 min; followed by exposure to degradation conditions at 75 °C. Following a 28 hours of light exposure, the initial batch of cells underwent complete degradation, while the second batch, subjected to regeneration at 130 °C, demonstrated degradation after 48 hours. It was observed that Mc-Si-based cells were more prone to LETID, with a 6% efficiency reduction, compared to a 4% decrease in Cz-Si cells. During the regeneration phase at 190 °C, a 0.8% and 2.5% decrease in electrical performance was observed in Cz-Si and Mc-Si cells, respectively. However, at 130 °C, a 1.6% increase in efficiency was observed, indicating performance regeneration. These results establish that the regeneration protocol diminishes the formation of the BO defect and alleviates degradation caused by metallic contaminants like iron. Furthermore, the findings suggest that the degradation in Mc-Si solar cells is associated with the infiltration of hydrogen into the bulk silicon from the SiN_x:H layer.

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1. Introduction

In 2022, monocrystalline and multicrystalline silicon dominated the photovoltaic cell and module manufacturing sector, accounting for over 95% of the market share [1]. Further mother, boron and gallium-doped P-type silicon wafers constituted over 80% of the global market. It is noteworthy that significant long-term performance degradation is anticipated in silicon-based P-type solar cells with diverse structures [2]. This degradation is know to accelerates under conditions light-and elevated-temperature-induced degradation (LETID) at 75 °C, with the degree of acceleration being contingent up on the injection level of electrical charges. The primary agents responsible of this degradation are the Boron Oxygen (BO) metastable defects and the formation of Iron Boron (FeB) pairs, along with other metallic elements [2-4]. LETID, a relatively recent discovery in multicrystalline silicon, arises due to the activation of recombination metallic defects [5]. The precise mechanism and configuration of metallic defects causing LETID remain elusive. Nevertheless, LETID has been shown to have a significant impact of the performance of P-type silicon wafers and cells, particularly in warmer climates.

The investigating of LETID's impact on the electrical performance of solar cells provides a direct assessment of the LETID effect through current-voltage measurements, considering the global effects. Degradation caused by FeB and/or BO pairs may also contribute during the initial minutes, but these dynamics are not yet fully understood [6]. However, Ramspeck et al. [7] in 2012 noted that Mc-Si-based solar cells could experience significant long-term degradation effects, asserting that neither Light Induced Degradation (LID) nor FeB dynamics fully account for this degradation, which is also carrier-induced and commonly referred to as LETID [8, 9]. In this study, the term LETID is employed chosen to distinguish it from LID and to emphasise that elevated temperatures are requisite to observe substantial degradation within accessible timescales.

Therefore, in order to thoroughly understand and mitigate the LETID phenomenon in P-type silicon-based solar cells, this study initiated a degradation protocol followed by a regeneration process under various illumination intensities and temperatures. This approach necessitated the development and optimization of strategies to effectively reduce LETID degradation.

2. Experimentation

The present study focuses on electrical performance degradation of silicon-based solar cells, with a particular emphasis on two types of boron-doped silicon solar cells:

multi crystalline silicon (Mc-Si) and monocrystalline Czochralski silicon (Cz-Si). These cells were exposed to tungsten halogen lamp illumination at (25 mW/cm^2) for an extended period; with the temperature maintained at a constant 75 °C under LETID conditions (see Fig. 1). The initial current-voltage (I-V) electrical performance of all cells was measured under standard test conditions (STC) with an AM (1.5G) spectrum. Prior to the LETID degradation cycle, two batches of solar cells were subjected to a regeneration protocol involving illumination at (25 mW/cm^2) for 30 minutes at temperatures of 190 °C and 130 °C, respectively. Batch 1, exposed to 190 °C, included cells A5 and C8, while Batch 2, exposed to 130 °C, included cells I3 and C4. It is noteworthy that,C z-Si cells were coated with a TiO_2 antireflection coating (ARC) layer, whereas Mc-Si cells had a SiNx:H layer. Cells A9 (Cz-Si) and C7 (Mc-Si) were not subjected to regeneration. Subsequently all cells were exposed to LETID cycle degradation under an illumination level of (25 mW/cm^2) at 75 °C. The tungsten halogen lamp was heated depending on the operating time, we have always kept the temperature of the LETID phenomenon equal to 75 °C. The experiment location air-conditioned environment, and the samples were cooled using a fan during the experiment. The I-V characteristics were continuously monitored and recorded at intervals of 30 min from the start (t=0) for several hours until complete degradation was observed.

