

Stability Enhancement of Crystalline Silicon Solar Cells Through Electrical Bias Induced Recovery of LeTID

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Abstract

LeTID presents a critical reliability issue in industrial c-Si PERC solar cells, especially under prolonged thermal and illumination stress. This study explores the application of DC electrical biasing as an external regeneration technique to mitigate LeTID effects in PERC cells. Cells were deliberately degraded under 1-sun illumination at three elevated temperatures: 75°C, 85°C, and 100°C for 11 hours, simulating accelerated aging conditions relevant to field operation. Temperature-dependent degradation was evident, with the most pronounced losses observed at 100°C, where normalized J_{sc} , V_{oc} , FF, and PCE values declined to 0.8933, 0.8886, 0.8851, and 0.8822, respectively. The series resistance increased significantly from 1.97 to 183 $\Omega \cdot \text{cm}^2$, indicating increased recombination activity due to bulk defect formation. Forward and reverse DC biasing were applied to the degraded cells to facilitate recovery. Forward biasing exhibited superior regeneration capability, restoring the initial efficiency up to 99.94% within 7 hours, compared to 99.64% in 9 hours for reverse biasing. EQE at 900 nm improved from ~ 72% (degraded) to ~ 89% (recovered), confirming the effective passivation of LeTID-induced defects. These results demonstrate that forward DC biasing is a promising, scalable approach for electrical recovery of LeTID-affected PERC cells, offering a potential post-process strategy to enhance long-term photovoltaic stability and performance.

1. Introduction

Passivated Emitter and Rear Contact (PERC) solar cells have become a cornerstone of the PV industry due to their superior power conversion efficiency and cost-effective fabrication. By introducing rear-side passivation and advanced light management techniques, PERC cells significantly outperform traditional Al-BSF cells. However, despite these advantages, their long-term performance reliability is challenged by Light and Elevated Temperature-Induced Degradation (LeTID), a phenomenon that causes substantial efficiency losses under prolonged exposure to illumination and elevated temperatures[1–5]. LeTID is particularly problematic in real-world applications where operating conditions often fall within the critical temperature range of 75°C to 100°C. Unlike conventional Light-Induced Degradation (LID), which predominantly affects boron-doped silicon through boron-oxygen (BO) complex formation, LeTID affects both boron- and gallium-doped silicon wafers. The degradation is primarily attributed to complex interactions involving hydrogen, charge carriers, and metal impurities. These interactions activate deep-level defects in the silicon bulk, increasing carrier recombination and leading to reduced short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and overall efficiency (η)[6–11].

Current strategies for mitigating LeTID, including optimized hydrogenation, thermal annealing, and process-level modifications, offer limited effectiveness and are sometimes inconsistent. For instance, thermal annealing can help recover performance but may increase series resistance, impacting fill factor and overall device output. Furthermore, process adjustments such as modified firing profiles or altered passivation layers often introduce trade-offs between stability and efficiency. Given these challenges, a promising alternative gaining attention is the application of external DC biasing to modulate carrier dynamics and influence defect activity within the solar cell structure. Forward and reverse biasing

provide mechanisms to suppress or deactivate recombination-active defect states by altering electric fields or by injecting excess carriers, thereby enhancing passivation and improving cell performance. While some studies have indicated the potential of DC biasing for LeTID suppression, its effectiveness under varying temperature conditions remains insufficiently understood[12–15].

This study investigates the effects of forward and reverse DC biasing on LeTID regeneration in PERC solar cells. Applying a controlled forward bias (constant current) and reverse bias (constant voltage) to degraded PERC at 75°C, 85°C, and 100°C. We explore the recovery behavior of key performance parameters, including J_{sc} , V_{oc} , and η . Through systematic experimentation and performance monitoring under realistic degradation conditions, this research seeks to establish DC biasing as a scalable, non-destructive, and efficient method for mitigating LeTID in industrial solar cells. The insights gained could pave the way for more durable and reliable PV systems, ensuring long-term energy yield and supporting continued growth in solar energy adoption [16–18].

2. Experimental methods

2.1 Performance Degradation in PERC Solar Cells and the Role of LeTID

Photovoltaic cell degradation remains a significant concern for the solar energy industry, particularly in PERC solar cells. These cells have gained widespread adoption due to their superior efficiency, achieved through improved light absorption, enhanced passivation layers, and better charge-carrier collection. As depicted in Fig. 1, the structural configuration of a p-type PERC (p-PERC) solar cell consists of a front silver (Ag) contact, an anti-reflective silicon nitride (SiN_x) coating, a doped emitter layer, a bulk silicon wafer, a passivation layer, a SiN_x capping layer, and an aluminum (Al) rear contact. While these layers optimize solar cell performance, they also introduce inherent material defects. Under illumination and elevated temperatures, previously inactive defects become active, leading to increased charge-carrier recombination. This activation reduces the carrier density and negatively impacts key solar cell parameters, including V_{oc} , J_{sc} , and FF. Effective mitigation strategies must therefore be developed to suppress degradation and facilitate regeneration processes to restore efficiency [19–23].

LeTID is one of the most critical degradation phenomena in PERC solar cells. Initially, boron-oxygen complexes were hypothesized to be responsible for LeTID, similar to the mechanism driving Boron-Oxygen Light-Induced Degradation (BO-LID). However, subsequent research has demonstrated that LeTID occurs even in boron-free wafers, indicating that its root cause extends beyond BO defects. To mitigate BO-LID, gallium (Ga) doping has been introduced as an alternative to boron. Nevertheless, Ga-doped PERC cells continue to exhibit LeTID, suggesting the involvement of other defect complexes in the degradation process[24, 25]. Further studies have identified metallic impurities, including iron (Fe), cobalt (Co), nickel (Ni), and titanium (Ti), as potential contributors to LeTID. These metal contaminants, introduced during wafer fabrication and firing, can interact with hydrogen, forming recombination-active

defect centres that accelerate degradation. In addition to metal impurities, hydrogen incorporation during passivation, doping, and firing processes has been recognized as a key factor influencing degradation and regeneration. Hydrogen plays a dual role in LeTID: it facilitates defect passivation and improves cell stability, but it can also contribute to defect activation and exacerbating degradation under certain conditions. The extent of LeTID degradation is directly correlated with the hydrogen content in the silicon bulk, reinforcing its significance in degradation mechanisms [26–29].

Hydrogen passivation has been widely used to mitigate BO-LID; however, its effectiveness in addressing LeTID is far more complex. Free hydrogen is inherently unstable within a perfect silicon lattice and must migrate to defect sites to enable effective passivation. Excessive hydrogen accumulation can be detrimental, particularly when it dissociates boron-hydrogen (B-H) complexes, further aggravating LeTID. Hydrogen diffusion dynamics depend on charge-state transitions, with a negative U-curve governing the shift from H^+ to H. During the firing process, hydrogen is driven into the silicon bulk, allowing it to interact with metallic impurities. Metal-hydrogen (M-H) complexes are formed, passivating the metal contaminants. However, these complexes may dissociate under prolonged illumination and elevated temperatures, forming highly recombination-active centers that accelerate LeTID. Strategies to optimize hydrogen passivation and minimize degradation effects have included modifications to SiN_x deposition conditions and the application of hydrogen-lean $AlO_x:H$ layers, both of which influence hydrogen distribution and passivation efficacy [30–33].

The primary driver of LeTID is the interaction between molecular hydrogen (H_2) and precursor defect sites in the silicon lattice. Hydrogen binds to these defect sites, forming recombination-active centers that reduce minority carrier lifetime and significantly impact solar cell efficiency. The dissociation of boron-hydrogen (BH) and gallium-hydrogen (Ga-H) complexes has also been identified as a potential mechanism contributing to LeTID. Recent research suggests that iron-gallium (Fe-Ga) pairs may play a role in Ga-doped cell degradation, further underscoring the influence of metallic impurities on LeTID behavior. Charge carriers play an essential role in activating and accelerating LeTID. Experimental observations have demonstrated that light exposure and voltage biasing significantly alter the rate and severity of degradation. Excess carrier injection can trigger the activation of metastable defects in the solar cell, thereby promoting recombination. Unlike a simple Fermi-level shift, this activation is strongly influenced by carrier recombination dynamics. Once a defect site accumulates sufficient activation energy, it transitions into a recombination-active state, further diminishing solar cell efficiency. Furthermore, recent findings indicate that excess electron density, rather than light or temperature alone, is the primary trigger of defect activation in LeTID [34–37].

