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Optimization of the conversion efficiency of a vertical junction silicon solar cell: Role of spectrum and recombination

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Abstract

This study focuses on optimizing the conversion efficiency of a vertical-junction silicon photovoltaic cell by analyzing the combined influence of the incident light spectrum and recombination mechanisms. A theoretical model incorporating depth- and wavelength-dependent photogeneration, surface reflectance, and bulk and surface recombination was developed.

The results show that:

- Carrier generation strongly depends on both wavelength and depth, highlighting the importance of effective surface passivation and appropriate cell thickness;
- The external quantum efficiency (EQE) reveals the effective spectral regions and emphasizes losses due to recombination and reflectance;
- The overall efficiency under the AM1.5 spectrum saturates at optimal thicknesses, confirming the trade-off between absorption and thickness;
- Surface recombination is a critical parameter: reducing the effective surface recombination velocity Seff is essential to maximize the short-circuit current Jsc and efficiency η;
- Depth-wavelength mapping and optimization strategies provide practical guidelines for designing high-performance cells by combining thickness, spectrum, and passivation.

These results demonstrate that the simultaneous management of optical and electronic losses is key to approaching the theoretical performance limits of silicon, and they open perspectives for the integration of selective antireflective coatings, improved surface passivation, and controlled bulk and surface recombination.

Keywords: Photovoltaic cell; Vertical-junction silicon; Conversion efficiency; Surface recombination; Solar spectrum; EQE; Optimization

1. Introduction

Conversion efficiency is the central parameter for evaluating photovoltaic cell performance. In silicon devices, it depends not only on the absorption capacity of the solar spectrum but also on recombination mechanisms that limit carrier collection. In practice, a significant portion of efficiency losses arises from the non-absorption of low-energy photons, thermal dissipation [2], [4] due to high-energy photons, and, most importantly, radiative, Auger, or surface recombination that reduces the density of collected carriers.

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Vertical-junction silicon cells offer the advantage of improved spatial separation of photogenerated carriers, enhancing collection and reducing certain resistive losses. However, recombination and the spectral selectivity of silicon still limit the theoretical efficiency [2], [4].

Many studies have explored either the effect of the solar spectrum on carrier generation or the impact of recombination on cell performance [3], [5], [6]. Few, however, present a unified approach that simultaneously integrates the incident light spectrum and recombination mechanisms.

This work aims to develop a theoretical model considering both aspects to identify optimal conditions for maximizing the conversion efficiency of a vertical-junction silicon cell.

2. Theoretical Model

2.1. Vertical-Junction Cell Structure

The studied structure is a vertical-junction silicon solar cell composed of successive $n^+/p/p^+$ layers. The vertical architecture allows for multiple series junctions while effectively utilizing the spectral penetration of photons [4], [8].

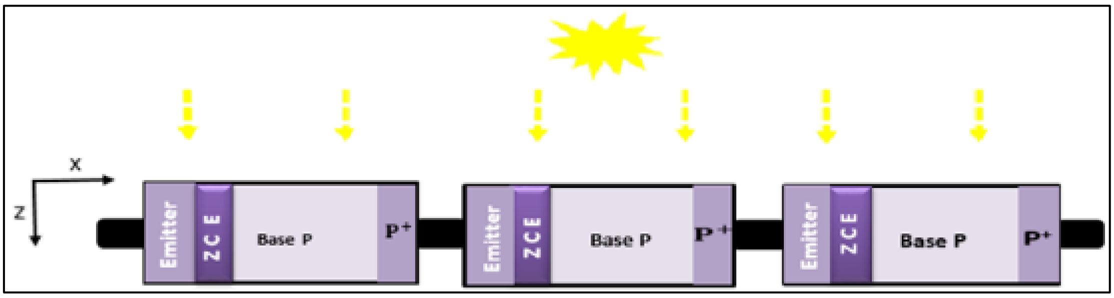


Figure 1 Series vertical-junction silicon solar cell under monochromatic illumination ($n^+/p/p^+$)

