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Analysis of the capacitance of a vertical-junction photocell under polychromatic illumination: Influence of temperature and depth

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Abstract

This study analyses the capacitance of a series-connected silicon vertical-junction photocell exposed to polychromatic illumination, by incorporating the influence of temperature and depth. Based on the diffusion and recombination model of minority carriers in the cell base, the continuity equation is solved while accounting for the temperature dependence of the diffusion length, carrier lifetime and photovoltage. The simultaneous study of depth and temperature provides a better understanding of the capacitive behaviour under real conditions, with the aim of optimizing the energy efficiency of photovoltaic cells.

Keywords: Diffusion capacitance; Polychromatic illumination; Temperature; Base depth; Energy efficiency;Vertical-junction photocell; Carrier recombination

1 Introduction

In view of global energy challenges and the growing need for renewable sources, silicon photovoltaic cells represent a promising and sustainable solution. However, their efficiency is limited by various physical phenomena, in particular the recombination of charge carriers and their sensitivity to environmental conditions [1], [2].

The diffusion capacitance is a fundamental electrical parameter that makes it possible to evaluate the quality of photogenerated carrier collection [3]. Most previous studies have considered monochromatic illumination [4], [5], thereby simplifying the analysis. However, under real conditions, cells are exposed to a polychromatic light spectrum as well as significant thermal variations [6], [7].

The aim of this work is to study the evolution of the capacitance of a vertical-junction photocell as a function of temperature and base depth under polychromatic illumination. This approach aims to gain a better understanding of the interaction between optical and thermal parameters in the capacitive response, and to identify optimisation strategies applicable to real operating environments.

2 Theoretical Model

The photocell considered is a silicon $n^+/p/p^+$ series vertical-junction cell subjected to polychromatic illumination in steady state [1].

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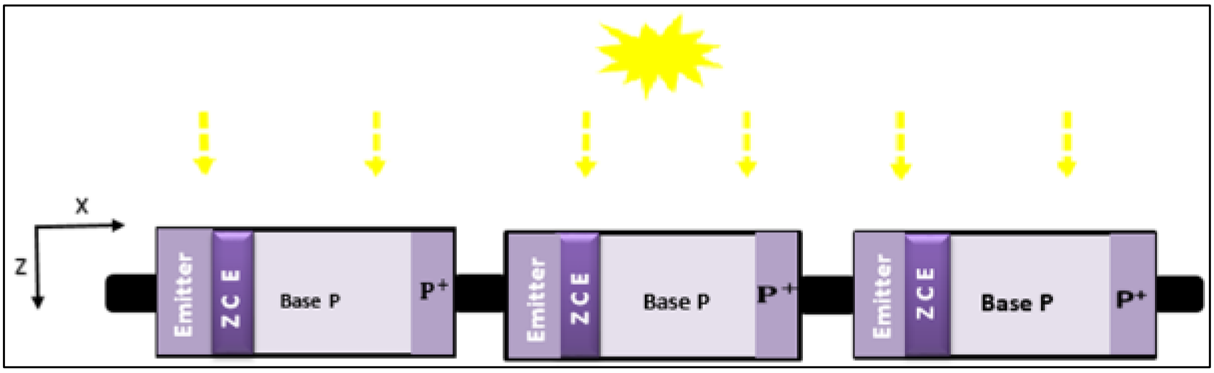

Figure 1 Silicon vertical-junction series-connected photocell under polychromatic illumination ($n^+/p/p^+$ structure)

The modelling is based on the continuity equation for minority carriers in the base, including generation, diffusion, and recombination [8].

The continuity equation is written 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 $\delta(x,z,\lambda)$ is the minority carrier density at the position(z,λ), L(T) is the temperature-dependent diffusion length, D(T) is the diffusion coefficient, and G (z, λ) is the optical generation rate, dependent on both wavelength λ and depth z.

The temperature dependence is introduced through:

$L^2(T) = D(T).\tau(T),\ V_T = \frac{k_B T}{q}$

where τ(T) is the minority-carrier lifetime, V_T is the thermal voltage, k_B is the Boltzmann constant, T is the absolute temperature and q is the elementary charge.

The generation term under polychromatic illumination is modelled as the weighted sum 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.

