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)

Influence of wavelength on the performance of a Vertical-Junction Photocell

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World Journal of Advanced Research and Reviews, 2025, 27(03), 1231-1237

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.2025.27.3.3239

Abstract

This article presents an in-depth analysis of the influence of the wavelength of monochromatic illumination on the electrical behavior of a vertical-junction series-connected photocell. Based on the modelling and simulation of characteristic quantities such as the photocurrent density, the photovoltage and the maximum power, we highlight the effects of spectral absorption and the carrier generation depth. The results show that the variation of the wavelength has a strong impact on charge collection and on the overall performance of the cell.

Keywords: Wavelength; Vertical-Junction Photocell; Monochromatic Illumination; Photocurrent Density; Photovoltage; Efficiency

1. Introduction

Photovoltaic solar energy is now a major alternative to fossil fuels in the energy transition [2][3]. Among the various conversion technologies, series vertical-junction solar cells, particularly those based on silicon, stand out for their ability to improve carrier collection, especially under concentrated illumination [1][4]. The efficiency of these devices relies largely on their spectral response, i.e., their ability to efficiently absorb light depending on its wavelength. In certain configurations, carrier generation depends not only on the depth z, but also on the lateral diffusion along x, making it necessary to use a two-dimensional modelling approach to describe the phenomena. The continuity equation for minority carriers must therefore be formulated by considering these two spatial variables in order to provide a realistic description of the Cel behaviour. In this work, we analyse the influence of the wavelength on the performance of a vertical-junction photocell. The aim is to highlight the effects of spectral matching on carrier separation, recombination losses and the overall efficiency of the device, with a view to identifying possible optimisation strategies.

2. Methodology

This study is based on the analysis of the behaviour of a silicon vertical-junction ($n^+/p/p^+$) photocell subjected to monochromatic illumination.

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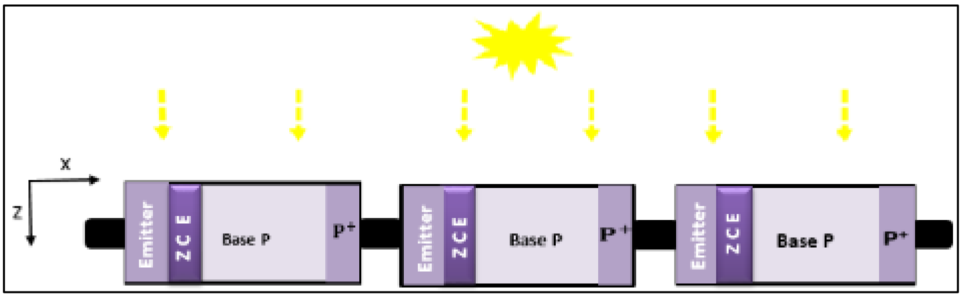

Figure 1 Silicon vertical-junction series-connected photocell under monochromatic illumination ($n^+/p/p^+$ structure)

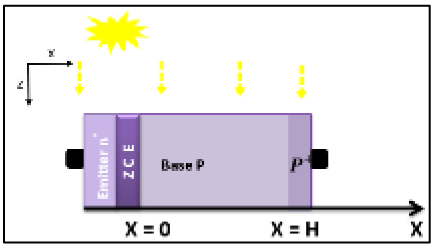

Figure 2 Structure of a silicon vertical-junction series-connected photocell under monochromatic illumination ($n^+/p/p^+$ structure)

The objective is to assess the influence of the wavelength on the optoelectronic performance of the device, particularly through the excess carrier density, the photocurrent density Jph, and the photovoltage Vph [7][8].

In vertical-structure cells, the photogenerated carriers may exhibit a spatial distribution that depends on both the depth z and the lateral direction x, especially in the case of complex geometries or non-uniform illumination. This configuration therefore requires a two-dimensional modelling approach [5][6].