The PERC solar cell features a passivated rear surface that enhances light absorption and minimizes recombination losses. The key electrical parameters include J_{sc} of 39.55 mA/cm², V_{oc} of 0.746 V, FF of 75.86%, and η of 22.38%. The power density (P, mW/cm²) curve in Fig. 2 represents the maximum power output achievable under standard conditions, peaking at the optimal operating point. The current density (J, mA/cm²) measures the charge generated per unit area and directly influences the power output. These parameters highlight the efficiency and reliability of PERC solar cells in photovoltaic applications.

The optical microscopy images in Fig. 3 illustrate the finger spacing and busbar width on the front and rear sides of a PERC solar cell, providing precise numerical measurements of the metal contact structure. These images are crucial for assessing the metallization pattern, which directly affects charge-carrier collection efficiency and electrical performance. The front-side image shows the finger spacing of 1335.2 μm and a busbar width of 650.4 μm . The delicate metal fingers efficiently collect photogenerated charge carriers while minimizing resistive losses. The spacing between the fingers affects the sheet and series resistance, influencing the overall cell efficiency. The busbars, which are significantly wider, transport the collected charge to the external circuit. The rear-side image shows finger spacings of 839.1 μm and 189.1 μm , along with a busbar width of 1726.8 μm . The rear contact pattern plays a significant role in optimizing charge carrier transport while reducing recombination losses. The variation in finger spacing suggests the presence of distinct current-collection regions, strategically designed to enhance efficiency and reduce electrical resistance. The optical micrographs in Fig. 3 show cross-sectional views of laser-cutting patterns in different types of c-Si solar cells, along with the finger and busbar width spacing, magnified 200 times. These images reveal the causes of electrical or resistive losses and provide detailed insights into laser-induced modifications to cell surfaces, which are essential for understanding the impact of laser processing on both structural and electrical properties. The micrographs emphasize the role of laser processing techniques in c-Si solar cell fabrication, highlighting how laser-cut patterns influence the cell's electrical behavior. The variations observed in these patterns across different solar cell types reflect the diverse manufacturing strategies employed to achieve high photovoltaic efficiency. Therefore, precise and optimized laser processing techniques are crucial for improving the structural integrity and electrical performance of solar cells.

These microscopy images provide insights into the precision of the metallization process, which is critical for improving the electrical conductivity and efficiency of p-PERC solar cells. The measured dimensions are within the expected range for high-efficiency solar cell designs, ensuring effective charge collection while balancing optical and electrical losses. The LeTID chamber depicted in Fig. 4(a) is designed explicitly to investigate LeTID in crystalline silicon (c-Si) solar cells under controlled experimental conditions. This setup enables accelerated degradation testing by replicating real-world environmental factors, including prolonged illumination and elevated temperatures, which contribute to charge-carrier recombination and efficiency losses in solar cells. The xenon lamp serves as a high-intensity light source, simulating natural sunlight, while the heating plate ensures precise temperature control to analyze degradation under varying thermal conditions. Additionally, a temperature sensor is integrated into the system to maintain accurate thermal monitoring, and a water-cooling line prevents overheating beyond predefined limits. The exhaust fan facilitates heat dissipation and stabilizes the chamber by maintaining optimal airflow conditions.

The system also incorporates a DC biasing mechanism, as illustrated in the power supply unit Fig. 4(b), allowing forward and reverse biasing to investigate their respective roles in LeTID mitigation and recovery. Forward DC biasing enhances charge-carrier injection, potentially accelerating the passivation of defects responsible for degradation and thereby facilitating recovery. Conversely, reverse DC biasing alters charge-carrier transport dynamics by redistributing mobile defects, thereby contributing to defect

deactivation and overall LeTID suppression. By applying controlled bias voltages, this system enables a systematic evaluation of the impact of electrical fields on defect states and charge carrier recombination, providing crucial insights into effective LeTID recovery strategies. The solar cell measurement jig, shown in Fig. 4(c), is employed to securely position the solar cell while ensuring stable electrical contacts for performance characterization. This fixture minimizes contact resistance and mechanical stress, allowing for precise current-voltage measurements under experimental conditions. The jig plays a critical role in assessing the impact of degradation and subsequent recovery mechanisms by facilitating repeated and accurate electrical characterization of the solar cells throughout the experimental cycle. This integrated setup is instrumental in evaluating the effectiveness of LeTID mitigation techniques, including DC biasing recovery, under simulated real-world operational conditions.

3. Results and Discussion

The investigation into LeTID and its recovery mechanisms in PERC solar cells was conducted using a structured experimental framework. The study aimed to analyze the impact of temperature variations on LeTID-induced degradation and to evaluate the effectiveness of forward and reverse DC biasing in facilitating performance recovery. The experiment commenced with an initial electrical characterization of the solar cells to establish baseline performance metrics. The characterization included Light Current-Voltage (LIV), Dark Current-Voltage (DIV), and External Quantum Efficiency (EQE) measurements. The LIV test provided crucial electrical parameters such as J_{SC} , V_{OC} , FF, and η under standard test conditions. The DIV measurement helped identify recombination processes and shunt resistance effects, while the EQE analysis assessed the spectral response and charge-carrier collection efficiency across various wavelengths. These measurements ensured a comprehensive understanding of the cell's initial performance before subjecting it to degradation stress.

The solar cells were subjected to LeTID degradation under controlled environmental conditions after the baseline characterization. This degradation phase involved exposing the cells to 1 sun illumination at 75°C, 85°C, and 100°C for 15 hours. The temperature was precisely controlled using a heating plate with a temperature sensor, while a xenon lamp simulated real-world light exposure. A water-cooling system was incorporated to maintain thermal stability and prevent overheating beyond the set limits. As the degradation phase progressed, a gradual decline in electrical performance was observed, attributed to the activation of hydrogen-related defects. These defects enhanced carrier recombination, leading to a decrease in J_{SC} , V_{OC} , and overall efficiency. The extent of degradation varied with temperature, with the highest degradation occurring at 100°C, where the defect-activation rate was most pronounced. The I-V characteristics after degradation, as depicted in Fig. 5, clearly show a drop in solar cell performance under different temperature conditions.

After the 15-hour degradation cycle, the recovery phase was initiated using DC biasing, where both forward and reverse DC biasing were applied to the degraded solar cells. In the forward biasing condition, a constant voltage and current were supplied, corresponding to the degraded V_{OC} and J_{SC} , as outlined in Fig. 5. Forward biasing accelerated defect passivation, enabling the cell to regain its initial

performance within 7 hours. The enhanced recovery efficiency under forward biasing is attributed to carrier injection into the bulk, which expedites hydrogen migration to defect sites. This interaction leads to the passivation of recombination centers, thereby restoring charge-carrier lifetimes and improving electrical parameters.

In the reverse-bias condition, the applied voltage was maintained at the same level as in forward biasing, but with opposite polarity. As illustrated in Fig. 6, the reverse-bias recovery process was slower, requiring 9 hours to restore performance to levels comparable to forward biasing. The slower recovery rate under reverse biasing is primarily due to the expansion of the depletion region, which alters charge-transport mechanisms and reduces the efficiency of hydrogen-defect passivation. Unlike forward biasing, which facilitates direct carrier injection, reverse biasing primarily influences carrier redistribution rather than directly neutralizing defect states. This redistribution process is less effective in rapidly passivating LeTID-induced defects, resulting in an extended recovery period. The I-V characteristics shown in Fig. 6 further emphasize the behavior of solar cells during reverse-bias recovery. The red curve represents the initial, undegraded condition of the cell, where optimal J_{sc} , V_{oc} , and FF were observed. The blue curve, corresponding to the degraded state, shows apparent reductions in current density and voltage, highlighting the impact of hydrogen-related defect activation on carrier recombination. The green curve, recorded after 9 hours of reverse biasing, shows partial recovery of electrical performance, confirming the effectiveness of reverse biasing in regenerating the cell, albeit at a slower rate than forward biasing.

The comparative evaluation of forward and reverse bias during recovery underscores the superior efficiency of forward bias in facilitating rapid defect passivation. While reverse biasing contributed to incremental regeneration, forward biasing significantly accelerated defect healing, reducing the recovery time by 2 hours. This finding is consistent with prior studies indicating that increased charge-carrier concentration under forward bias enhances hydrogen-defect interactions, thereby expediting passivation and improving cell stability. The expansion of the depletion region under reverse bias modifies defect behavior but does not inject carriers as efficiently as forward biasing, resulting in a delayed recovery process.