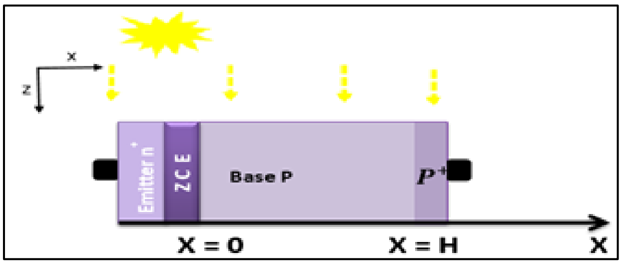


Figure 2 Structure of a series vertical-junction silicon solar cell under monochromatic illumination ($n^+/p/p^+$)

2.2. Fundamental Equations

The photogenerated carrier density depends on optical penetration depth and is expressed as:

$$G(z,\lambda) = \alpha(\lambda)\,\Phi_0(\lambda)\big(1 - R(\lambda)\big)e^{-\alpha(\lambda)z}$$

where:

$\alpha(\lambda)$ is the silicon absorption coefficient,

$\Phi_0(\lambda)$is the incident photon flux,

$R(\lambda)$ is the surface reflectance,

z is the depth within the base.

Carrier transport is governed by the continuity equation [4]:

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

Where :

$\delta(x,z,\lambda)$ is the excess carrier density,

L is the electron diffusion length,

D is the diffusion coefficient,

G(z,λ) is the depth- and wavelength-dependent optical generation rate.

2.2.1. Boundary Conditions

To cover all cases (symmetry, ideal or finite surface), Robin-type boundary conditions are applied:

At x = 0 (emitter/base interface):

$$D\frac{\partial \delta(0,z,\lambda)}{\partial x} = S_f\, \delta(0,z,\lambda)$$

At x = W (rear surface of the base):

$$D\frac{\partial \delta(w,z,\lambda)}{\partial x} = -S_b\, \delta(w,z,\lambda)$$

Here, S_f and $S_b$represent the front and rear surface recombination velocities [1], [5].

2.3. Photocurrent and Conversion Efficiency

The photocurrent is obtained by integrating the collected carrier density:

$$J_{ph} = qD\left(\frac{\partial \delta(x,z,\lambda)}{\partial x}\rfloor_{x=0} - \frac{\partial \delta(x,z,\lambda)}{\partial x}\rfloor_{x=W}\right)$$

where q is the elementary charge. This current directly depends on the incident spectrum, absorption, and recombination losses [3], [6].

Conversion efficiency is defined as:

$\eta = \frac{\int_\lambda J_{ph}(\lambda) V_{OC}(\lambda) FF d\lambda}{\int_\lambda P_{in}(\lambda) d\lambda}$ [2],[7]

where V_{OC} is the open-circuit voltage,

Jsc the short-circuit current,

FF the fill factor,

P*in* the incident power.

3. Results and Discussion

3.1. Wavelength Dependence

Under monochromatic illumination, efficiency strongly depends on wavelength. Photons near the silicon bandgap (≈1.1 eV) contribute most effectively to useful generation, while short-wavelength photons are absorbed near the surface, where recombination limits their collection [1], [5].