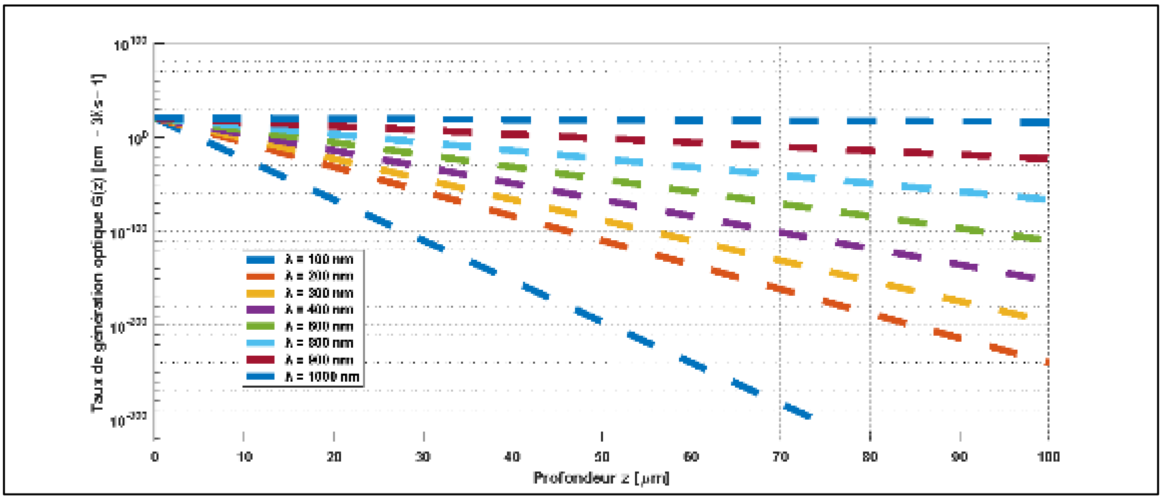

Figure 2 Optical generation rate as a function of depth

where F_λ is the incident light flux at wavelength λ, α_λ the absorption coefficient, and R_λ the reflection coefficient.
The boundary conditions are applied at the n^+/p and p/p^+ interfaces according to the recombination velocities S_f (emitter–base interface) and S_b (base–rear interface), which are also temperature-dependent.

3 Results and Discussion

1.1. Influence of Temperature

Temperature directly affects several key parameters influencing diffusion capacitance: the thermal voltage $V_T = \frac{k_B T}{q}$, the minority-carrier lifetime τ, and the diffusion coefficient D.

As the temperature increases, thermal noise promotes recombination, reducing τ due to more frequent phonon–electron collisions, while D may increase slightly. These combined effects lead to a gradual decrease in the capacitance, since fewer photogenerated carriers reach the junction without recombining.

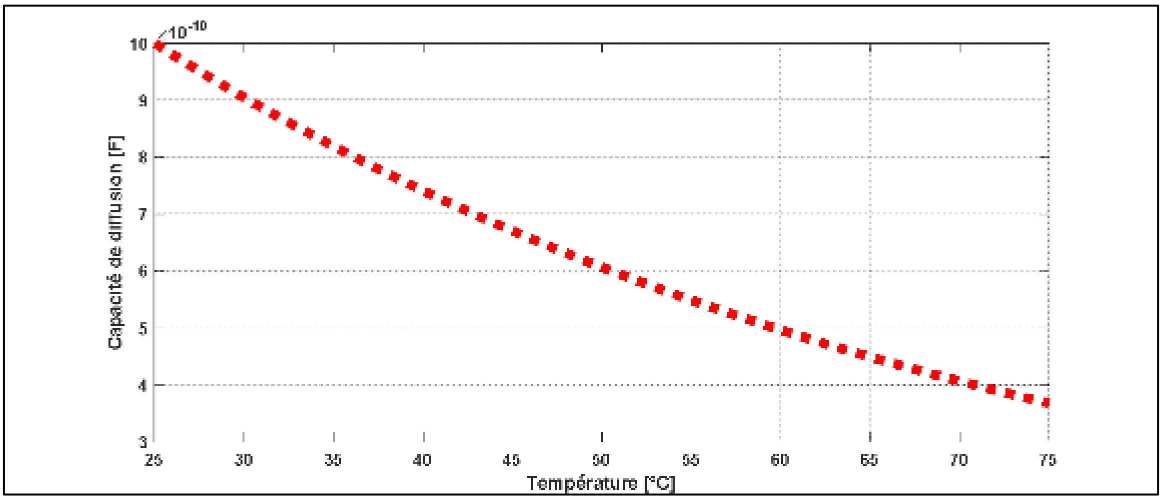

Figure 3 Evolution of diffusion capacitance as a function of temperature

The analysis reveals that the decrease is not linear: between 25 °C and 45 °C, the capacitance decreases moderately, whereas above 60 °C the degradation accelerates sharply, suggesting the need for cooling systems or structural adaptations to maintain performance.