The results of this study reinforce the critical roles of temperature and electrical biasing in the dynamics of LeTID-induced degradation and recovery. Higher temperatures accelerate defect activation, leading to more severe performance loss, while electrical biasing, particularly forward biasing, effectively mitigates degradation effects by enabling charge-assisted defect passivation. The ability to restore degraded solar cells using electrical stimulation presents a promising strategy for in-situ LeTID mitigation, which could be integrated into PV systems to enhance long-term reliability and operational efficiency. Future research should focus on optimizing biasing conditions, exploring alternative passivation approaches, and investigating the impact of charge-state interactions in defect passivation to improve the effectiveness of electrical biasing in commercial solar cells. Additionally, further studies should explore the long-term stability of regenerated cells and the feasibility of implementing active biasing techniques in field-deployed photovoltaic systems. These insights advance high-efficiency solar cell technologies,

reinforcing the potential of electrical biasing as a viable strategy for performance stabilization and degradation suppression in next-generation PV modules.

Figure 7 illustrates the variations in key electrical parameters, including J_{sc} , V_{oc} , FF, and η of PERC solar cells, throughout three experimental phases: initial state, degradation, and recovery. The experiments were conducted at controlled temperatures of 75°C, 85°C, and 100°C, allowing a comprehensive assessment of the effects of LeTID degradation and the subsequent regeneration process following electrical biasing. In the initial state, the solar cells exhibited normalized electrical parameters J_{sc} , V_{oc} , FF, and η , each set to 1.0000, signifying optimal performance before exposure to elevated temperatures and prolonged illumination. These values served as reference benchmarks for evaluating the impact of degradation and the effectiveness of the recovery process. During the degradation phase, a notable reduction in electrical performance was observed, attributed to the activation of hydrogen-related defects, leading to increased non-radiative recombination and a decline in carrier lifetime. At 75°C, J_{sc} decreased to 0.9563, V_{oc} to 0.9558, FF to 0.9546, and efficiency to 0.9539, indicating a moderate degradation effect. At 85°C, the impact of LeTID became more pronounced, as J_{sc} dropped to 0.9253, V_{oc} to 0.9239, FF to 0.9222, and efficiency to 0.9215. The most substantial degradation occurred at 100°C, where J_{sc} was reduced to 0.8933, V_{oc} to 0.8886, FF to 0.8851, and efficiency to 0.8822, confirming that higher temperatures accelerate defect activation, resulting in greater efficiency losses.

Following the recovery phase, where DC biasing was employed to facilitate defect passivation, the solar cells demonstrated near-complete restoration of their electrical characteristics. At 75°C recovery, J_{sc} , V_{oc} , FF, and efficiency were restored to 0.9996, 0.9993, 0.9987, and 0.9993, respectively. Similarly, at 85°C recovery, J_{sc} , V_{oc} , FF, and efficiency returned to 0.9991, 0.9996, 0.9992, and 0.9996, respectively. Even at 100°C, despite the more severe degradation, the solar cells successfully regained their initial performance, with J_{sc} , V_{oc} , FF, and efficiency reaching 0.9996, 0.9993, 0.9993, and 0.9994, respectively. The trends observed in Fig. 7 confirm that while higher temperatures result in more significant degradation due to enhanced defect activation, the application of DC biasing effectively restores the electrical performance of the cells to near-original levels. This suggests that electrical biasing is highly effective for mitigating LeTID effects, demonstrating minimal residual degradation post-recovery. These findings underscore the importance of temperature management and defect passivation strategies for ensuring the long-term stability and efficiency of PERC solar cells, particularly in real-world photovoltaic applications.

Figure 8 illustrates the normalized electrical parameters of J_{sc} , V_{oc} , FF, and efficiency in PERC solar cells across three experimental phases: initial, degradation, and recovery at 75°C, 85°C, and 100°C. The plotted curves depict the impact of LeTID degradation on the device performance and the subsequent recovery process, emphasizing the role of electrical biasing in defect passivation. In the initial state, the solar cells exhibited normalized values of J_{sc} , V_{oc} , FF, and efficiency, all set at 1.0000, representing optimal performance before exposure to stress conditions. These values serve as the baseline for evaluating degradation and recovery behavior. During the degradation phase, a significant decline in

electrical performance was observed, driven by the activation of hydrogen-related defects that enhanced charge-carrier recombination. At 75°C, J_{sc} was reduced to 0.9553, V_{oc} to 0.9548, FF to 0.9536, and efficiency to 0.9529. As the temperature increased to 85°C, the degradation effects became more severe, with J_{sc} declining to 0.9243, V_{oc} to 0.9229, FF to 0.9212, and efficiency to 0.9205. The highest degradation was observed at 100°C, where J_{sc} dropped to 0.8923, V_{oc} to 0.8876, FF to 0.8841, and efficiency to 0.8812. These trends confirm that higher temperatures accelerate defect activation, leading to increased non-radiative recombination and efficiency loss. Following recovery using DC biasing, the solar cells exhibited a near-complete restoration of their initial performance. At 75°C recovery, J_{sc} , V_{oc} , FF, and efficiency improved to 0.9946, 0.9953, 0.9937, and 0.9933, respectively. Similarly, at 85°C recovery, these values reached 0.9955, 0.9966, 0.9952, and 0.9946, showing effective defect passivation. Even at 100°C, where degradation was the most severe, the recovery process successfully J_{sc} , V_{oc} , FF, and efficiency to 0.9966, 0.9973, 0.9983, and 0.9964, respectively.

The DIV characteristics shown in Fig. 9 provide a comprehensive assessment of the electrical behavior of PERC solar cells under initial, degraded, and recovered conditions. The DIV measurement is an essential tool for evaluating key parameters, such as carrier recombination, series resistance, and shunt resistance, which are crucial for understanding the impact of LeTID and the effectiveness of recovery strategies. The variations observed in the DIV curves highlight the extent of defect activation during degradation and the degree of passivation achieved through electrical biasing[38].

In the initial state, the solar cell exhibits an ideal diode response, characterized by an exponential increase in current with applied voltage and minimal non-idealities. The series resistance (R_s) in this state is measured at 1.97 Ω/cm^2 , indicating efficient charge carrier transport with minimal resistive losses. The low recombination current suggests that the bulk and surface passivation layers effectively suppress defect-mediated recombination, ensuring high carrier collection efficiency. This represents the optimal operational condition before exposure to degradation stress. During the degradation phase, the DIV characteristics undergo significant changes, reflecting the impact of metastable defect activation and increased carrier recombination. A noticeable increase in leakage current, particularly at low voltages, indicates an increase in shunt paths and defect-assisted recombination mechanisms. The R_s increases drastically to 183 Ω/cm^2 , signifying a severe impediment to charge transport. This substantial rise in resistance is attributed to the activation of hydrogen-related defects and metallic impurities, which create deep-level recombination centers and hinder carrier mobility. The increased recombination current further confirms that non-radiative recombination pathways dominate in the degraded state, thereby significantly reducing the solar cell's efficiency.

Following the recovery phase, the DIV characteristics show substantial improvement, with the electrical behavior returning closer to the initial state. The R_s decreases to 7.69 Ω/cm^2 , significantly recovering from the degraded state. However, this value remains slightly higher than the initial resistance, suggesting that while DC biasing effectively passivates most activated defects, some residual deep-level traps persist, impacting carrier transport efficiency. The reduction in recombination current in the

intermediate-voltage region confirms that defect passivation has occurred, restoring charge-carrier lifetimes and minimizing non-radiative recombination losses. Despite this, minor deviations from the initial state indicate that complete recovery is impossible, likely due to incomplete hydrogen migration or persistent impurity-related defects.

The DIV measurement was conducted by applying a controlled DC voltage sweep to the solar cell under dark conditions, ensuring that only intrinsic electrical properties were measured, free from the influence of photogenerated carriers. The experimental setup included a high-precision source meter for voltage application and current measurement, a temperature-controlled environment to minimize thermal noise, and a four-point probe configuration to reduce contact resistance errors. The analysis of the DIV curve involves evaluating different voltage regimes:

Shunt resistance and leakage currents influence the low-voltage region (near 0 V), and this effect becomes more pronounced in the degraded state due to defect formation. The intermediate-voltage region is dominated by defect-assisted recombination, with charge-carrier losses due to trap states evident. The high-voltage region is controlled by series resistance, and the impact of resistive losses on charge-carrier transport is analyzed. The results confirm that LeTID degradation induces significant alterations in the electrical properties of PERC solar cells, as evidenced by the substantial increase in series resistance and recombination currents. However, the successful restoration of DIV characteristics following DC biasing treatment highlights its effectiveness in mitigating defect activation and improving carrier transport. While some residual degradation effects remain, the findings underscore the potential of electrical biasing techniques to enhance the long-term stability and performance of PERC solar cells, ensuring their resilience under real-world photovoltaic operating conditions.

