

UV Light-Induced Degradation of Industrial Silicon HJT Solar Cells: Degradation Mechanism and Recovery Strategies

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Abstract: The demand for Silicon heterojunction solar cells (HJT) has significantly grown recently. These solar cells have gained recognition for their remarkable performance, which can be attributed to the exceptional passivation properties of bilayers consisting of intrinsic and doped hydrogenated amorphous silicon. This study investigates alternative recovery methods and looks into the deterioration caused by UV radiation in commercial Silicon HJT solar cells. The carrier lifetimes of the samples were measured before and after the HJT solar cells were exposed to ultraviolet radiation. The findings revealed a decrease in carrier lifetime, $iVoc$, and iFF , indicating the creation of defects in the bulk of a-Si:H and the interface between c-Si and a-Si:H. It was assessed how SiO_x performed as a passivation layer. It has been discovered that SiO_x can passivate dangling bonds, increase carrier lifetime and reduce trap density. In addition, recovery techniques like current injection, infrared, light soaking, and annealing were applied. The current injection, infrared, and light soaking treatments were discovered to be able to partially restore the efficiency of the solar cells without the combination of temperature, while annealing was found to be more effective. Additionally, the effects of both short and prolonged exposure to UV are investigated. The HJT solar cells exposed to prolonged UV radiation for an extended period of time could not fully regain their efficiency and displayed irreparable flaws. Overall, this study demonstrates the potential of recovery treatments and passivation techniques in increasing the efficiency of Si HJT solar cells and illuminates the processes underlying ultraviolet-induced deterioration. Overall, this study sheds light on ultraviolet-induced degradation mechanisms and highlights the potential of recovery treatments and passivation techniques in enhancing the efficiency of Si HJT solar cells.

Keywords: UV light-induced degradation, Si HJT solar cells, Efficiency, Fill factor, Passivation, Recovery treatments.

1. INTRODUCTION

The Si HJT (Silicon Heterojunction with Intrinsic Thin layer) solar cells, introduced by Sanyo (Now Panasonic) in the 1970s, [1] is a distinctive high-efficiency solar cell with an impressive efficiency of up to 26.81% [2]. The unique passivating contacts have contributed to its growing popularity in the photovoltaic industry. Risen Solar Energy is a prominent manufacturer of HJT solar cells in China, has spearheaded large-scale production of cells and contributed to the growth and advancement of the industry. This commendable endeavour has positioned Risen as a key player in the manufacturing sector alongside other industry leaders in the country. This trend highlights the industry's growing interest and investment in the production of Si HJT technology. The production capacity of Risen Solar Energy has witnessed a substantial increase, reaching 500 MW

with projections indicating a remarkable growth to 15GW by the end of 2023. These cells achieve high open-circuit voltages through the deposition of intrinsic hydrogenated amorphous silicon (i-a-Si:H) on crystalline Si, providing excellent passivation to silicon surface states [3]. Carrier selective contacts are formed by depositing doped amorphous silicon (a(p/n)-Si:H) layers on both sides of the ai-Si:H film [4]. Transparent conductive oxide (TCO) films serve as conducting paths for carriers and are capped with metal contacts using screen printing [5]. Si HJT solar cells exhibit better performance in real-world operating environments due to their lower temperature coefficient, with average operating temperatures reaching up to 50°C and peak temperatures up to 90°C [6]. Additionally, HJT solar cells. Offer the advantage of a lower thermal budget during manufacturing, as their deposition methods of doped a-Si:H layers require processing temperatures below 200°C, significantly reducing energy consumption compared to traditional Si solar cells [7-9]. These characteristics have attracted significant commercial and academic interest, establishing Si HJT solar cells as a compelling option in the industry.

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The emergence of advanced cell technologies, such as Si HJT solar cells, has revealed their higher sensitivity to ultraviolet light as compared to PERC (Passivated Emitter and Rear Cell), PERT (Passivated Emitter and Rear Totally-diffused) and TOPCon (Tunnel oxide passivated contact) solar cells [10]. In the case of bifacial Si HJT solar cells, both the front and back surfaces of the cells are potentially susceptible to ultraviolet light-induced degradation, making it a critical consideration [11]. Ultraviolet light-induced degradation manifests as a gradual decline in cell's performance over time. Several research groups have identified specific wavelengths within the 200 nm to 400 nm range as the damaging wavelengths responsible for the degradation in HJT solar cells [11-18]. For example, JinkoSolar reported an efficiency reduction of approximately -4% to -7% in industrial solar cells after exposure to about 0.54 GJ/m² of ultraviolet light [19]. The degradation in performance is commonly attributed to deep-level defects with recombination activity, such as dangling bonds, induced by ultraviolet illumination.