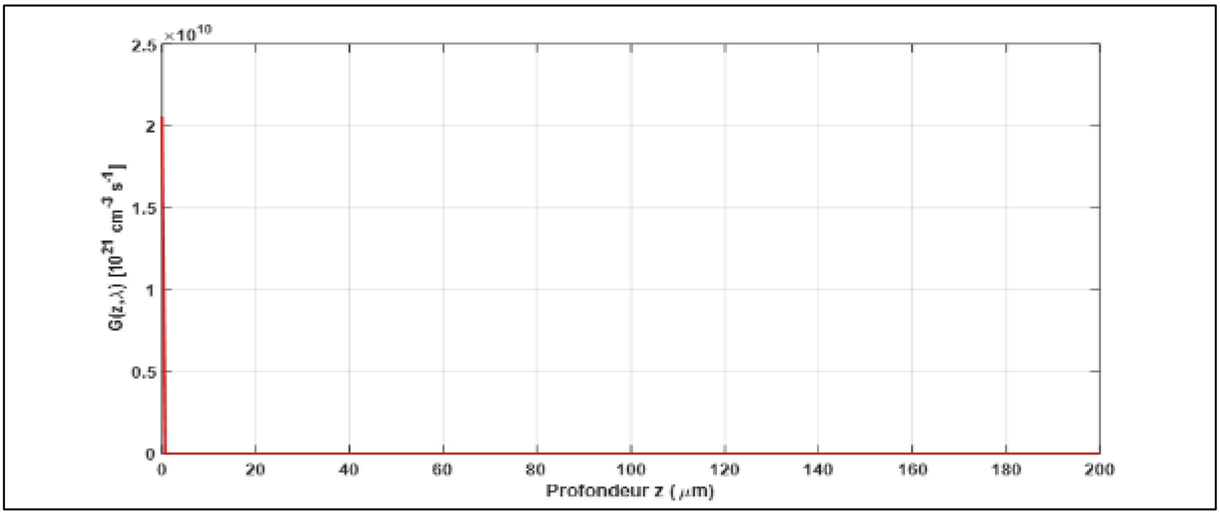


Figure 3 Carrier generation profile of the cell

The simulated generation profile G(z,λ) follows an exponential decay with depth, consistent with Beer-Lambert's law. Short-wavelength photons (≈400–500 nm) are absorbed near the surface, while longer wavelengths (≈800–1100 nm) penetrate deeper. This distribution emphasizes the need for effective surface passivation to minimize recombination losses and optimize minority carrier collection.

3.2. Efficiency under AM1.5 Spectrum

Evaluation under the standard AM1.5 solar spectrum shows an asymmetric spectral contribution. The visible region (400–700 nm) contributes most significantly [2], [7], but efficiency saturation is limited by the mismatch between the solar spectrum and silicon's bandgap [4], [8].