The EQE spectra in Fig. 10 comprehensively evaluate the carrier collection efficiency of PERC solar cells under the initial, degraded, and recovered conditions. EQE measurement is crucial for assessing a solar cell's ability to convert incident photons into electrical current across various wavelengths. This characterization is instrumental for understanding the effects of LeTID degradation, charge-carrier recombination, and defect passivation mechanisms. The variations observed in the EQE curves reflect the impact of defect activation during degradation and the subsequent effectiveness of the recovery process, via DC biasing, in restoring charge-transport properties. The EQE response remains high across the measured wavelength range in the initial state, indicating optimal carrier collection with minimal recombination losses. The short-wavelength response (300–500 nm) suggests that surface passivation effectively reduces front surface recombination losses. Similarly, the long-wavelength response (800–1200 nm) is well-maintained, confirming efficient bulk carrier collection with minimal deep-level recombination. The maximum EQE reaches approximately 96%, demonstrating high spectral response under optimal conditions.

During the degradation phase, a significant reduction in EQE is observed, particularly in the long-wavelength region (800–1200 nm), suggesting enhanced recombination within the silicon bulk. This degradation is attributed to the activation of hydrogen-related defects and metallic impurities, which

introduce additional recombination centers, thereby reducing charge-carrier lifetimes and collection efficiency. At 500 nm, the EQE decreases to approximately 87%; at 900 nm, it drops to approximately 72%, indicating severe bulk recombination. The increased recombination losses in this state are accompanied by higher series resistance, leading to an overall decline in the device's photovoltaic efficiency. Following the DC biasing recovery phase, the EQE spectrum exhibits significant improvement, closely approaching the initial state. The restoration of carrier collection efficiency across both short- and long-wavelength regions confirms the passivation of LeTID-induced defects and a reduction in recombination losses. At 500 nm, the EQE is restored to 94%, while at 900 nm, it increases to approximately 89%, demonstrating that most bulk and surface defects have been successfully passivated. However, minor deviations from the initial EQE curve indicate that some residual deep-level defects persist, which could contribute to minor carrier losses even after recovery. The EQE measurement was conducted by illuminating the solar cell with monochromatic light of varying wavelengths and recording the resulting photocurrent response. The measurement setup consists of a broad-spectrum light source, such as a xenon or tungsten-halogen lamp, a monochromator to filter light into discrete wavelength bands selectively, a calibrated reference detector to measure photon flux, and a source meter to record the photocurrent generated by the solar cell. The EQE is calculated using the relationship:

$$EQE (\%) = \frac{I_{ph}(\lambda)}{q \cdot \Phi(\lambda)}$$

Where $I_{ph}(\lambda)$ represents the measured photocurrent at wavelength λ , q is the charge of an electron, and $\Phi(\lambda)$ is the incident photon flux at wavelength λ . The interpretation of EQE data provides insight into specific loss mechanisms affecting the solar cell. A decrease in EQE at short wavelengths (300–500 nm) suggests increased surface recombination or degradation of the passivation layer. A decline in mid-range wavelengths (500–800 nm) indicates bulk recombination losses due to defect activation, while a drop in EQE at longer wavelengths (800–1200 nm) signifies the formation of deep-level recombination centers in the silicon bulk, leading to reduced carrier lifetimes. The results confirm that LeTID degradation significantly impacts carrier collection efficiency, as indicated by the reduction in EQE across all wavelengths. However, the successful restoration of the EQE spectrum following DC biasing recovery highlights the effectiveness of electrical biasing in defect passivation, ensuring long-term stability and improved performance of PERC solar cells in real-world photovoltaic applications.

4. Conclusion

This study presents a detailed investigation into the degradation and electrical regeneration behavior of industrial p-type PERC crystalline silicon (c-Si) solar cells affected by LeTID. The experimental protocol involved degrading the cells at 75°C, 85°C, and 100°C for 15 hours under 1-sun illumination, followed by electrical regeneration through forward and reverse DC biasing. LeTID was strongly temperature-dependent, with maximum degradation observed at 100°C, where the normalized values of J_{sc} , V_{oc} , FF, and PCE declined to 0.8933, 0.8886, 0.8851, and 0.8822, respectively. This was accompanied by a

significant increase in series resistance (R_s) from 1.97 to 183 $\Omega\cdot\text{cm}^2$, indicating severe charge carrier recombination and mobility losses due to the activation of hydrogen-related metastable defects. Regeneration via DC biasing yielded promising results, with forward biasing outperforming reverse biasing in both recovery speed and final restoration levels. Forward biasing recovered the degraded cells within 7 hours, restoring normalized performance parameters to 0.9996 J_{sc} , 0.9993 V_{oc} , 0.9993 FF, and 0.9994 η . Reverse biasing achieved similar results over a more extended period (9 hours), reaching 0.9966, 0.9973, 0.9983, and 0.9964, respectively. These differences underscore the greater efficacy of forward biasing, attributed to enhanced carrier injection and field-assisted hydrogen migration, which accelerates the passivation of recombination-active defects. Supporting measurements, including Dark I–V analysis, revealed that R_s decreased post-regeneration to 7.69 $\Omega\cdot\text{cm}^2$, indicating a significant restoration of charge-transport properties. EQE at 900 nm improved from $\sim 72\%$ (degraded) to $\sim 89\%$ (recovered), validating the suppression of deep-level recombination in the silicon bulk. Structural inspection by optical microscopy further emphasized the importance of metallization geometry, with front-side finger spacing and busbar widths measured at 1335.2 μm and 650.4 μm , respectively, and rear-side features at 839.1 μm and 1726.8 μm , respectively, reinforcing their role in current collection efficiency and resistive losses.

Declarations

Declaration of competing interest:

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.

Data available:

Data will be made available on request.

Conflict of Interest:

The authors declare no conflict of interest

Author Contribution

RUR performed the conceptualization, data curation, formal analysis, Investigation, and writing of the original draft. MNA, XW, MC, A, and HY performed the data curation and formal analysis. M.Q.K. performed the investigation. J. Y. contributed to supervision, Investigation, visualization, project administration, and fund acquisition.

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Data Availability

Data will be made available on request.