The modelling is based on solving the continuity equation for minority carriers (electrons in a p-type base) in steady state:

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

where:

- $\delta(x,z,\lambda)$ is the excess carrier density,
- L is the electron diffusion length,
- D is the diffusion coefficient,
- $G(z,\lambda)$ is the optical generation term, which depends on the depth and the wavelength.

The boundary conditions take into account the rear-surface recombination velocity Sb, as well as the axial symmetry of the device [11][13].

At the front side (□ =0), corresponding to the junction interface:

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

where S_f denotes the front surface recombination velocity. In practice, two limiting cases are often considered:

S_f **= 0, leading to** δ (0) =0, which corresponds to axial symmetry,

$S_f \to \infty$**, which gives** δ (0) =0, representing a perfectly recombining surface.

At the rear side (=W), corresponding to the back surface of the base:

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

where S_b is the rear surface recombination velocity.

From this boundary condition, S_b can be explicitly written as:

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

Thus, the surface recombination velocity at the rear contact is directly related to the carrier gradient and the excess carrier concentration at x = W.

Once the excess minority carrier distribution $\delta(w,z,\lambda)$ has been obtained, the main photovoltaic parameters can be derived.

2.1. Photocurrent density

Photocurrent density the photocurrent density collected at the junction is expressed as :

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

This relation highlights that the photocurrent originates from the gradient of the minority carrier distribution at the depletion region boundary.

2.2. Photovoltage

Photovoltage The photovoltage under illumination can be expressed using the illuminated diode equation:

$$V_{ph} = \frac{nkT}{q} ln\left(1 + \frac{J_{ph}}{J_0}\right)$$

where J_0 is the dark saturation current density and n the ideality factor of the junction.

2.3. Output Power

The instantaneous output power of the solar cell is given by:

$$P = J_{ph}\, V_{ph}$$

At the maximum power point (MPP), this relation becomes:

$$P = J_{mpp}\, V_{mpp}$$

2.4. Conversion Efficiency

The conversion efficiency of the solar cell is defined as the ratio between the maximum output power and the incident optical power:

$$\eta = \frac{P_{mpp}}{P_{in}} = \frac{J_{mpp}V_{mpp}}{P_{in}}$$

where P_{in} is the incident optical power density, given by the product of the irradiance and the cell surface area.

The spectral response is simulated by sweeping a set of wavelengths in the visible and near-infrared ranges, and by incorporating the characteristic absorption coefficients of silicon.

3. Results and Discussion

The analysis of the results obtained from numerical simulations highlights the significant impact of the wavelength of monochromatic illumination [9][10][12] on the characteristic quantities of the vertical-junction photocell.