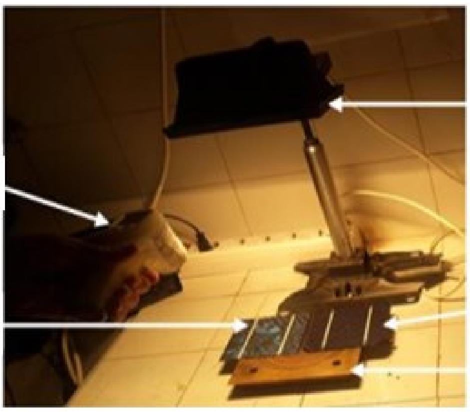

Fig. 1. LETID degradation bench by illumination of mono- and multicrystalline silicon-based cells (colour online)

3. Results and discussions

As demonstrated in Fig. 2, the electrical performance of both regenerated and non-regenerated solar cells at 190 °C was investigated before and after LETID degradation under illumination. For Cz-Si cells, the initial open-circuit voltage (Voc) of non-regenerated cell A9 and regenerated cell A5 were (595 mV) and (594 mV), respectively. Following a full LETID cycle, the (Voc) values for both cells remained unchanged. However, a slight degradation of (0.01A) in short-circuit current (Isc) was observed in the non-regenerated cell. The efficiency of the cells underwent a degradation of approximately 0.1% the regenerated cells and 0.5% for the non-regenerated cells, respectively.

With regards to the (Mc-Si) cells, the initial Voc for the non-regenerated cell C7 and regenerated cell C8 were (600 mV) and (602 mV), respectively. Subsequent to the LETID cycle, a decline in the V_{oc} values was observed, reaching (595 mV) for the non-regenerated cell and maintaining a relativity stable level at (601 mV) for the regenerated cell. This decline indicates a degradation of (5 mV) and (1 mV), respectively.

The efficiency of the solar cells exhibited a degradation of approximately 0.1% in absolute terms and 0.8% relative to Cz-Si. For both regenerated and non-regenerated Cz-Si solar cells, the efficiency degradation is 0.5%, equivalent to a 4% reduction relative to the initial efficiency. This finding suggests that the regeneration cycle effectively neutralizes the defects that cause LETID degradation. The regenerated Cz-Si cell (represented by full black circles in the Fig. 2) exhibits an increase in efficiency value from the initial 30 min up to 24 hours, then returns to its initial value stabilizes, experiences at drop at 26 hours, and stabilizes again at 28 hours.

During the LETID cycle, an increment in Isc is observed for both regenerated and non-regenerated Cz-Si cells. Cells A5 and A9 exhibited an increase of 0.3% in absolute efficiency. The remaining parameters, Voc and FF, remained stable, with only Isc increasing by approximately (64 mA) and (20 mA), respectively, after 24 hours. The observed increase in Isc is attributed to a decrease in series resistance, given the established correlation between V_{oc} and series resistance, and the know influence of band gap narrowing at higher temperatures and series resistance

For regenerated Mc-Si cells (full Blue circles), only a very slight degradation is observed, with an efficiency dropfrom 11.7% to 11.4%, representing a relative degradation of 2.5%. In both regenerated and non-regenerated Mc-Si cells, the measured relative degradation is 2.5% and 6%, respectively. These findings confirm that the regeneration protocol not only mitigates the formation of the BO defect but also attenuates degradation caused by metallic elements such as Fe [10].