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Figures

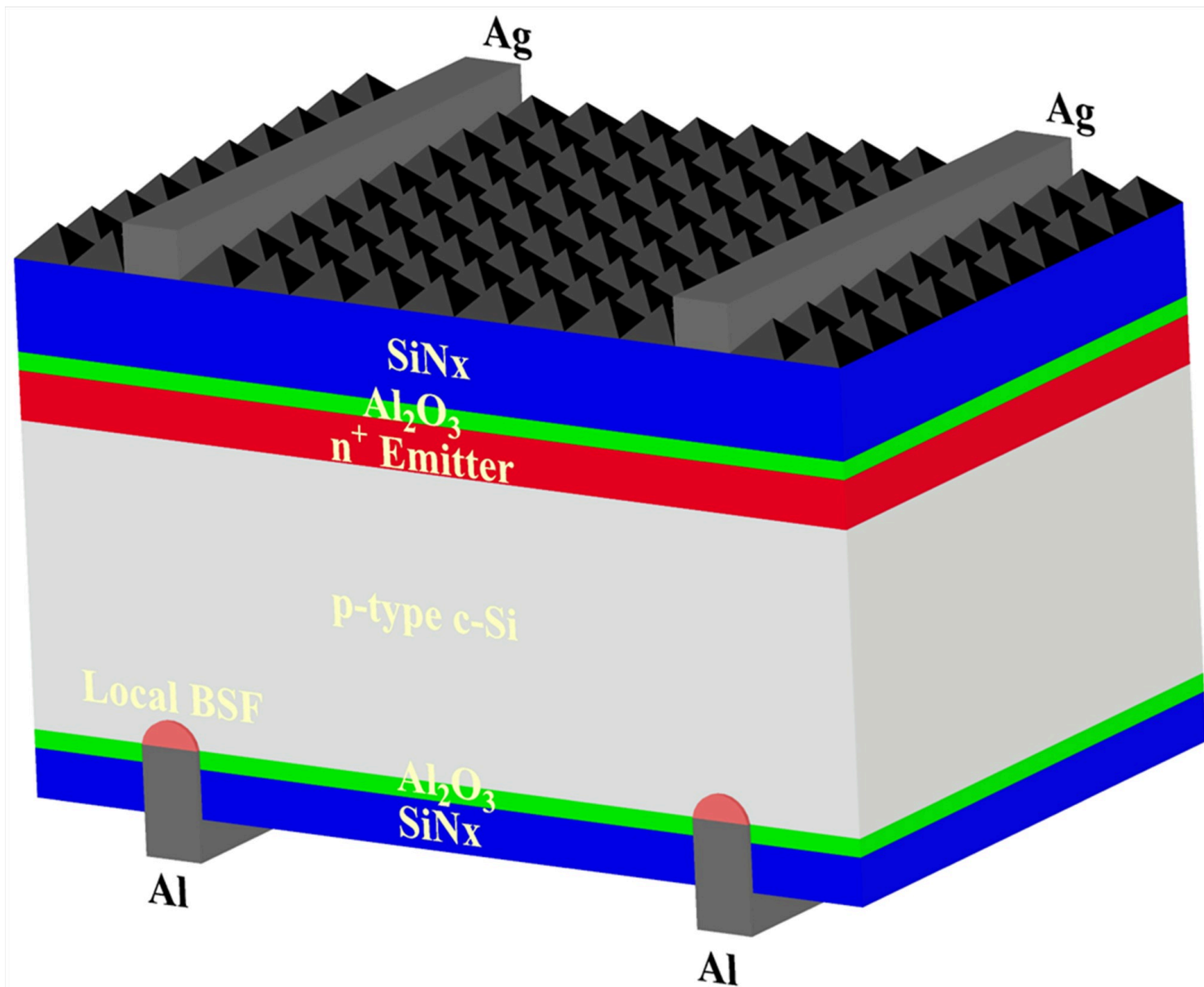


Figure 1

Schematic cross-sectional representation of a PERC solar cell

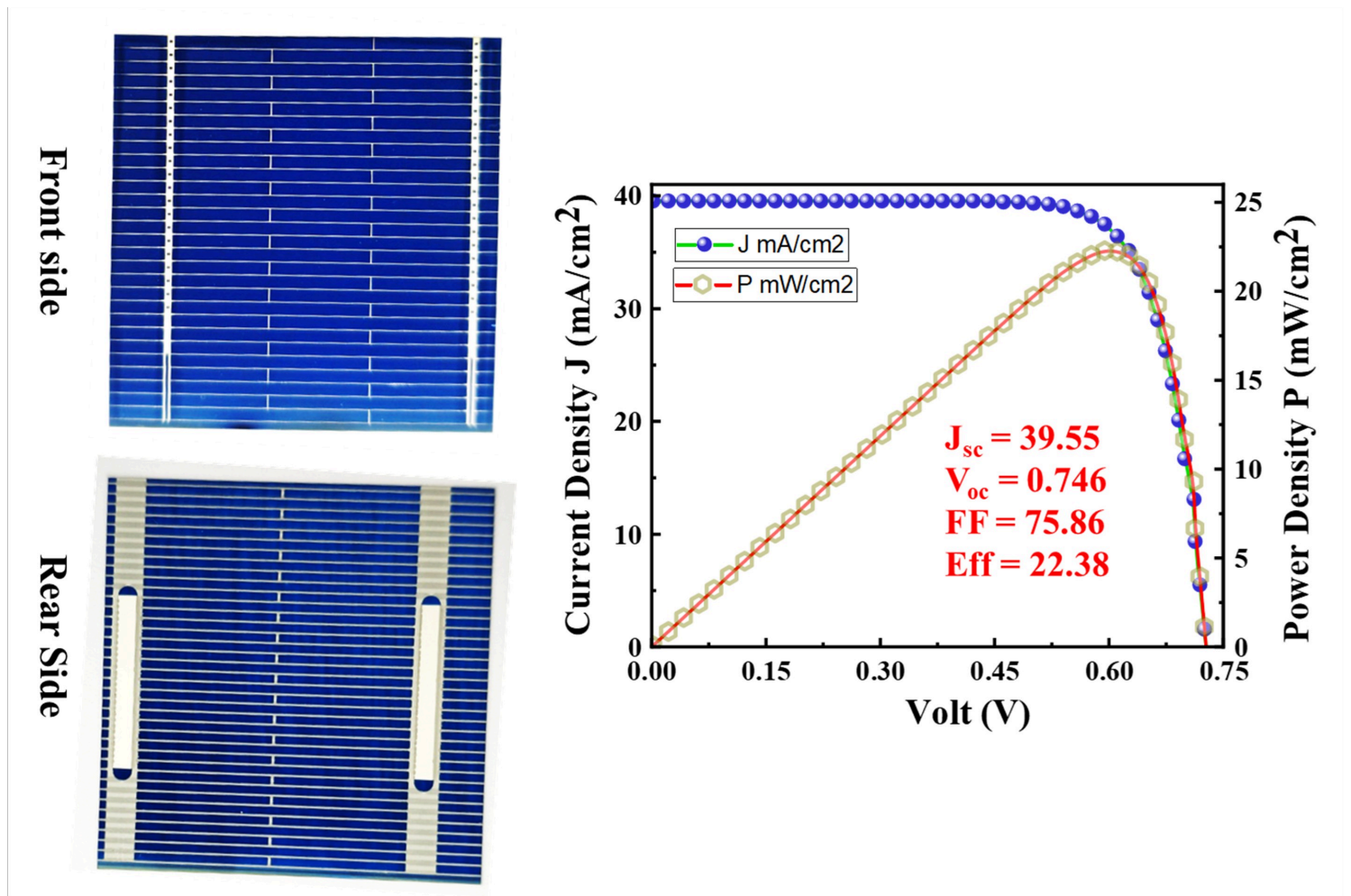


Figure 2

Front and rear side views of a PERC solar cell, I-V, and power density characteristics.

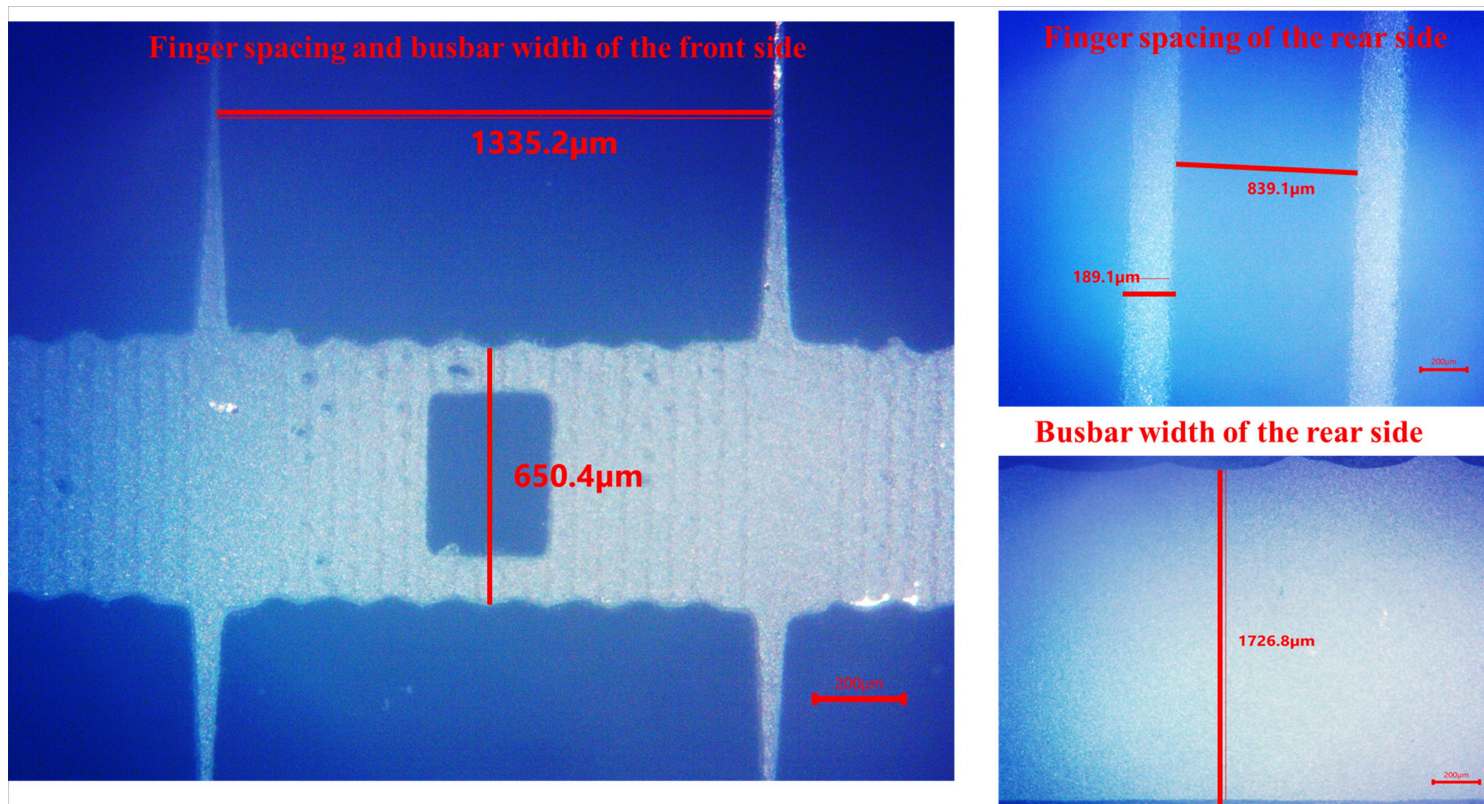
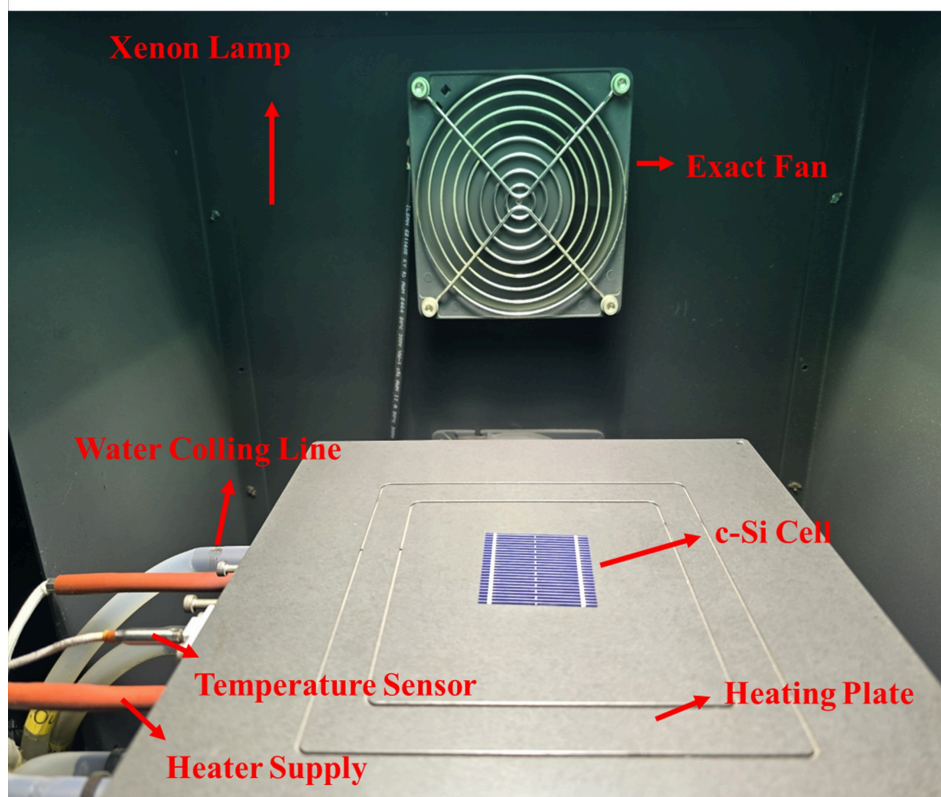