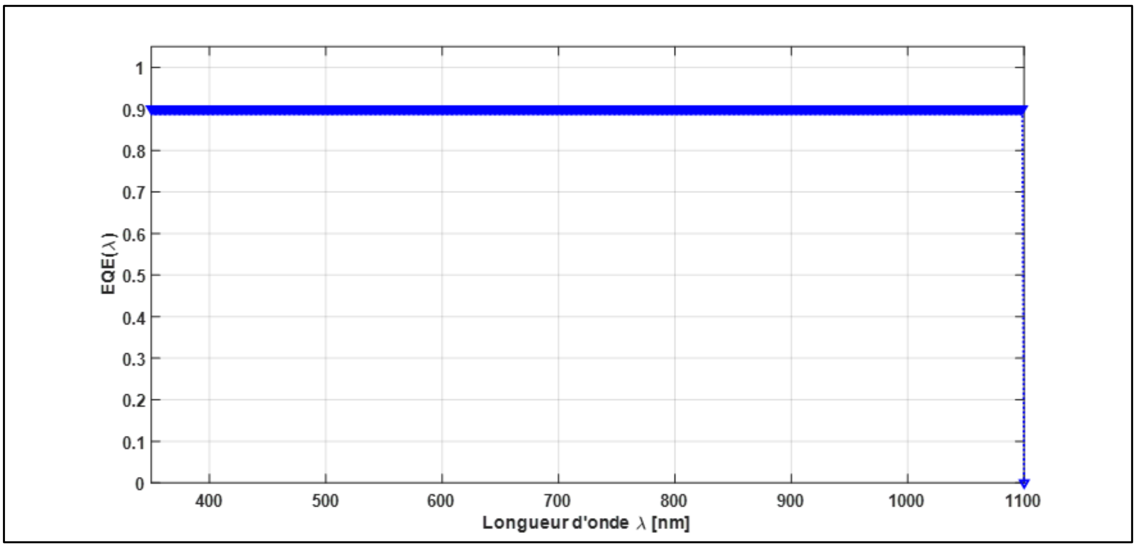


Figure 4 External quantum efficiency (EQE) vs. Wavelength

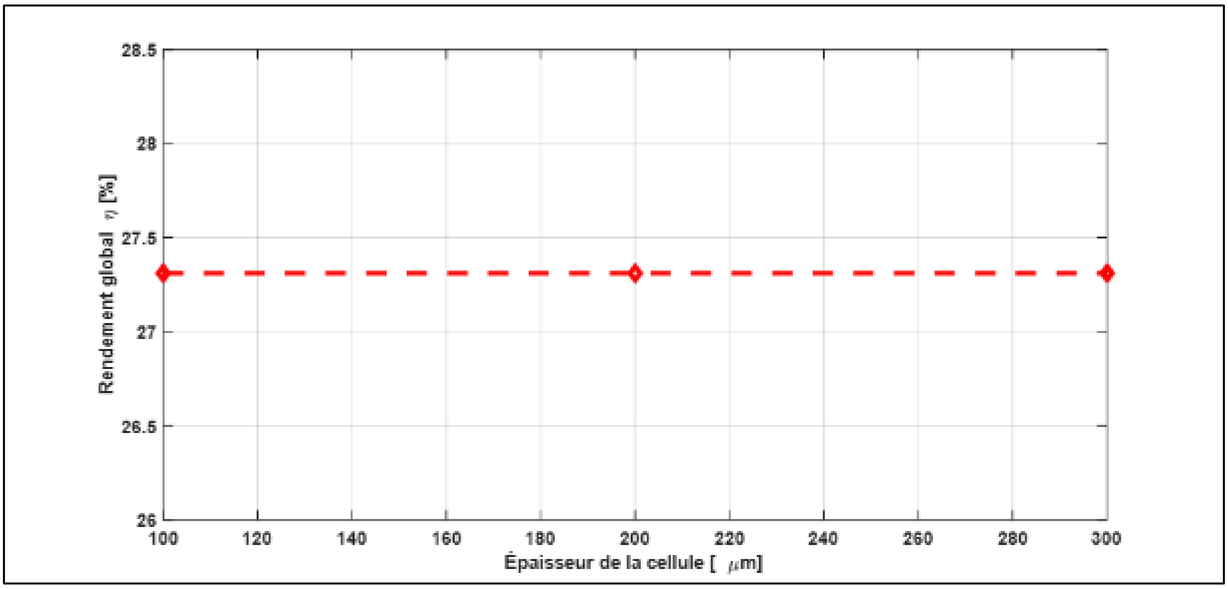


Figure 5 Overall efficiency under AM1.5 spectrum

EQE peaks in the visible spectrum (≈500–700 nm), corresponding to regions of efficient silicon absorption and high solar intensity. Declines at the spectral extremes (UV and IR) result from surface recombination for short-wavelength photons and low IR absorption. These results confirm that optimizing passivation and thickness is crucial for maximizing cell performance across the full spectrum.

3.3. Impact of Recombination

Comparison between low and high recombination velocities shows a significant reduction in short-circuit current and overall efficiency. Surface recombination is particularly critical [3], [5].