1.2. Influence of Base Depth

The depth z affects the generation rate G(z) through exponential attenuation of the light. The farther the absorption point is from the junction, the more difficult carrier collection becomes due to increased recombination.

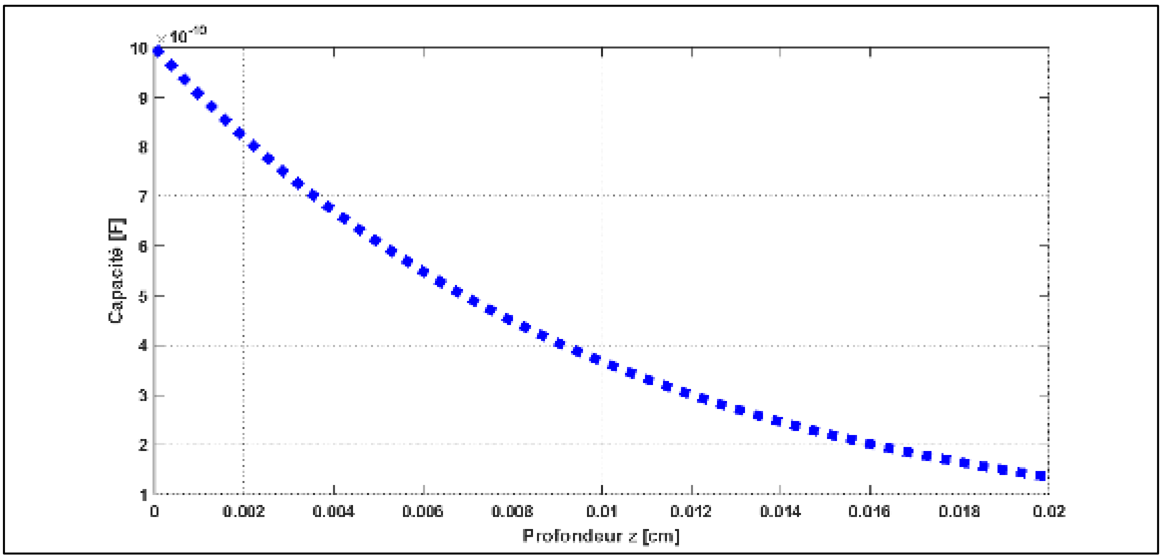

Figure 4 Evolution of diffusion capacitance as a function of depth

Three distinct regimes appear :

For z ≤ 0.008 cm, the capacitance is high due to the proximity of the generated carriers.

Between 0.0080.008 cm < z ≤ 0.014 cm, a regular decrease in capacitance is observed, linked to progressive recombination.

For z >0.015 cm, the capacitance reaches a low plateau, indicating that most carriers generated at this depth no longer contribute effectively.

These results suggest that designing a base that is too deep is counter-productive, increasing cost without capacitive gain.

