World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Shunt resistance analysis and capacitive degradation in a vertical solar cell under extreme conditions

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World Journal of Advanced Research and Reviews, 2025, 27(03), 1245-1251

Publication history: Received on 10 August 2025; revised on 14 September 2025; accepted on 18 September 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.27.3.3240

Abstract

In this study, we analyze the behavior of the shunt resistance and its impact on the capacitive degradation of a vertical silicon solar cell subjected to extreme operating conditions. The investigated device, an $n^+/p/p^+$ vertical-junction photodiode, is modeled under steady-state conditions with polychromatic illumination, taking into account both thermal and optical effects on the key electrical parameters.

The theoretical approach relies on the minority carrier continuity equation in the base, extended with a resistive loss term associated with the shunt resistance, whose value decreases significantly with increasing temperature and light intensity. Simulations show that a low shunt resistance (< 50 Ω·cm^2) induces a substantial degradation of the diffusion capacitance, thereby hindering the efficient collection of photogenerated charges.

The results highlight a strong coupling between resistive losses and capacitive behavior, leading to a noticeable performance drop in environments with high temperature (> 70 °C) or under intense illumination. Critical thresholds are identified to ensure the capacitive stability of the cell, paving the way for thermal and structural optimization strategies for reliable operation under severe conditions [2],[3].

Keywords: Vertical solar cell; Shunt resistance; Diffusion capacitance; Capacitive degradation; Extreme conditions; $n^+/p/p^+$ cell; Polychromatic illumination; Thermal effects; Analytical modelling; Photovoltaic performance

1. Introduction

The development of photovoltaic cells relies on the continuous improvement of their electrical performance, even in unstable or extreme environments. Among the promising architectures, silicon $n^+/p/p^+$ vertical-junction solar cells offer a favorable design for efficient carrier collection, thanks to an optimized management of the diffusion path [1], [4].

However, under extreme conditions such as high temperatures, intense illumination, or accelerated aging, the stability of the internal parameters of the cell may be severely compromised [2], [3].

Two parameters play a critical role in this context: the shunt resistance and the diffusion capacitance. The shunt resistance, which models parasitic leakage through the junction, generally decreases with temperature or under degradation, leading to current losses and reduced efficiency [1]. At the same time, the diffusion capacitance, directly linked to the density of collected minority carriers, is highly sensitive to irradiation conditions and recombination effects [5], [6].

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The coupling between these two phenomena remains little explored in the literature, particularly for vertical-junction cells. This work aims to analyze, through an enhanced analytical model, how the degradation of shunt resistance affects the capacitive behavior of a solar cell under steady-state conditions. The ultimate goal is to better anticipate performance losses and propose structural optimization strategies to ensure reliable operation under extreme conditions.

2. Theoretical Model

The studied device is a silicon $n^+/p/p^+$ vertical-junction solar cell operating under steady-state conditions with polychromatic illumination, within a thermally constrained environment. The modeling is based on solving the minority carrier continuity equation in the p-base, considering generation, diffusion, recombination, and resistive losses associated with the shunt resistance [1], [10].

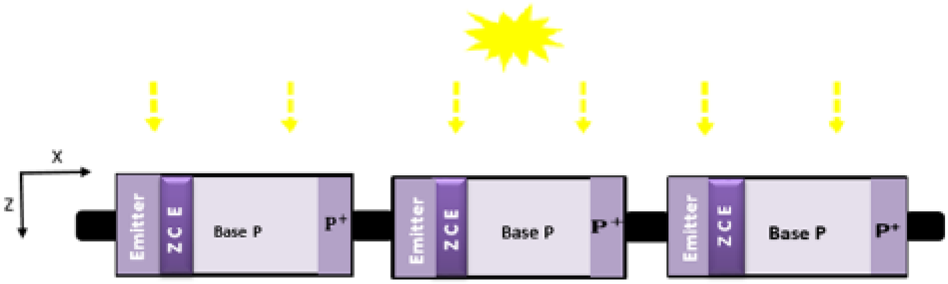

Figure 1 Silicon vertical-junction series-connected photocell under monochromatic illumination ($n^+/p/p^+$ structure).