The ultraviolet light can damage the passivation at the amorphous/Si interface and also could cause subsurface damage in silicon. As ultraviolet light penetrates into the HJT solar cells, it breaks the weak Si-H bonds and induces interface defects (interface between amorphous and crystalline Si) and defects within a-Si. These defects act as recombination centres, which trap and recombine charge carriers, thereby reducing their mobility and cell efficiency. Furthermore, the defects can also create localized electric fields that alter the charge transport properties within the solar cell, leading to decreased current output.

It is important to note that the ultraviolet light-induced degradation described here primarily affects the surface region and/or interface, which is distinct from the conventional light-induced degradation associated with the evolution of boron and oxygen or boron and iron complexes within the bulk silicon, as well as light and elevated temperature induced degradation.

To address the challenge of ultraviolet light-induced degradation in Si-HJT solar cells, various strategies have been explored. Among these approaches, utilizing the SiO_x as a passivation layer on HJT solar cells has emerged as a promising solution to enhance overall performance and minimize the detrimental effects of ultraviolet-induced degradation. The current manuscript focuses on identifying the UVID and specifically investigated the influence of SiO_x passivation on Si HJT solar cells. Additionally, various post-exposure recovery treatments, including current injection (CI), infrared light (IR), light soaking (LS) and annealing have been applied to assess their effectiveness in rejuvenating the HJT solar cells after exposure to ultraviolet light.

2. EXPERIMENTAL SECTION

2.1. Fabrication Process

The photovoltaic cells were fabricated by a commercial Si HJT production line on Risen Solar Energy G12 N-type phosphorus-doped Czochralski (Cz) silicon wafers. These wafers were obtained by slicing an ingot with a resistivity 2Ω cm, thickness 150 μm, size 220 cm² and orientation <100>. The textured Si wafers were exposed to an oxygen (O₂) environment for a duration of 48 hours. This treatment aimed to improve the passivation properties of the HJT solar cells. In addition, cells without an oxide layer were also prepared to facilitate a comparative analysis between the samples. The wafers were textured using an anisotropic wet-etching method in a dilute alkaline solution. The wafers were then sequentially cleaned followed by the process mentioned in Figure 1. We employed plasma-enhanced chemical vapour deposition (PECVD, 13.56 MHz) to deposit the intrinsic and doped (n/p-type) microcrystalline layers on both sides of textured wafers. This deposition process utilized the mixture of SiH₄, B₂H₆, PH₃, and H₂ as source gases and was carried out in a parallel plate configuration. The resulting HJT cell precursors exhibited a niNip structure, where "N" represents the n-type Si wafer. The deposition process for these layers was carried out at temperatures of 180 °C. The indium tin oxide (ITO) sputtered (with PVD) on both sides, which was subsequently capped with silver (Ag)



Figure 1: Cleaning process after texturing Si wafers.

screen-printed electrodes followed by dark thermal annealing at 200°C for 30 minutes.

2.2. Characterization

UV-IR Reliability Testing Machine is responsible for measuring cell's degradation rate under UV light and recovery treatments including CI, IR and annealing. Solar Light Soaking is responsible for the light soaking treatment. The quasi-steady-state photo-conductance (QSSPC) measurement setup provided by Sinton Instruments (WCT-120) is utilized to measure effective minority carrier lifetimes, implied open-circuit voltage (iV_{oc}) and implied fill factor (iFF). The I-V tester under standard testing conditions (1.5AM, 25°C) is responsible for J-V characteristics. The Spectroscopic Ellipsometer (M-2000) by J.A. Woollam measures the standard thickness of ITO, intrinsic and doped hydrogenated a-Si on the glass substrate. The thickness of both i layers 5 nm, n-layer 8 nm, p-layer 14 nm, front ITO 80 nm and rear side 50 nm was measured. All the cells were characterized under illumination from the n side (front side). Figure 2 shows a visual representation of the Si HJT solar cells.

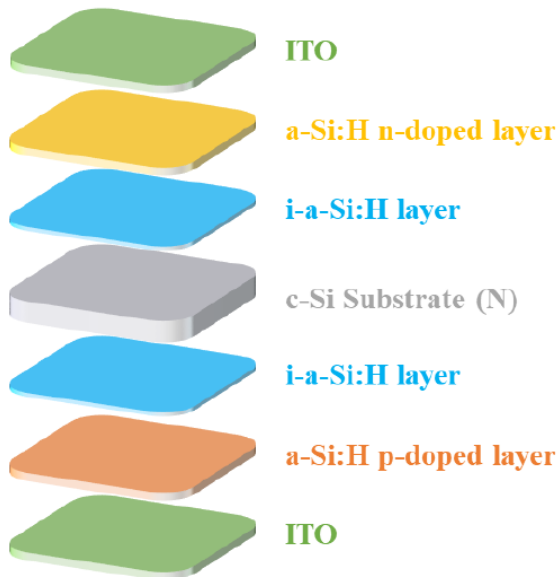


Figure 2: Schematic of Si HJT solar cells.