1.3. Combined Effect of Temperature and Depth

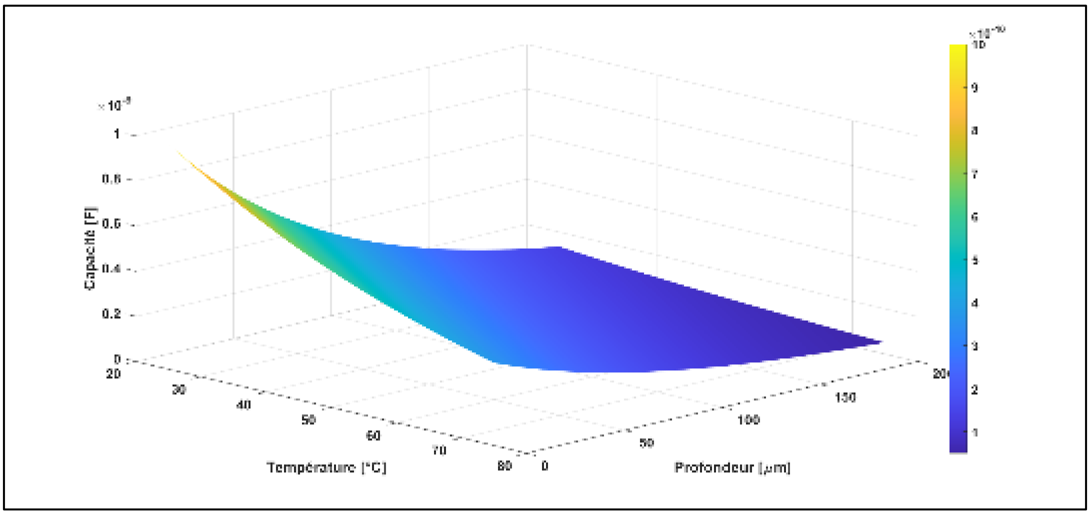

Figure 5 Capacitance as a function of temperature and depth (3D)

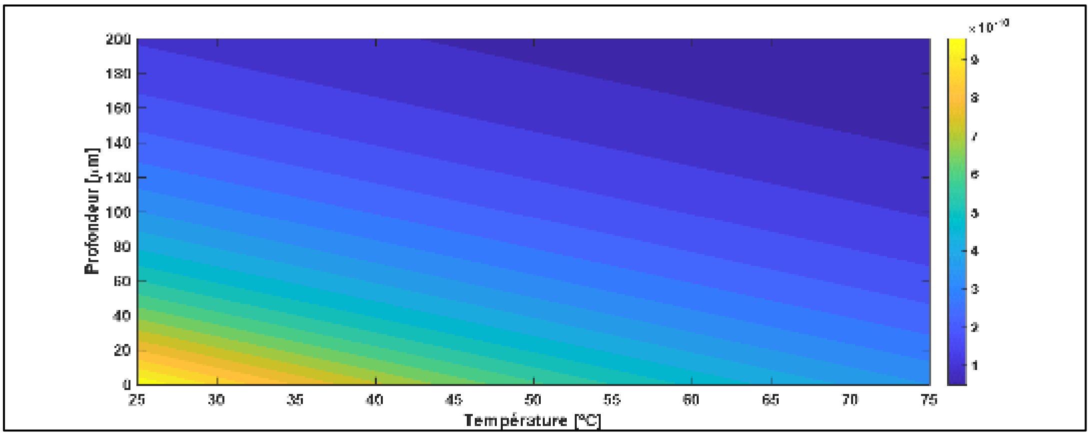

Figure 6 Capacitance map as a function of temperature and depth

The combined study of the two parameters shows that:

- At shallow depth and moderate temperature (25–35 °C), the capacitance is maximal, as carriers have good mobility and limited losses.
- At large depth and high temperature (60–75 °C), the capacitance is minimal due to frequent recombination and longer diffusion distances.
- A transition zone highlights the importance of a compromise between thermal and geometric parameters.
- This makes it possible to define optimal conditions according to the operating environment:
- In a moderate climate, a depth ≤ 0.01 cm and a temperature ≤ 40 °C are ideal.
- In hot regions, materials with lower recombination rates or passive cooling systems are recommended.

4 Conclusion

This study analysed the capacitive behaviour of a vertical-junction photocell under polychromatic illumination, taking into account the combined effects of temperature and base depth.

The results show that:

- The diffusion capacitance decreases as the temperature increases, particularly above 60 °C, due to the reduction in the effective minority-carrier density.
- Increasing the depth also leads to a significant decrease in capacitance due to higher recombination.
- The combined effect reveals an optimal operating range at shallow depths (≤ 0.01 cm) and moderate temperatures (25–40 °C).

These conclusions highlight the crucial role of diffusion capacitance in the optimal design of photovoltaic cells, especially under variable climatic conditions.

This work therefore opens perspectives for:

- Thermal optimisation of cells in hot environments;
- Design of thin structures with controlled rear-side recombination;
- Integration of predictive models for dynamic adaptation to real operating conditions.

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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