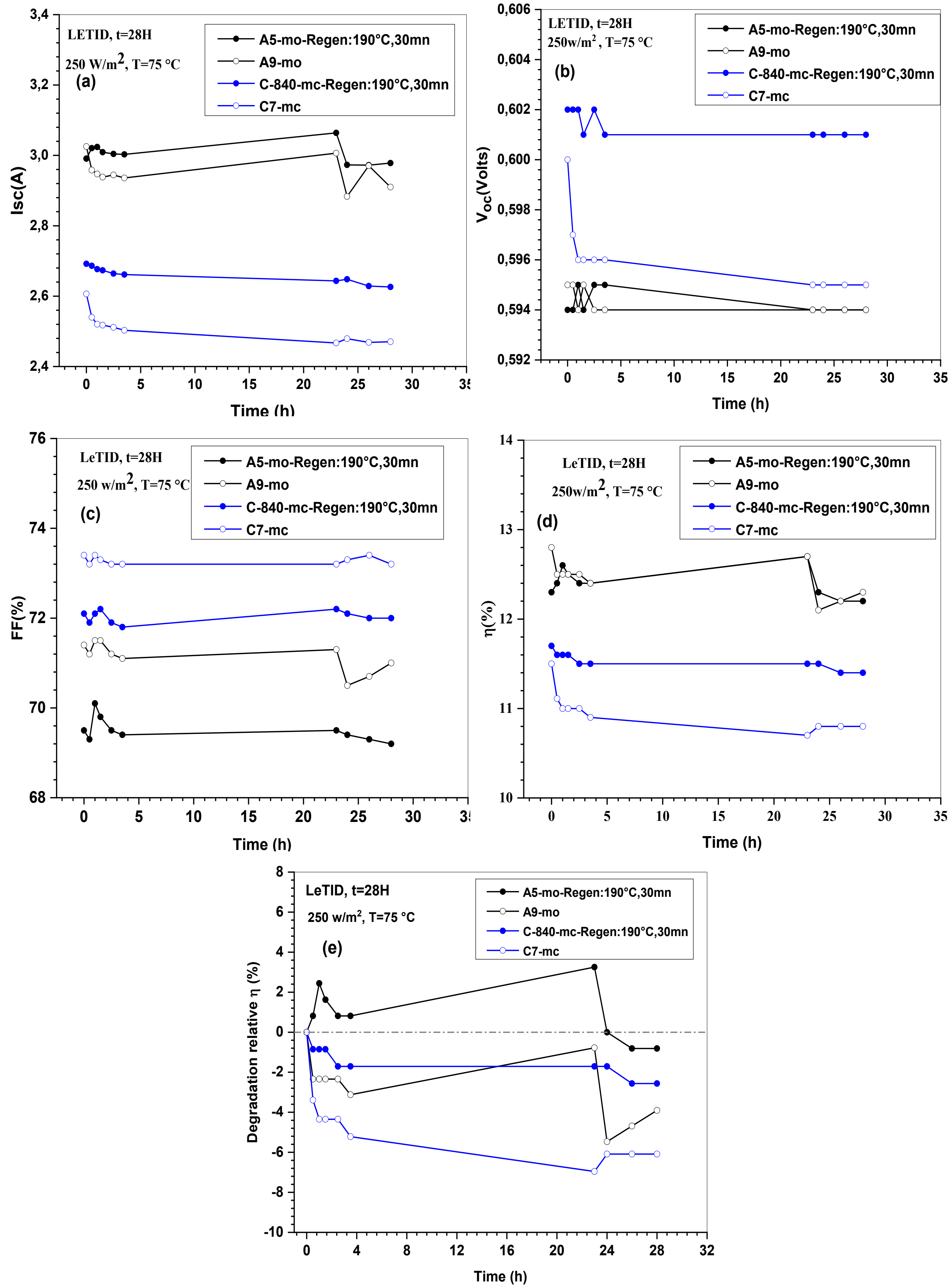

Fig. 2. Degradation of the electrical performances a) Isc, b) Voc, c) FF, d) η, and e) degradation relative η of the Cz-Si and Mc-Si solar cells without and with a regenerated LETID cycle at 190 °C (colour online)