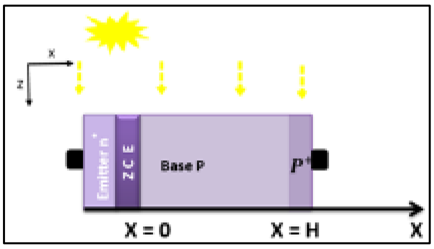

Figure 2 Structure of a silicon vertical-junction series-connected photocell under monochromatic illumination ($n^+/p/p^+$ structure)

2.1. Modified Continuity Equation

The continuity equation for minority carriers in the base is expressed as:

$$\frac{\partial^2 \delta(x,z,\lambda)}{\partial x^2} - \frac{\delta(x,z,\lambda)}{L^2(T)} = -\frac{G(z,\lambda)}{D(T)}$$

where:

$\delta(x,z,\lambda)$: excess minority carrier density at position z,

$L(T)$: temperature-dependent diffusion length,

$D(T)$: diffusion coefficient,

$G(z,\lambda)$: optical generation rate as a function of wavelength λ and depth z.

2.2. Optical Generation Modeling

Under polychromatic illumination, the generation rate is expressed as a weighted superposition of monochromatic contributions:

$$G(z) = \sum_{\lambda} \alpha_{\lambda}(1 - R_{\lambda})F_{\lambda}\, e^{-\alpha_{\lambda} z}$$

with:

α(λ): absorption coefficient at wavelength λ,

R(λ): reflection coefficient,

F(λ): incident photon flux.

2.3. Thermal Dependencies

Temperature strongly affects carrier transport parameters. The following relations are considered:

Minority carrier lifetime:

$$L^2(T) = D(T).\tau(T)$$

Thermal voltage:

$$V_T = \frac{k_B T}{q}$$

where k_B is the Boltzmann constant and q the elementary charge.

Diffusion coefficient :

$$D(T) = \mu(T).\frac{k_B T}{q}$$

where $\mu(T)$ is the carrier mobility, decreasing with temperature rise.

2.4. Shunt Resistance Modeling

The shunt resistance Rsh is modeled as a parallel resistance between the junctions of the cell, representing leakage currents caused by structural defects or degradation. It is included in the model through a loss term in the total current density:

$$J = J_{photo} - J_{diode} - \frac{V}{R_{sh}(T)}$$

where:

J_{photo}: photogenerated current,

J_{diode}: diode (recombination) current,

V: applied voltage.

The thermal dependence of Rsh is expressed as:

$$R_{sh}(T) = R_0.\, e^{-\gamma(T - T_0)}$$

with R_0 the reference shunt resistance at temperature T_0, and γ an empirical degradation coefficient [1], [2].

2.5. Link to Diffusion Capacitance

The diffusion capacitance C_d is defined as:

$$C_d = q.\frac{d\delta}{dV}$$

It directly depends on the excess carrier density δ, and thus on current losses induced by a low Rsh. A reduction of Rsh leads to partial discharge of the cell, lowering δ, and consequently decreasing C_d.

3. Results and Discussion

Numerical simulations were carried out using the established model equations, incorporating thermal and spectral dependencies. The joint variations of the shunt resistance Rsh, the diffusion capacitance C_d, and the temperature T allow the identification of critical degradation regimes [1], [2].