3. RESULTS AND DISCUSSION

3.1. Identification of Uvid in Si HJT Solar Cells

This study measured the effective carrier lifetimes (τ_{eff}) of 30 samples before and after UV light exposure. It should be noted that the data presented in Table 1 represents the average values of 28 samples, as two samples were broken during the process. The minority carrier lifetime of samples was measured after the CVD process (before ITO deposition). The experimental parameters were carefully adjusted as follows: temperature (T) = 25°C, time (t) = 30 minutes, and Power (P) = 50%. Upon analyzing the results, a significant decrease in τ_{eff} from 2613.031 μ s to 1898.996 μ s, iV_{oc} from 758V to 755 V, and iFF from 85.92 to 85.03 were recorded. These changes in τ_{eff} , iV_{oc} , and iFF can be attributed to the creation of new defects within the bulk of a-Si:H and at the interface between c-Si and a-Si:H. The exposure to UV light led to the generation of these defects, impacting the overall performance of HJT solar cells.

3.2. Role of SiO_x Passivation

To investigate the influence of SiO_x as a passivation layer, a set of 30 textured Si wafers was exposed to O₂ environment for 48 H. The primary objective of this treatment was to mitigate UV degradation by passivating the dangling bonds present at the interface between c-Si and a-Si.

Additionally, for comparative analysis, cells without native oxides layer were also prepared. In the initial stage, a comparison was made between the IV characteristics of samples with and without SiO_x passivation. Notably, the samples had not been exposed to UV light at this point. The observed increase in efficiency strongly indicates that SiO_x effectively passivates the dangling bonds present on the crystalline Si surface. This passivation process results in a reduced density of traps.

Subsequently, the HJT solar cells underwent a 30-minute exposure to UV light at a $P = 50\%$ and $T = 25^\circ\text{C}$. Notably, the samples lacking SiO_x passivation

Table 1: Comparison Data of Minority Carrier Lifetime Before and After UV Exposure

HJT solar cells	Samples	τ_{eff} (μ s)	ρ (Ω .cm)	1-Sun iV_{oc} (mV)	iFF
Before UV	28	2613.031	1.000	758.04	85.92
After UV	28	1898.996	0.237	755.31	83.03

displayed more pronounced UV-induced degradation. When HJT solar cells are exposed to UV light, it break the Si-H bonds which leads to change the distribution of hydrogen across the amorphous/crystalline Si interfaces. It increases the concentration of hydrogen near the n-doped amorphous Si and intrinsic amorphous Si layers, while exhibiting a lower hydrogen concentration near the amorphous/crystalline Si interface and crystalline Si bulk. The observed reduction of hydrogen near the amorphous/crystalline Si interface suggests a decrease in the availability of hydrogen for effective passivation of dangling bonds and interfacial defect density [20]. This phenomenon contributes to an increase in carrier recombination, ultimately leading to a decrease in SiO_x , as evidenced by the IV data presented in Table 2.

When the cells are passivated with SiO_x , the presence of oxygen provides an alternative mechanism for passivating the dangling bonds at the hydrogenated amorphous/crystalline Si interfaces, especially when the hydrogen concentration is lower in that region. Oxygen has a strong affinity for bonding with silicon, and the Si-O bonds formed at the interface can effectively passivate the dangling bonds, minimize carrier recombination, and reduce the interface defects density. So, the lower degradation rate can be seen in J_{sc} , Eff, and FF of samples passivated with SiO_x .

3.3. Recovery Treatments

In this section, we presented different efficiency recovery treatments after UV exposure including Current Injection CI and Infrared IR, LS and Annealing to verify the effectiveness of these recovery treatments for production line cells.

3.3.1. CI, IR and Annealing Treatments

For this investigation, a total of 60 samples (30 samples for each treatment) were prepared. The short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), fill factor (FF) and efficiency of chosen samples are close to

each other. The average I-V data of samples before UV exposure and after recovery treatments are mentioned in Table 3. Two different recovery treatments CI and IR were applied to recover the efficiency of the samples. The following parameters were set for CI treatment; $I = 8.5A$, $T = 85^\circ C$ and $t = 10$ min. The average baseline (initial) efficiency of the samples was measured to be 24.739%. The samples were then exposed to UV light, resulting in a decrease in efficiency to 24.547%. After the CI recovery treatment, the average Eff of the samples increased to 24.661%, and resulting the relative growth (recovery) in I_{sc} , V_{oc} , EFF, and FF are 10%, 22%, 46% and 14% respectively, as mentioned in Figure 3. The recovered efficiency is still lower than the initial baseline efficiency before UV exposure.