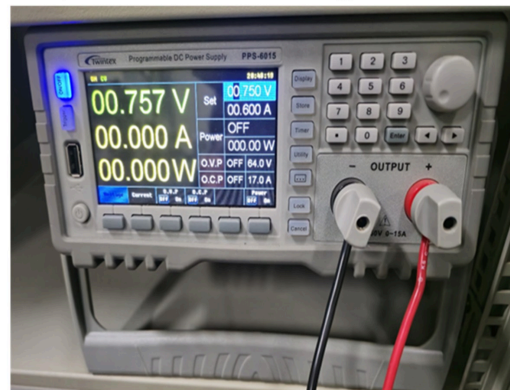
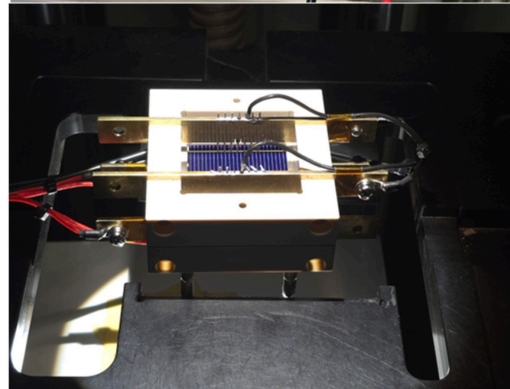
Figure 3

Optical microscopy images displaying the finger spacing and busbar width on a PERC solar cell's front and rear sides.



a) LeTID Chamber

b) Current and Voltage Source



c) Jig solar cell testing

Figure 4

Experimental setup for LeTID degradation and DC biasing recovery of c-Si solar cells.

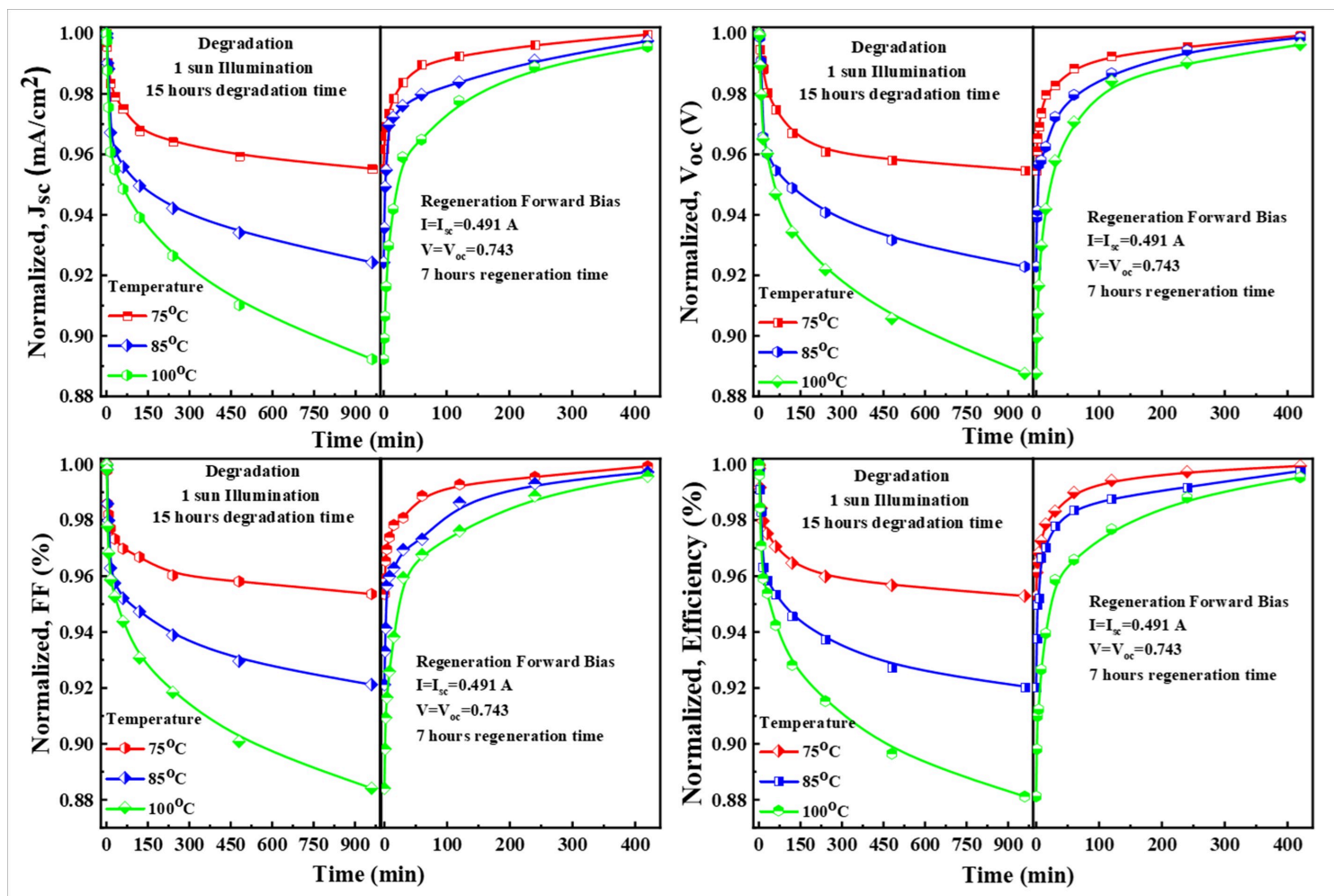


Figure 5

I-V characteristics of PERC solar cells under different LeTID degradation and recovery conditions.