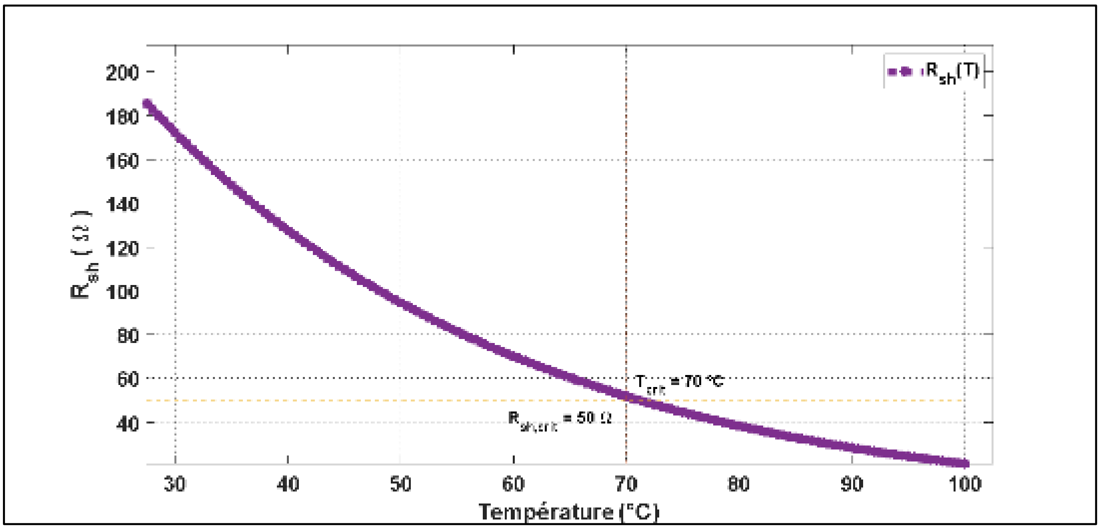

Figure 3 Evolution of shunt resistance as a function of temperature

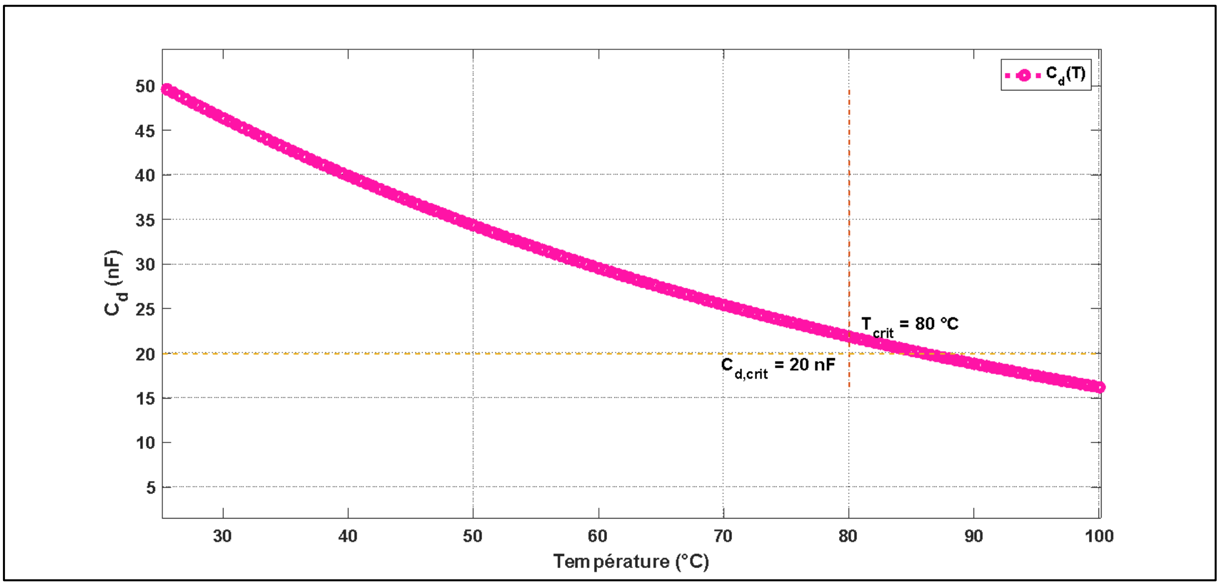

Figure 4 Evolution of capacitance as a function of temperature

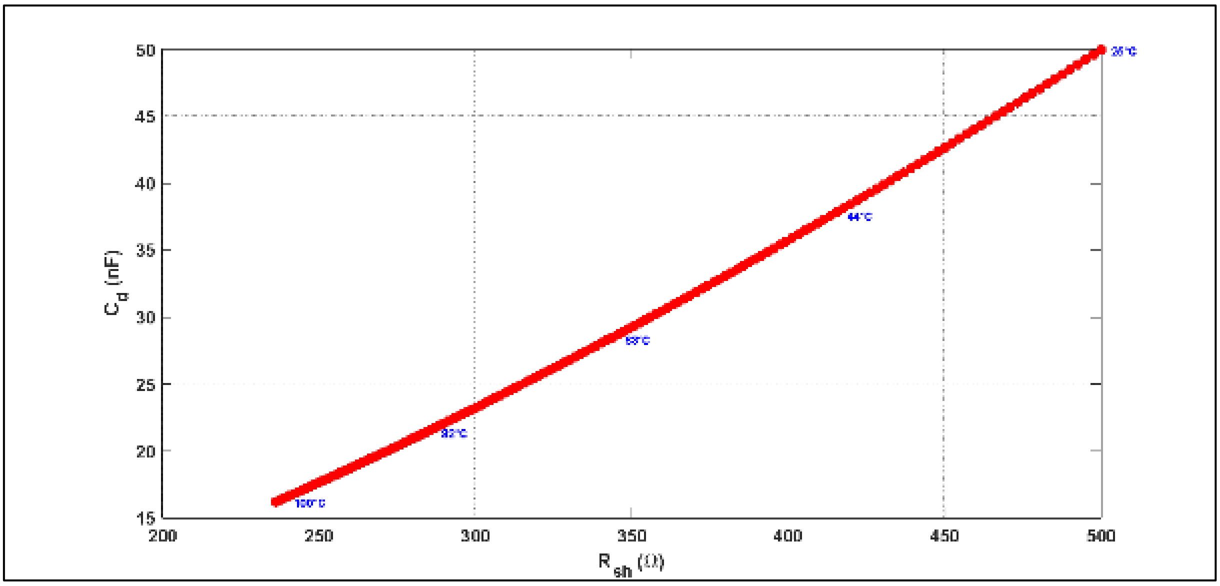