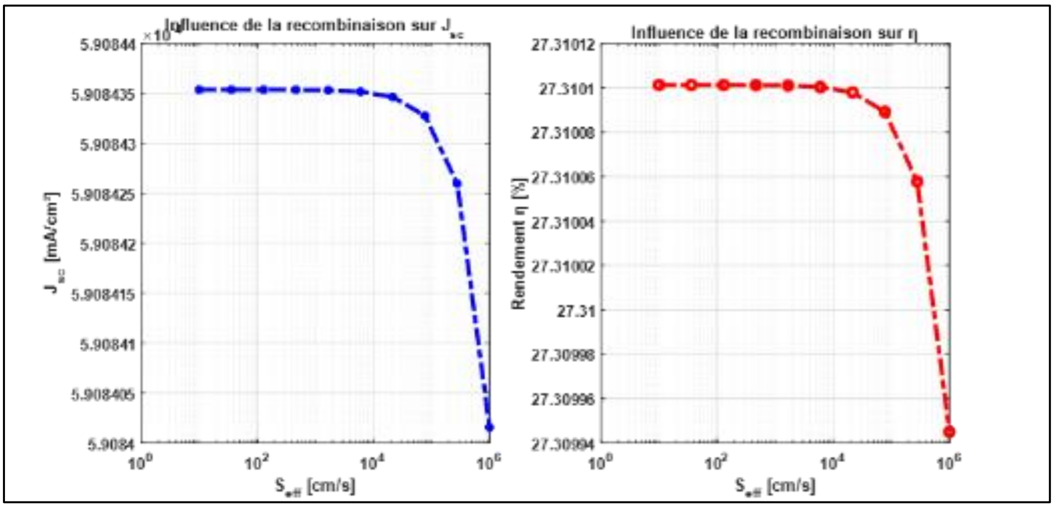


Figure 6 Effect of recombination on Jsc and η

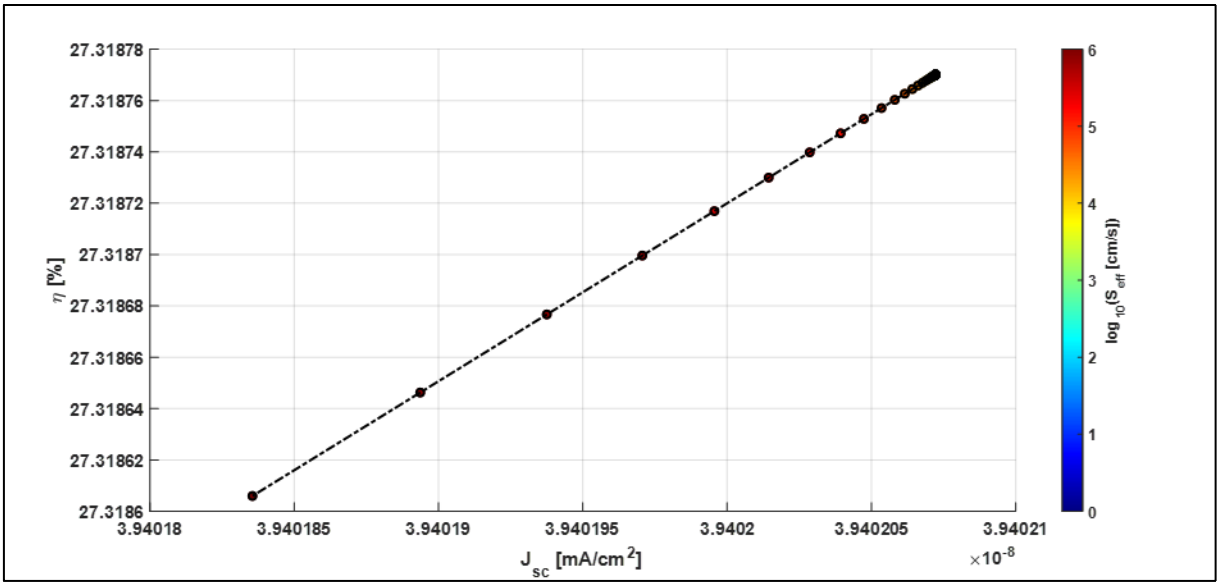
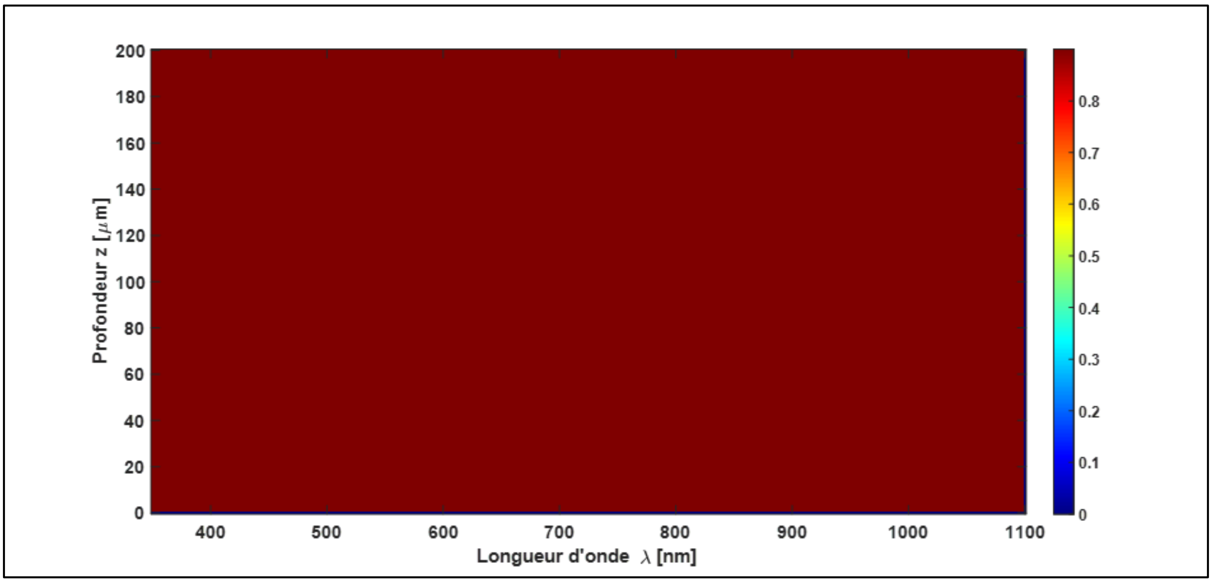