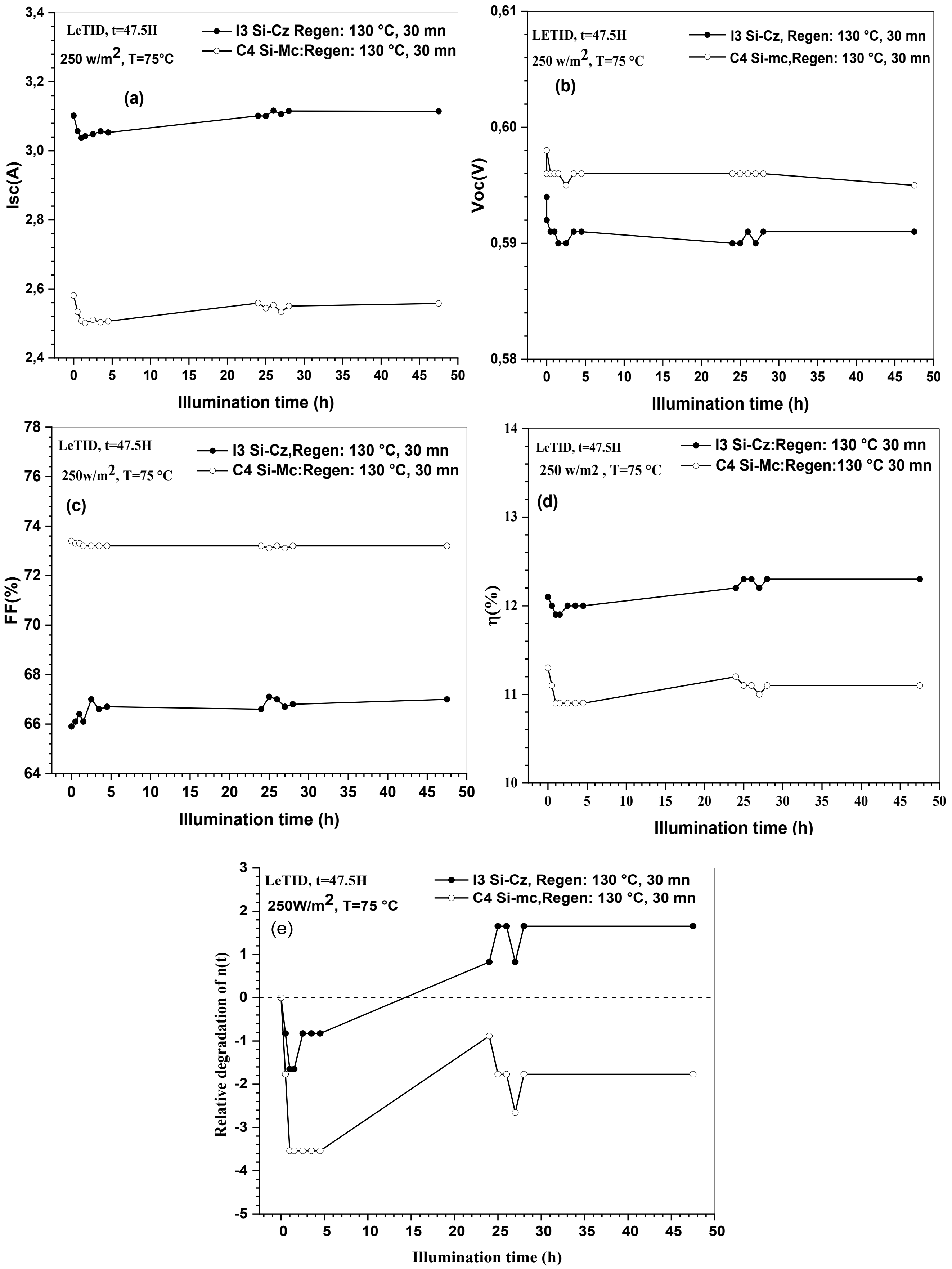

Fig. 3. Degradation of the electrical performances a) Isc, b) Voc, c) FF, d) η, and e) degradation relative η of the Cz-Si and Mc-Si solar cells without and with a regenerated LETID cycle at 130 °C