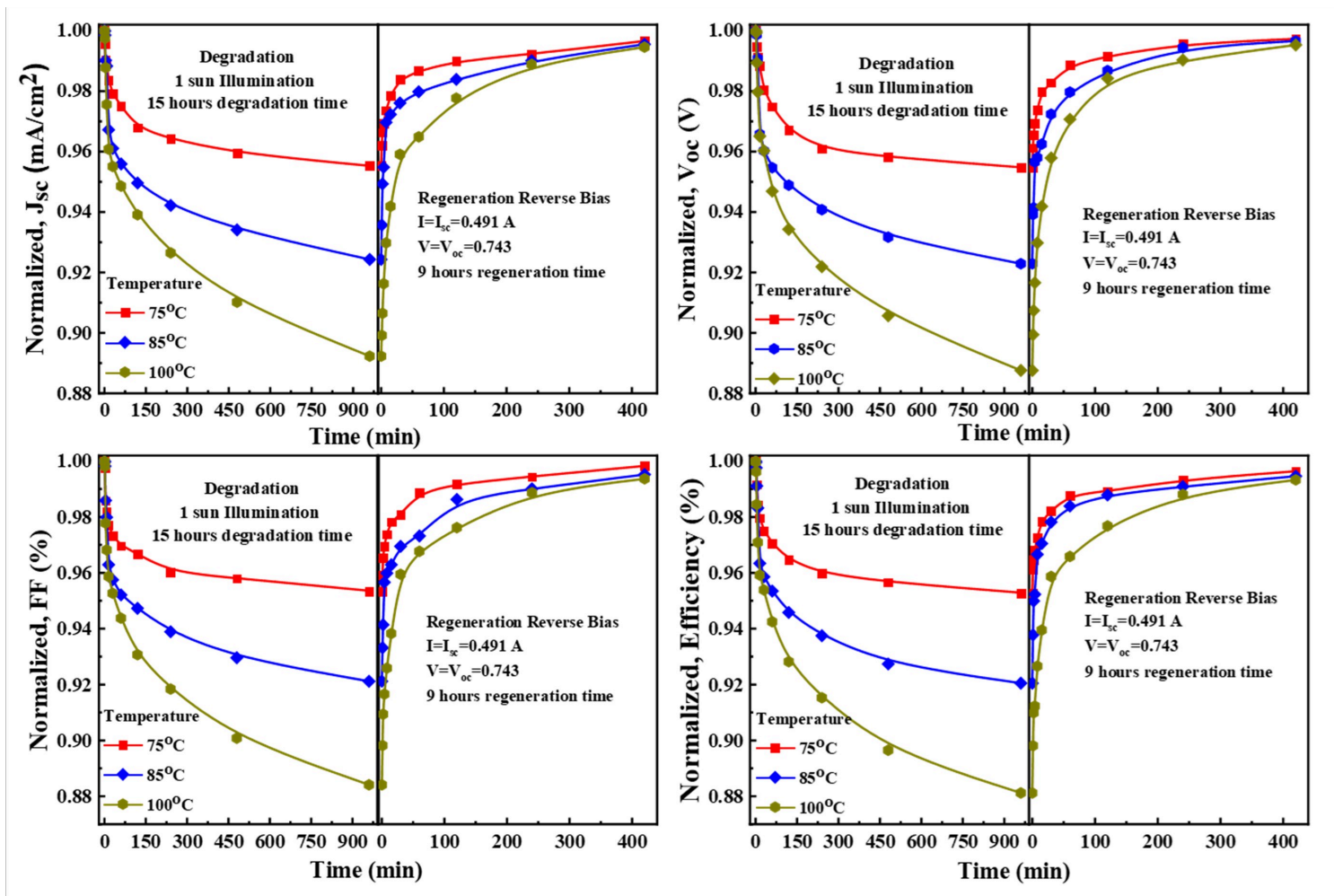


Figure 6

I-V characteristics of PERC solar cells during LeTID degradation and recovery under reverse DC biasing.

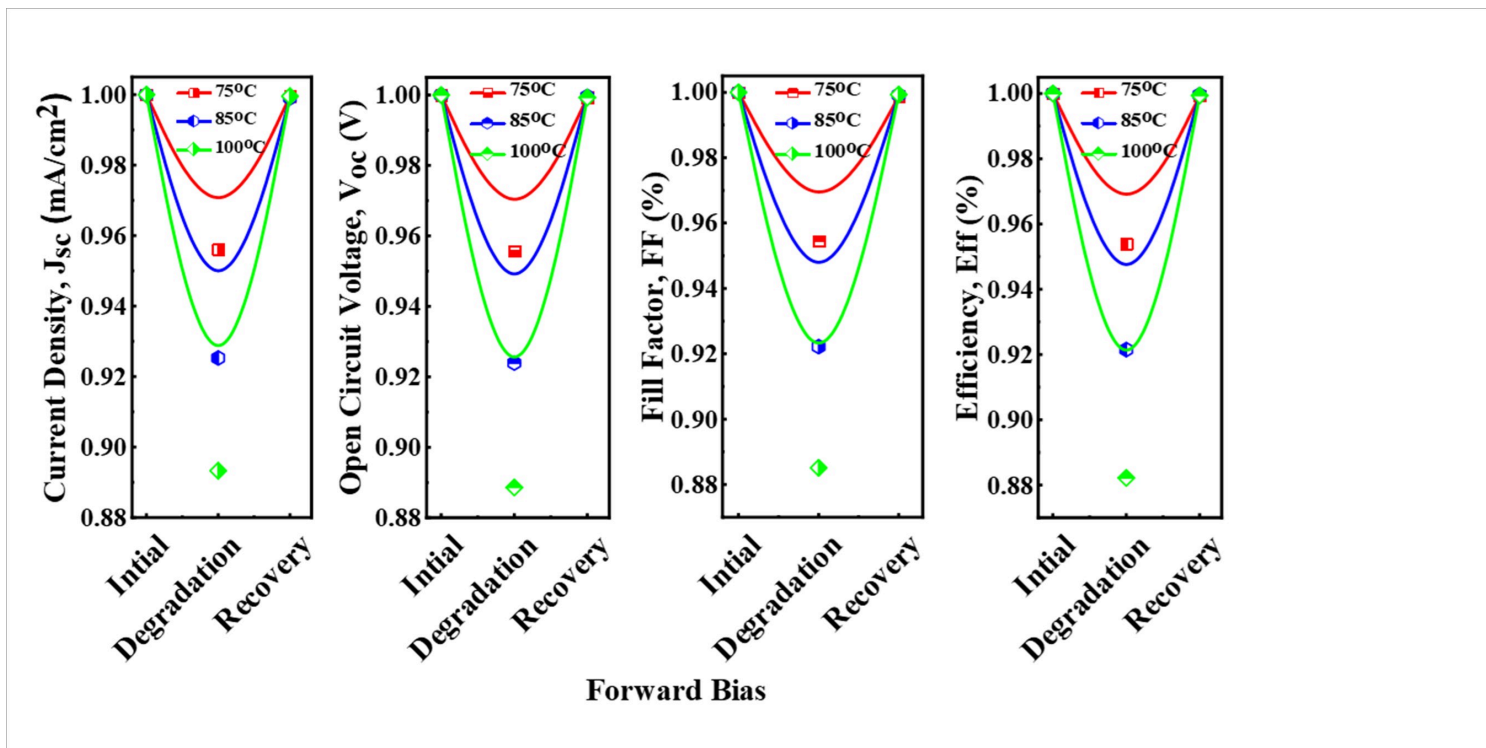


Figure 7

Normalized electrical parameters J_{sc} , V_{oc} , FF, and η of PERC solar cells during initial, degradation, and recovery states at different temperatures (75°C, 85°C, and 100°C).