For the IR treatment, the samples were subjected to 17-suns, $T = 180^\circ C$ and $t = 2$ min. The initial efficiency was 24.728% before UV exposure and 24.536% was noted after UV. After the IR recovery treatment, the efficiency of the samples increased to 24.775% with the relative growth of 98%, resulting in a recovery of more than 100%.

It should be noted that the $180^\circ C$ as the highest temperature for all recovery treatments was based on careful considerations. HJT solar cells utilize amorphous silicon (a-Si) as a passivation layer. It is known that higher temperatures can potentially deteriorate the morphology and properties of a-Si, which may lead to a decrease in the solar cell's efficiency.

To explore the impact of higher temperatures, we conducted experiments using $250^\circ C$. The results indicated a lower V_{oc} , suggesting that higher temperatures could indeed damage the passivation layer and impact the overall performance of the solar cells. Considering these factors, we determined that a temperature range of $180^\circ C$ to $200^\circ C$ would be the most suitable for recovering the efficiency of HJT solar cells without compromising the morphology and passivation.

Table 2: Performance of HJT Solar Cells with and Without SiO_x under UV Exposure

HJT solar cells	$J_{sc} (mA/cm^2)$		$V_{oc} (mV)$	Eff (%)	FF	$R_s (\Omega)$	$R_{sh} (\Omega)$
Cells with SiO_x	Before UV	39.37	751	25.29	85.63	0.00171	8543.58
	After UV	39.33	748	25.05	85.31	0.00186	8060.73
Cells without SiO_x	Before UV	39.00	750	24.73	84.69	0.00299	847.59
	After UV	38.78	749	24.08	83.12	0.0041	21.32

This temperature range allows for effective recovery while minimizing the risk of detrimental effects on the a-Si passivation layer.

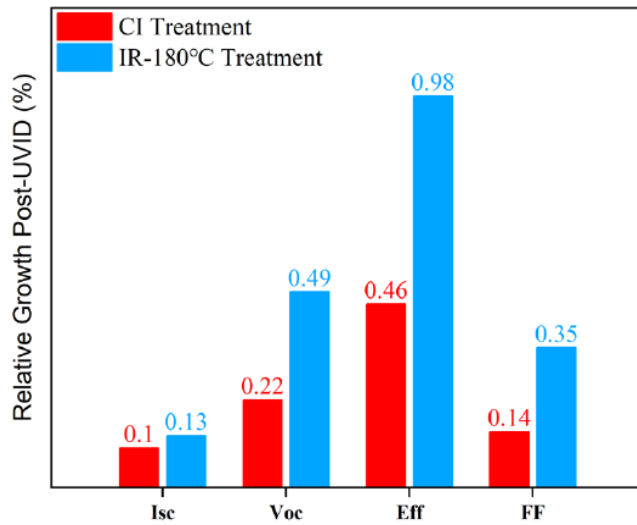


Figure 3: Comparison of CI and IR Recovery treatments after UV.

It has been found that IR-180°C is an effective treatment to recover the efficiency of HJT solar cells after UVID. Further experiments were conducted to investigate the separate effects of IR and temperature on the recovery efficiency of HJT solar cells. For IR treatment, 17-suns, $T = 25^{\circ}\text{C}$ and $t = 2$ mins. The annealing treatment was conducted with two different temperatures $T = 140^{\circ}\text{C}$ and 180°C , each applied for a duration of 2 mins. Furthermore, the comparison of electrical parameters between IR and different annealing temperatures can be seen in Figure 4.

IR-17SUNS: The average initial efficiency of the cells was 25.299%. After UV exposure, the efficiency dropped to 25.103%. The IR-17Suns treatment was applied to the HJT and the efficiency increased to 25.145%. However, it is still lower than the initial efficiency before UV exposure.

ANNEALING AT 140°C: The average initial efficiency of the cells was 25.35%. After UV exposure, the efficiency dropped to 25.19%. The cells were then annealed at a temperature of 140°C for 2 minutes, and the efficiency increased to 25.23%. However, it is still lower than the initial efficiency before UV exposure.

ANNEALING AT 180°C: The average initial efficiency of the cells was 25.411%. After UV exposure, the efficiency dropped to 25.197%. The cells were then annealed at a temperature of 180°C for 2 minutes, and the efficiency increased to 25.424%. After annealing at 180°C , the efficiency was higher than the initial efficiency before UV exposure, indicating a complete recovery of efficiency, with a recovery rate of more than 100%.