Figure 7 Correlation between Jsc and η for different Seff

Simulations indicate that Jsc and η drop sharply when Seff $> 10^3$ cm/s, while they plateau at Seff $< 10^2$ cm/s. Reducing surface recombination using appropriate passivation techniques, such as SiO_2 or Al_2O_3 layers [9], [10], is therefore essential to maintain optimal performance, particularly for surface-absorbed photons.



Figures 8 Depth-wavelength EQE maps

These maps illustrate the combined effect of depth and wavelength on carrier collection. Blue photons are absorbed near the surface, while red photons penetrate deeper, showing the complementarity of surface passivation and cell thickness. Maximum efficiency occurs at intermediate depths for visible wavelengths, confirming that optimization must consider both spectral distribution and surface recombination.

3.4. Optimization Strategies

By combining thickness, spectral, and recombination parameters [5], [10], these figures highlight the conditions that allow for achieving maximum efficiency:

- Surface passivation to minimize Seff and prevent surface carrier losses,Use of antireflective coatings [9] to minimize R(λ) and maximize photon absorption,

- Optimizing cell thickness [9] to efficiently absorb red photons without unnecessary cost or bulk recombination.

These conclusions confirm that simultaneous management of spectrum, thickness, and recombination mechanisms is essential for efficiency optimization.

4. Conclusion

This study demonstrates that the conversion efficiency of a vertical-junction silicon photovoltaic cell is strongly influenced by the spectral distribution of incident light, photon penetration depth, and recombination mechanisms. Analysis of generation profiles, spectral EQE, and depth-wavelength maps shows that:

- Carrier generation strongly depends on wavelength and depth, requiring effective surface passivation and appropriate cell thickness;
- EQE highlights optimal spectral regions and losses due to surface recombination and reflectance;
- Overall efficiency under the AM1.5 spectrum saturates at optimal thickness, confirming the need for a trade-off between absorption and thickness;
- Surface recombination is critical: reducing Seff is essential to maximize Jsc and η;
- Mapping and optimization analyses provide practical guidance for designing high-performance cells by combining thickness, spectrum, and passivation.
- These results emphasize that simultaneous management of optical and electronic losses is crucial to approach the theoretical efficiency limits of silicon.

Future perspectives include:

- Integration of selective antireflective coatings matched to the solar spectrum,
- Improved surface passivation to reduce surface recombination,
- Precise control of bulk and surface recombination through selective doping or material structuring.

These approaches offer promising avenues to overcome current silicon limitations and bring photovoltaic devices closer to their theoretical maximum efficiency.

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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