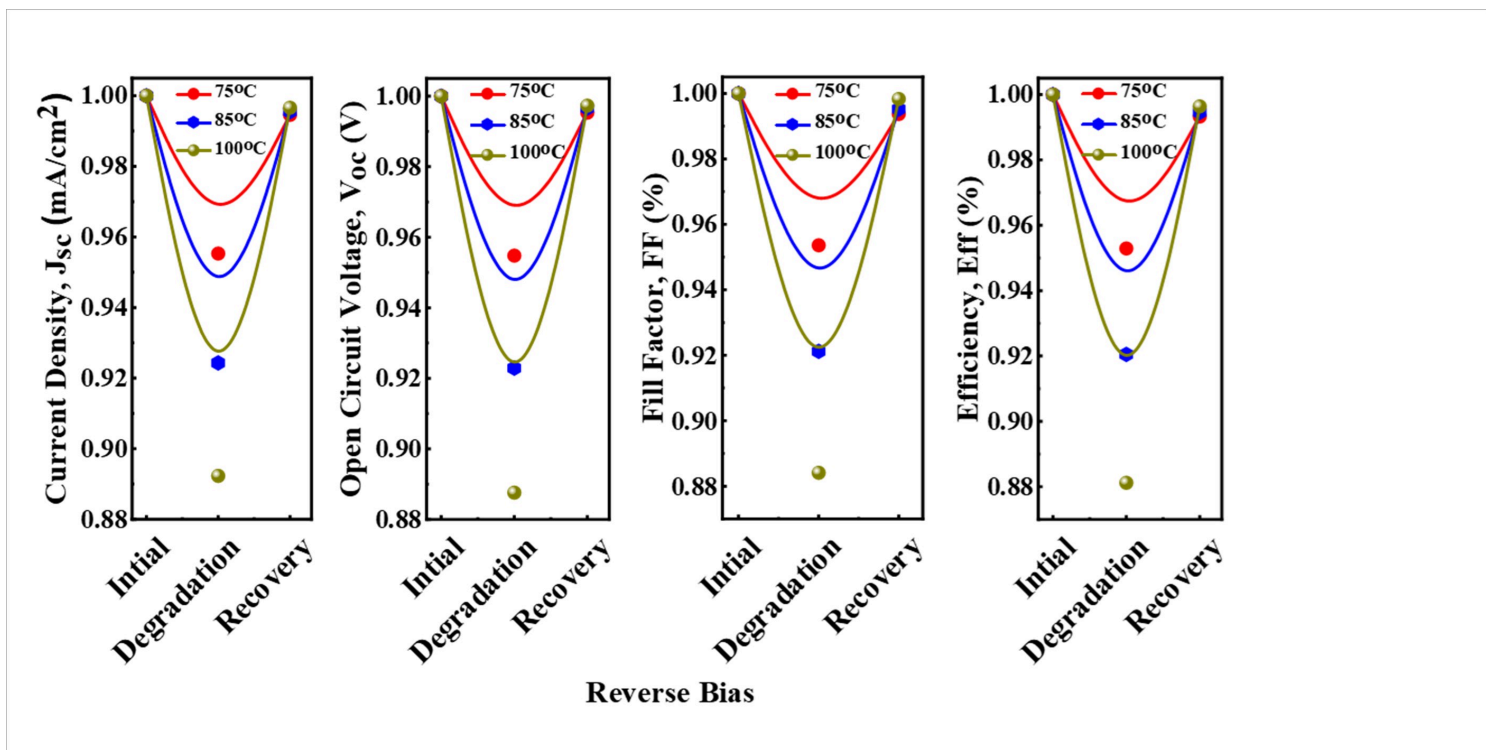


Figure 8

Normalized electrical parameters J_{sc} , V_{oc} , FF, and efficiency of PERC solar cells at 75°C, 85°C, and 100°C during initial, degradation, and recovery states.

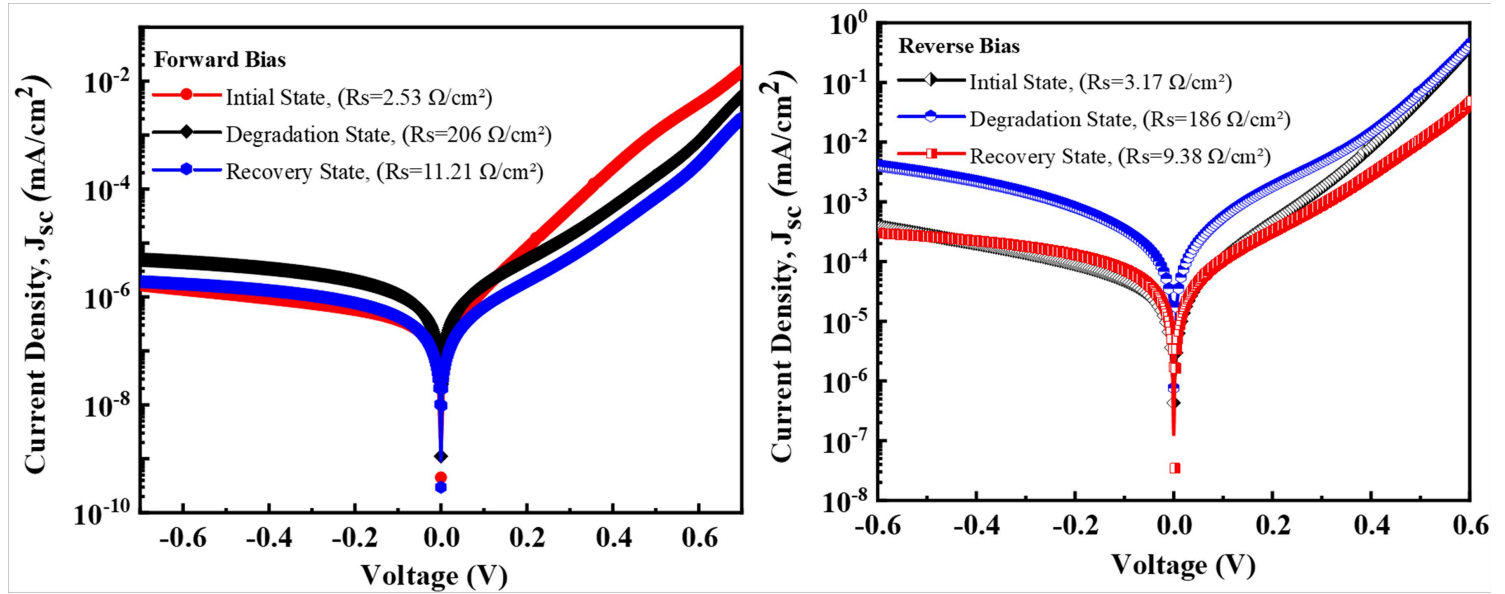


Figure 9

DIV characteristics of PERC solar cells in initial, degraded, and recovered states.

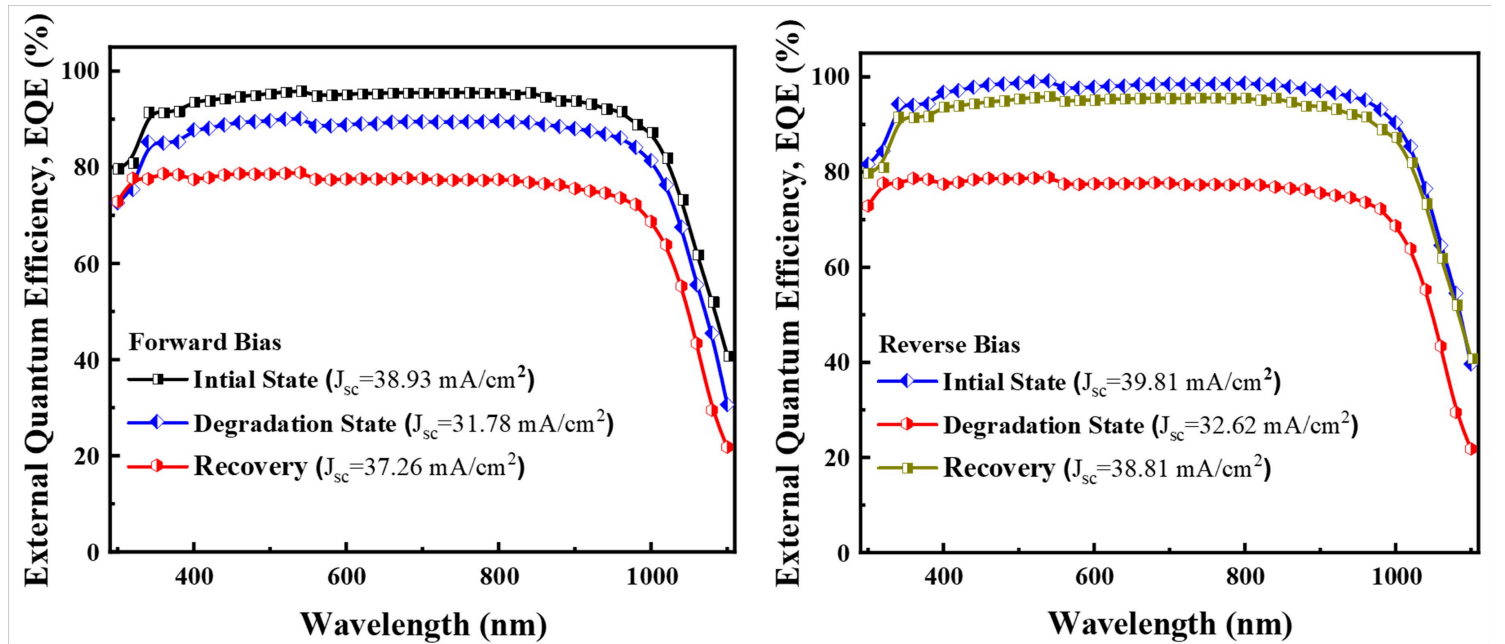


Figure 10

EQE spectra of PERC solar cells in initial, degraded, and recovered states.