3.3.2. Light Soaking Treatment

Figure 5 shows the experimental results from the conducted light soaking recovery treatment. In Experiment 1, where pure light soaking was performed at 25°C for a duration of 1 minute with an intensity of $8e^5$ Lux. The cells exhibited a partial recovery in efficiency after the post-UV exposure treatment. Although the increase in efficiency was noticeable, it did not reach 100%. This suggests that at 25°C , the recovery process is not able to fully reverse the detrimental effects of UV-induced degradation.

Table 3: Comparison of Recovery Treatments: Current Injection vs Infrared

CI Treatment							
HJT solar cells	Quantity	$J_{sc}(\text{mA}/\text{cm}^2)$	$V_{oc}(\text{mV})$	Eff (%)	FF	$R_s(\Omega)$	$R_{sh}(\Omega)$
Before UV	90	38.52	749	24.74	85.81	0.00179	7436.64
Post-UV	90	38.40	747	24.55	85.76	0.00171	5347.82
Post-CI	90	38.44	748	24.66	85.88	0.00170	8502.40
Recovery (%)		30.740	85	59.375	240	12.5	151.02
IR-180°C Treatment							
Before UV	90	38.52	750	24.73	85.75	0.00184	8572.12
Post-UV	90	38.41	747	24.54	85.71	0.00177	6454.12
Post-CI	90	38.45	750	24.78	86.01	0.00175	9601.17
Recovery (%)		41.263	100	124.48	750	350	148.59

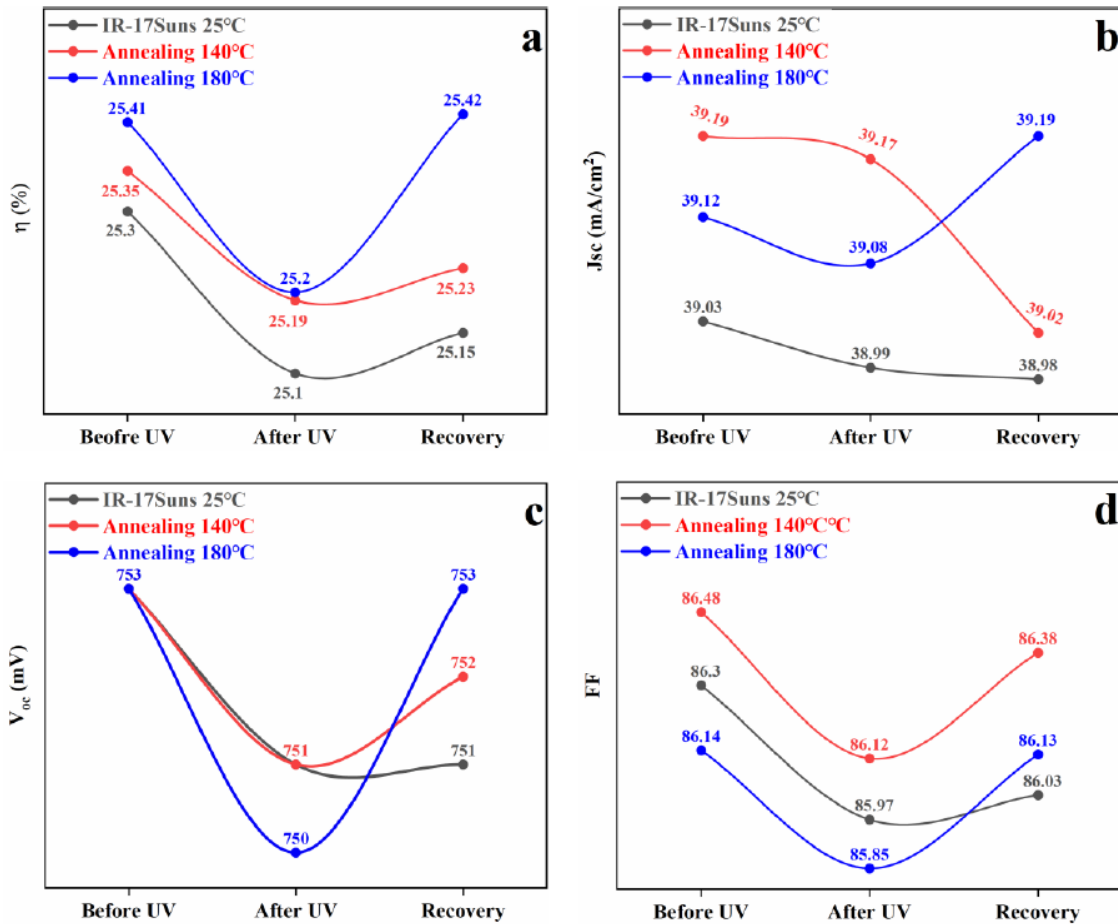


Figure 4: Comparison of IR and Annealing Recovery Treatments.