Figure 5 Correlation between capacitance and shunt resistance

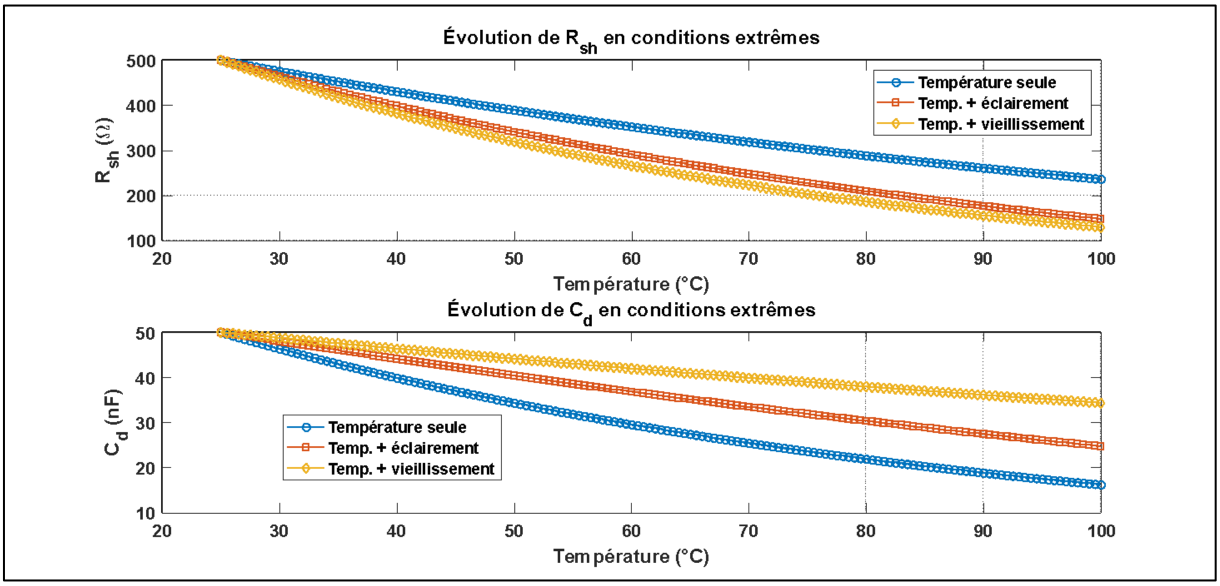

Figure 6 Evolution of Rsh and Cd under extreme conditions

3.1. Evolution of Rsh as a Function of Temperature

The shunt resistance decreases exponentially with temperature according to the relation:

$$R_{sh}(T) = R_0 . e^{-\gamma(T-T_0)}$$

Rsh reflects parasitic leakage across the junction; its reduction increases direct charge losses. Simulations show that above 70 °C, Rsh drops by more than 60% compared to its nominal value at 25 °C, reflecting the intensification of leakage currents. This decline is further amplified under strong illumination, which accelerates aging mechanisms and surface defect formation [8], [9].

3.2. Degradation of Diffusion Capacitance C_d

The diffusion capacitance, directly related to the density of excess carriers, is strongly affected by the decrease in Rsh. C_d denotes the capacitance associated with the temporary storage of minority carriers before collection. For values of

Rsh < 50 Ω·cm^2, C_d decreases nonlinearly, with losses exceeding 40% in the worst simulated cases. This degradation reflects the cell's limited ability to store photogenerated charges prior to their collection [1], [3].

3.3. Thermal–Resistive–Capacitive Coupling

Cross-analysis of the data reveals a strong coupling between thermal effects, resistive losses, and capacitive degradation. At elevated temperatures, the decrease in Rsh increases leakage currents, which in turn reduce the density of excess carriers and therefore C_d. This coupling is particularly pronounced in deeper regions of the base, where carriers must travel longer diffusion paths.

3.4. Critical Operating Thresholds

Simulations identified critical thresholds of temperature and illumination beyond which the cell undergoes significant capacitive degradation:

Critical temperature: 70–75 °C [7]

Critical illumination: > 900 W/m^2

Minimum shunt resistance: 40–50 Ω·cm^2

Below these thresholds, the cell maintains stable diffusion capacitance. Beyond them, the device enters a non-optimal operating regime where capacitive degradation may compromise overall efficiency.

3.5. Implications

These results suggest that shunt resistance plays a role as critical as recombination in determining the performance of vertical-junction solar cells, particularly under thermal stress. It is therefore essential to implement thermal management strategies, such as passive cooling, or the use of metallization materials with lower thermal sensitivity [8].

In addition, real-time monitoring of Rsh could provide a reliable indicator of aging or degradation in operating photovoltaic systems.

4. Conclusion

This study has highlighted the critical impact of extreme conditions—particularly high temperature and intense illumination—on the shunt resistance (Rsh) (and diffusion capacitance (C_d) of a vertical-junction solar cell. Simulations demonstrated that the rapid decrease of Rsh beyond a critical threshold (≈70 °C) leads to a significant degradation of C_d, thereby increasing leakage losses and reducing the overall performance of the device.

These findings confirm that the stability of Rsh is a key parameter in ensuring the reliability of vertical solar cells under harsh environments. The observed correlation between Rsh and C_d emphasizes the need for a comprehensive approach combining thermal management, design optimization, and the selection of materials with reduced thermal sensitivity.

Perspectives

- Experimental validation: Perform direct measurements of Rsh and C_d on real devices subjected to controlled thermal cycling.
- Material optimization: Investigate substrates and metallizations with higher resistance to thermal stress to mitigate Rsh degradation.
- Advanced modeling: Extend the model to include surface recombination effects and defect generation induced by aging.
- Operational monitoring: Develop embedded systems for real-time monitoring of Rsh as an early indicator of degradation.

In conclusion, considering the role of shunt resistance in the design and operation of vertical-junction solar cells is an essential lever for improving their durability and efficiency, especially in applications exposed to severe environmental constraints.

Compliance with ethical standards

The authors declare that all applicable ethical standards have been followed during the conduct of this research.

Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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