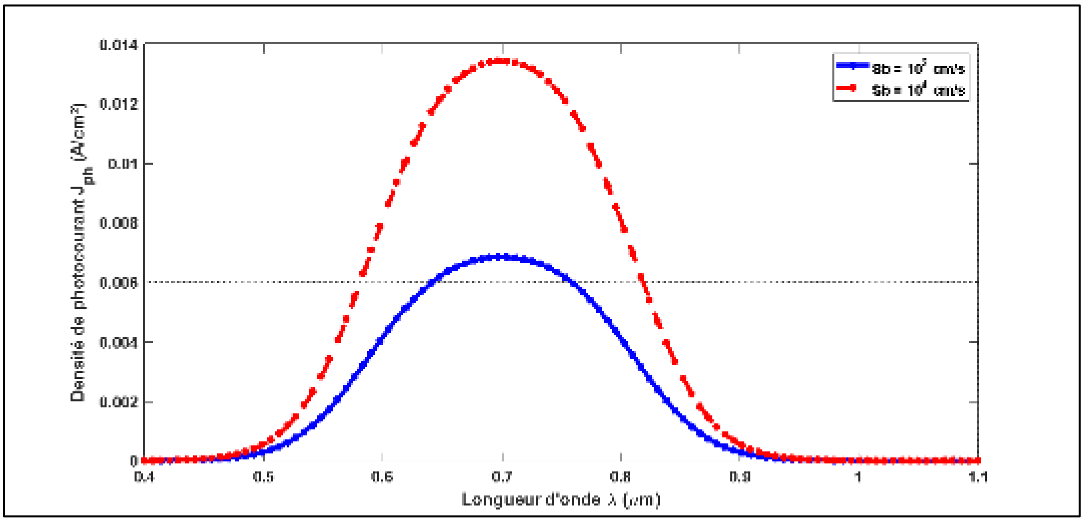

Figure 3 Photocurrent density as a function of wavelength

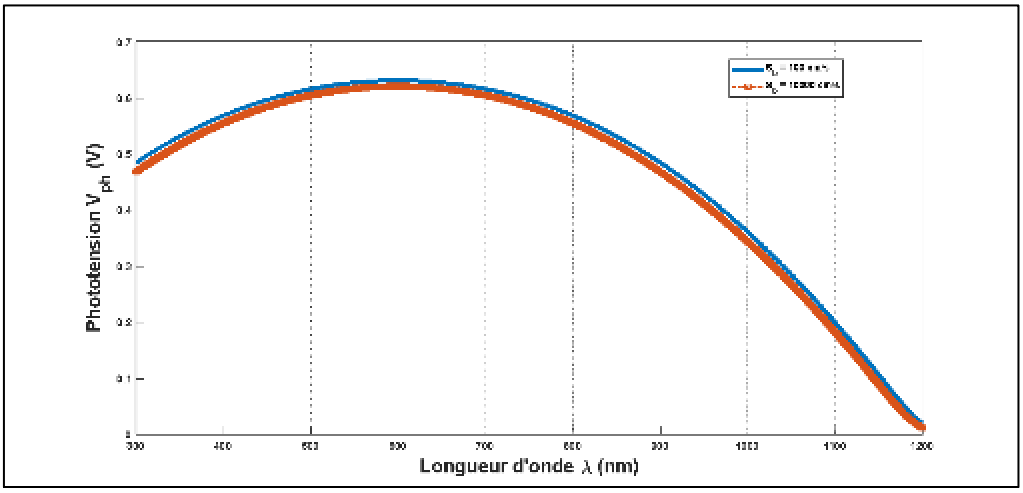

Figure 4 Photovoltage versus wavelength

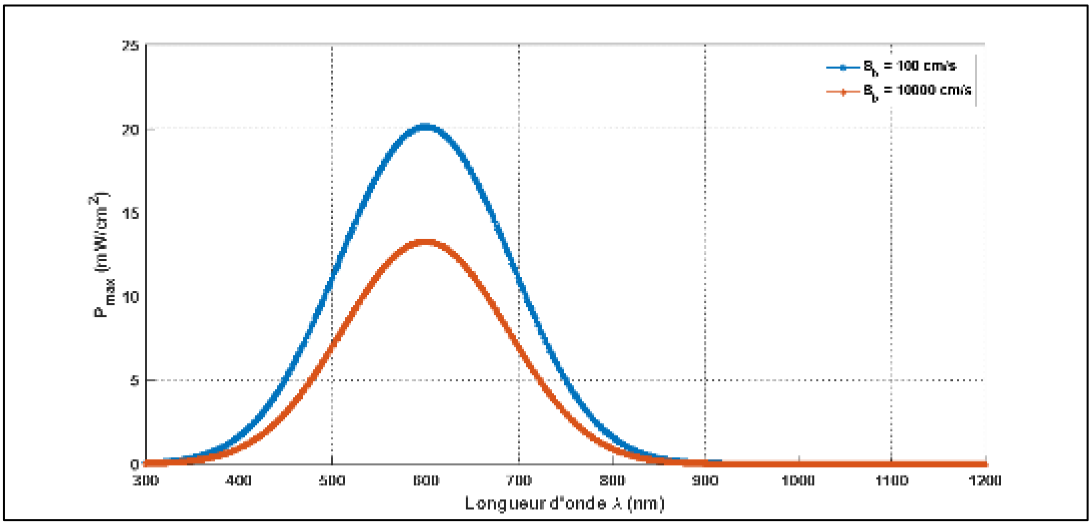

Figure 5 Maximum power as a function of wavelength

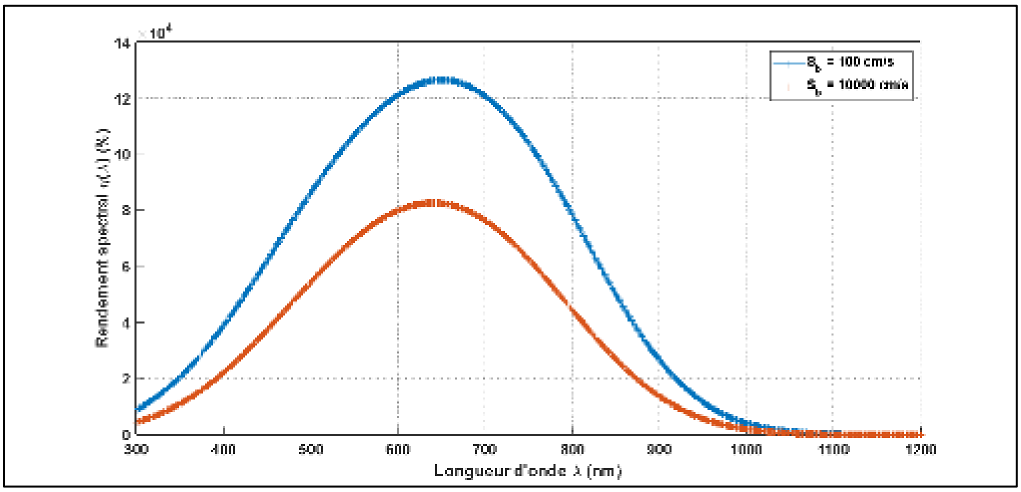

Figure 6 Spectral conversion efficiency as a function of wavelength

The evolution of the various studied quantities can be interpreted in light of the absorption and carrier generation mechanisms within the cell:

For short wavelengths (λ < 0.5 µm): Optical absorption occurs primarily near the top surface of the cell. This region is generally prone to surface recombination, which reduces the efficiency of photogenerated carrier collection. Consequently, the photocurrent density Jph is limited, and the overall efficiency remains moderate.

For intermediate wavelengths (0.6 µm ≤ λ ≤ 0.8 µm): Light penetrates deeper into the base, promoting more volumetric carrier generation in regions where the probability of collection is high. This results in a significant increase in Jph, an improvement in the photovoltage Vph, as well as an increase in the maximum power Pmax and the spectral efficiency.

For long wavelengths (λ > 0.9 µm): The absorption coefficient of silicon drops sharply, reducing the overall carrier generation. This decrease in generation leads to lower electrical quantities, particularly Vph and η, thereby compromising the overall performance of the cell.

By comparing the different rear-surface recombination velocity profiles Sb (denoted Sb1 and Sb2), it is observed that lower recombination velocities lead to better performance, especially at long wavelengths where carriers must travel a greater distance before being collected.

4. Conclusion

This study highlighted the decisive influence of the wavelength of monochromatic illumination on the electrical performance of a vertical-junction photocell. The results show that intermediate wavelengths Favor efficient carrier generation in the active region, thereby improving photocurrent density, photovoltage, and maximum power.

In contrast, short wavelengths lead to surface losses due to shallow absorption, while long wavelengths suffer from low absorption in silicon, limiting carrier generation. These effects underline the importance of optimal coupling between the incident spectrum and the physical structure of the cell.

A spectral optimization approach therefore appears to be a promising way to enhance the overall efficiency of the device. Future work includes the study of polychromatic and bifacial configurations, as well as the integration of advanced passivation techniques to reduce recombination losses and maximize charge collection.

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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