In contrast, Experiment 2, where the temperature was elevated to 180°C during light soaking, resulted in a more substantial recovery of efficiency after the treatment. Interestingly, the efficiency after the recovery treatment surpassed the initial baseline efficiency before UV exposure, indicating a recovery of more than 100%. This suggests that the combination of light soaking at 180°C provides a more effective means of reversing the UV-induced degradation and restoring the efficiency of the HJT solar cells.

The graphical representations of the experimental data in Figure 5 further illustrate the differences in recovery between the two temperature conditions. The graph corresponding to Experiment 2, with the higher temperature of 180°C, demonstrates a more pronounced upward trend in efficiency compared to the graph for Experiment 1 at 25°C. This visual representation supports the notion that 180°C, enhances the recovery process and enables the cells to surpass their initial efficiency levels.

3.3.3. Raman Spectroscopy

Figure 6 represent the Raman spectroscopy results of the HJT solar cells before UV exposure, after UV exposure, and after the recovery treatment indicate a consistent peak at 519.12 nm in the intensity versus wavelength graph. This peak is a significant observation that warrants an in-depth explanation. Raman spectroscopy is a technique that provides insights into the vibrational and rotational modes of molecules and crystals. In the case of solar cells, Raman spectroscopy can reveal information about the material composition, crystal structure, and defects present in the sample. The observed peak at 519.12 nm corresponds to a specific Raman scattering event associated with the HJT solar cell structure or its constituent materials. The peak's presence in all three groups of samples suggests that structure of HJT solar cells is unaffected by UV exposure or the subsequent recovery treatment.

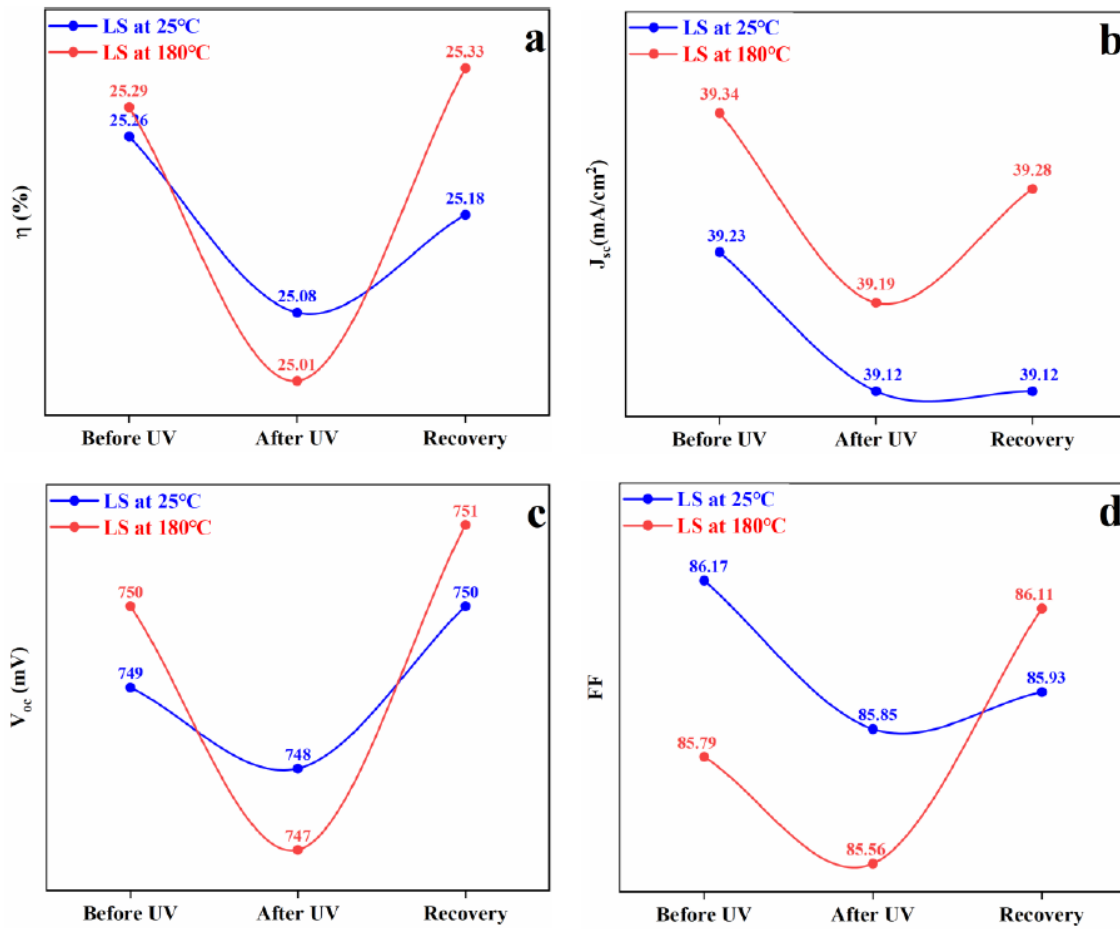


Figure 5: Light soaking recovery treatment at 25°C and 180°C.