Conversely, degradation is prominently observed in non-regenerated Mc-Si cells during the initial hours (represented by open blue circles) and continues up to 26 hours in monocrystalline Cz silicon. This behaviour can be attributed to a higher concentration of vacant sites (V) in Mc-Si compared to Cz-Si, resulting from crystalline defects such as grain boundaries, which favour rapid kinetics of interstitial oxygen dimer O_{2i} in the material and the formation of substitutional boron-interstitial oxygen dimer BsO_{2i} bonds. Prior to manufacturing the cells, the short-circuit current densities of Cz-Si cells were relatively close to those of Mc-Si cells, which can vary between different ingots. This observation lends supports to the hypothesis that the observed phenomenon is predominantly attributable to the variations in metallic element contents within the ingots, as previously noted by Jordi Veirman [11]. Furthermore, the density of active defects, BO, is higher in Cz-Si than in Mc-Si, partly due to the elevated concentration and oxygen content in silicon produced using the Czochralski technique. As illustrated in Fig. 3, the electrical performances of the cells were examined before and after LETID degradation under illumination, as well as for regenerated solar cells I3 and C4 at 130 °C for 30 min. For non-regenerated solar cells, we refer to A9 and C7. The degradation of regenerated cells is minimal in the initial hours, followed by stabilization.

In the case of Cz-Si solar cells, the initial open-circuit voltage V_{oc} was measured at (594 mV) and (591 mV), respectively.

Following a complete light-to-dark LETID cycle, a relative degradation of approximately 0.5% was observed. The current of the incident light-to-current conversion remained almost stable without degradation, while the efficiency of the of light into electricity experienced a slight degradation of 1.7%. The results obtained using regeneration at 130 °C demonstrate improved passivation of defects responsible for electrical performance degradation in both Cz-Si and Mc-Si. The observed light degradation is likely due to the role of hydrogen atoms diffusing into the bulk, leading to the activation of recombination centers.

When comparing the degradation of Cz-Si solar cells with TiO_2 layers to Mc-Si cells with a PECVD SiNx:H layer, the role of hydrogen in the kinetics of regeneration becomes evident, as extensively reported in numerous studies. These studies analyze the differences in electric fields and conclude that such fields' influence on hydrogen flux towards the surface can explain an increase in the formation of surface-related degradation defects [12]. Fischer et al. reported that the observed increase in H in-diffusion for samples with highly doped layers could possibly be attributed to surface damage caused by the formation of layers with high dopant concentrations. Consequently, when assessing degradation studies, there is a tendency to underestimate degradation phenomena related to H in solar cells [13].

Furthermore, it is crucial to acknowledge the impact of antireflection layers on cell performance during the LETID cycle degradation. This study aims to investigate the role of SiNx passivation layers in the lifetime-limiting defect. During rapid thermal annealing, hydrogen diffuses into the silicon bulk the SiNx films. Bredemeier, who asserts that hydrogen is directly involved in the LETID degradation mechanism [14, 15], has confirmed a direct correlation between silicon’s bulk hydrogen concentration and the degree of degradation. The SiNx:H layer is thermally unstable duetoits composition, which contains a greater number of Si-H bonds with lower minimum energy than N-H bonds. This results in the release of hydrogen during heat treatments [16, 17].

4. Conclusion

This study examined the impact of LETID on P-Type boron-doped silicon solar cells with a BSF architecture. LETID degradation cycles were conducted on Cz-Si cells with a TiO_2 ARC layer and Mc-Si cells with a SiNx:H ARC, both with and without a regeneration process at 130 °C and 190 °C, each lasting 30 minutes, under (30 mW/cm^2) illumination using a tungsten halogen lamp. For Cz-Si solar cells, the regenerated cells at 190 °C exhibited a relative degradation of about 0.8%, whereas the non-regenerated cells showed a 4% degradation following the LETID cycle. In comparison, Mc-Si cells with a regeneration process at 190 °C displayed a 2.5% degradation, while non-regenerated cells showed a 6% degradation. Solar cells subjected to regeneration at 130 °C exhibited a relative efficiency enhancement of approximately 1.6% for Cz-Si cells; however, Mc-Si cells demonstrated a relative degradation of 1.7%. These findings indicate that the optimal regeneration temperature is approximately 130 °C, which results in enhanced electrical performance in Cz-Si solar cells and a slight degradation in Mc-Si cells compared to those treated at 190 °C.

A further comparison of the degradation of Cz-Si solar cells with a TiO_2 ARC layer to that of Mc-Si cells with a PECVD SiNx:H layer, sheds further light on the role of hydrogen in the kinetics of regeneration. This is likely due to the involvement of hydrogen atoms diffusing in the bulk, leading to the activation of recombination centers.

Declaration of competing interest

The author’ s declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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*Corresponding author: medkrarroubiasmaa@gmail.com