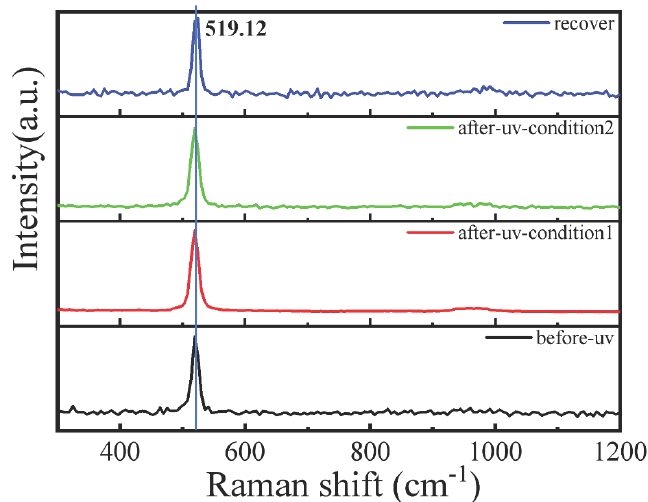


Figure 6: Raman spectroscopy of HJT solar cells before and after UV exposure and recovery treatment.

3.3.4. Short and Prolonged UV Exposure

To study the influence of short and long-time UV exposure on degradation and efficiency recovery, the

240 samples were divided into four different groups: Group A (60 samples) were exposed to UV light for 20 minutes, Group B (60 samples) for 40 minutes, Group C (60 samples) for 60 minutes, and Group D (60 samples) for 11 hours. After UV exposure, all groups underwent a recovery treatment of 180°C for 1 minute, which was the same for every group.

Figure 7(a, b & c) demonstrates that short-term UV exposure for durations of 20 minutes, 40 minutes, and 60 minutes results in relatively mild degradation in HJT solar cells, which can be effectively mitigated through annealing treatment. Group A, B, and C showed 100% recovery in efficiency after the annealing treatment. The UV light breaks the Si-H/Si-Ox bonds, leading to the movement of hydrogen/oxygen ions towards the n-doped amorphous Si and crystalline Si. Some of the H form metastable states, which can also lead to reducing the efficiency of cells. In the recovery treatment, when the samples are annealed at 180°C, the hydrogen/oxygen migrate back towards the amorphous/crystalline Si interface and re-passivates

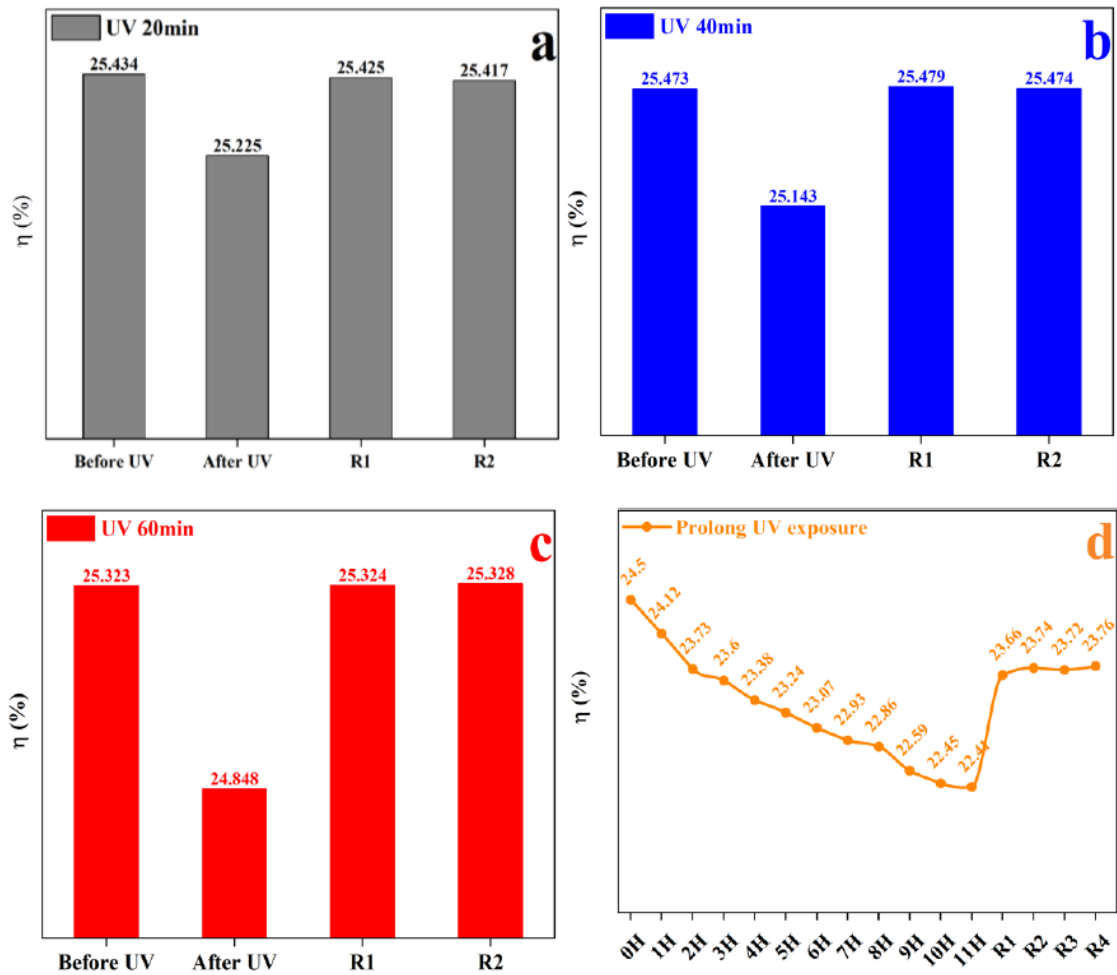


Figure 7: (a, b, c) Recovery treatment after short, (d) prolonged UV exposure.

the dangling bonds. This process completely restores the efficiency of the HJT solar cells.

In contrast, as shown in Figure 7d, samples were exposed to UV light for 11H and did not fully recover their efficiency even after multiple annealing treatments. There was no further increase in efficiency after the first 2-recovery treatments. There might be several potential reasons. Firstly, prolonged UV exposure can lead to the accumulation of defects within the amorphous Si. As the exposure time increases, the accumulation of defects may reach a threshold where they become difficult to fully recover, even with subsequent recovery processes. Secondly, prolonged UV exposure may also contribute to the formation of irreversible defects. These irreversible defects can have a long-term detrimental impact on the performance of the solar cells, resulting in a reduced efficiency that cannot be fully recovered.

Our recent experiments conducted on HJT modules in outdoor environments have revealed minimal

ultraviolet light-induced degradation. These findings suggest that the impact of UVID on the performance of HJT solar cells is significantly reduced in hot areas. These promising results will be documented in our upcoming article. To overcome UVID, the HJT solar cell module manufacturers have adopted a practical solution by incorporating UV-block ethylene-vinyl acetate (EVA) encapsulation material. This innovative approach offers an effective means of minimizing UVID in HJT solar cells. The UV-blocking properties of the EVA material prevent harmful UV radiation from reaching the microcrystalline a-Si:H and interface of a-Si:H/c-Si of the solar cells, thereby mitigating degradation and preserving their efficiency over extended periods. The another possible solution is to introduce the downconversion (DC) materials into the EVA films. These DC materials have the potential to absorb UV light and emit light near visible range, it facilitate more efficient utilization of solar radiation. This conversion process not only reduced the UV light-induced degradation but also allows a broader range of

photons to be absorbed by the solar cells, leading to an increase in overall efficiency.

4. CONCLUSION

In conclusion, the study provides valuable insights into UV light-induced degradation in industrial Si HJT solar cells. The experimental results demonstrated a decrease in carrier lifetime, iV_{oc} , and iFF due to the creation of defects in the a-Si:H bulk and the c-Si/a-Si:H interface. SiO_x passivation was found to be beneficial in mitigating UV-induced degradation and enhancing the efficiency of the solar cells. Current injection, infrared, and light soaking recovery treatments without temperature showed limited recovery in efficiency after UV light-induced degradation. It is indicating that it may not be as effective in mitigating the effects of UV-induced degradation. However, annealing at 180°C–200°C is the key factor to restore the efficiency of HJT solar cells. The prolonged UV exposure resulted in reduced recovery potential, likely due to the accumulation of irreparable defects. The generation of hot carriers can be a UV damage mechanism, and SiO_x exhibited resistance against hot carrier damage. The findings of this study contribute to the understanding of UV-induced degradation mechanisms and provide important insights for the development of strategies to improve the performance and longevity of HJT solar cells.

LIST OF ABBREVIATION

HJT solar cells: Heterojunction solar cells

CI: Current Injection

IR: Infrared

LS: Light soaking

UV: Ultraviolet

J_{sc} : Current density

V_{oc} : Open circuit voltage

FF: Fill factor

EFF: Efficiency

Lux: illuminance = one lumen per square metre

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CONFLICT OF INTREST

The authors 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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