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3D Modeling of a Polycrystalline Solar Cell under Guinean Climatic Conditions: Determination of Diffusion Length Using the Inverse of the External Quantum Yield as a Function of the Inverse of the Absorption Coefficient at Temperature

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Abstract

A rise in temperature, respectively, leads to an increase in external quantum efficiency, giving broad spectral bands that shift to shorter wavelengths: from infrared to visible, then to ultraviolet. This effect is linked to the increased kinetic energy of the particles, leading to more intense collisions and greater absorption or emission of photons of different energies. EQE can increase in specific wavelength ranges, while the overall energy efficiency of the cell decreases. Spectral sensitivity increases sharply as temperature rises. This is due to a higher probability of creating electron-hole pairs. Photovoltaic cells work by absorbing light and generating electrons. A material's ability to absorb light depends on its crystalline structure. In polycrystalline silicon, crystal boundaries can act as traps for charge carriers, reducing the number of electrons generated when the crystal size is small. Crystal boundaries are transition regions between different crystals, where the crystal pattern is distorted or disorganized. These defects act as capture zones for charge carriers, preventing the current from flowing efficiently. This can significantly reduce the efficiency of the solar cell. Very small crystal sizes and higher defect densities lead to a reduction in EQE, spectral sensitivity, and effective scattering length, particularly in spectral regions where light is normally well absorbed. Low effective scattering lengths are thus due to small crystal sizes and high temperatures. Polycrystalline solar cell manufacturers need to optimize crystal size to increase electricity production. Larger crystals (not too large) give better yields than smaller ones. In addition, Guinea, like all Sahelian countries, faces significant environmental challenges, including deforestation and air pollution. Aerosols, particularly from biomass combustion and agriculture, have a direct impact on air quality and can reduce the efficiency of solar panels by reducing solar irradiation. Increased aerosols in the atmosphere can reduce the efficiency of solar installations, a crucial aspect in optimizing energy projects. This study is part of the response to the lack of studies on the analysis of renewable energy potential in general, as well as solar energy in Guinea.

Keywords

External Quantum Yield, Spectral Sensitivity, Effective Diffusion Length, Polycrystalline

1. Introduction

Guinea's climate is very hot, with an annual average of 31 degrees (304.15 K) [1], but there are few truly tropical and humid months. It is hot and scorching all year round. The hottest and rainiest part of the state is Boké. The coldest is Labé [1]. In July 2003, a record temperature of 43.2˚C (316.35 K) was recorded here [1]. As part of the energy transition process, Guinea will have to choose between two photovoltaic technologies: monocrystalline and polycrystalline solar panels.

Both monocrystalline and polycrystalline solar panels use silicon to convert sunlight into electricity. But their design has a major influence on their efficiency.

Monocrystalline is made from a single silicon crystal, giving it a purer structure and a uniform deep-black appearance. Thanks to this design, it boasts superior efficiency, fluctuating between 16% and 24%. It captures light better, even in weak sunlight, making it particularly effective in regions with unstable climates.

Polycrystalline cells are made from several silicon crystals fused together. Less expensive to produce, it has a slightly lower yield, around 14 and 18%. Its bluish appearance and lower efficiency make it a relevant choice only in very sunny regions such as Africa, particularly Guinea, where light intensity is almost constant all year round.

While pure performance is a key criterion, long-term profitability is just as essential. A monocrystalline solar panel is generally more expensive to buy, but offers greater energy efficiency and a longer lifespan, up to 35 years. Its ability to produce electricity even in difficult conditions means that the investment pays for itself more quickly.

Although more affordable, polycrystalline often requires a larger roof surface area to produce the same amount of energy. It is therefore less attractive for those with limited space. However, if budget is a determining factor and solar exposure is optimal, it can be a viable alternative, particularly for large-scale installations.

The choice between monocrystalline and polycrystalline depends above all on our geographical location, budget, and self-consumption objectives. If we're looking for maximum efficiency and long-term profitability, and are prepared to invest a little more, monocrystalline is without doubt the best option. On the other hand, if we have a tighter budget, as is the case in many African countries where the sun generally shines all year round, such as Guinea, polycrystalline is an interesting alternative. To improve the efficiency of these solar cells, many researchers have focused on the effect of doping [2], temperature [3] [4], and crystal size [5] on the performance of polycrystalline silicon solar cells.

In this work, we will evaluate the effect of temperature, crystal size, and interface capture on the external quantum efficiency (EQE) and sensitivity of a polycrystalline solar cell under monochromatic illumination. We began with a theoretical study to establish the analytical expression of the EQE as a function of temperature, crystal dimensions, and the capture effect at the contact surfaces between two crystals. We then used Mathcad software to simulate the impact of temperature, crystal dimensions, and the capture effect on EQE, as well as spectral sensitivity. We then exploited the effect of temperature on the effective diffusion length of a polycrystalline solar cell. The aim of this work is to determine the effective scattering length in high-temperature zones (Guinea) from the variation of the inverse of the external quantum yield as a function of the inverse of the absorption coefficient.

2. Mathematical Models and Formulas

The three-dimensional model **Figure 1** used is that of a polycrystalline silicon crystal whose dimensions are limited as follows: from 0 to Hb along the z axis, whose origin is taken from the junction and is none other than the center of the crystal, from $-g_x/2$ to 0 and 0 to $+g_x/2$ along the x axis and finally from $-g_y/2$ to 0 and 0 to $+g_y/2$ along the y axis. The mathematical equations given in the paragraph below are obtained taking into account certain assumptions such as [5] [6]:

The crystal dimensions along x and y are the same.

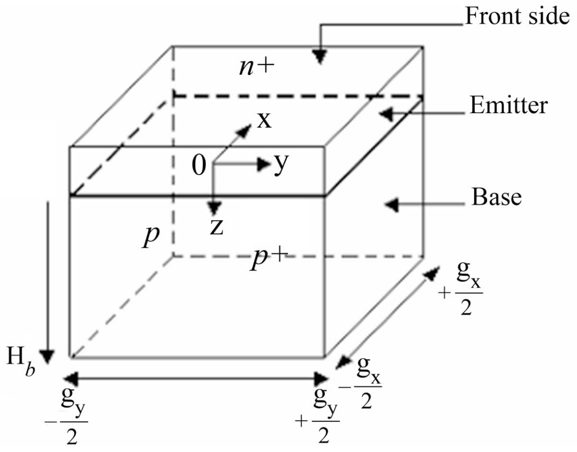

Figure 1. Geometry of a square crystal.

An anti-reflective layer on the n$^+$ layer, which receives the polychromatic radiation.

The concentration of carriers along x and y is identical; the generation rate is a function of z

The recombination planes are perpendicular to the O-x and O-y axes.

The contribution of the n$^+$ layer is negligible compared with that of the p layer.

Only the electric field at the junction is taken into account.

Grain boundaries are perpendicular to the junction.

Environmental factors in Guinea, such as aerosols from biomass combustion, are not included in the model. This is a limitation for future work.

As our analysis is limited to the p-layer, we present the three-dimensional continuity equations for p-layer carriers in the static regime under polychromatic illumination [5]-[8].

$$\frac{d^2\Delta\delta n(x,y,z)}{dx^2}+\frac{d^2\Delta\delta n(x,y,z)}{dx^2}+\frac{d^2\Delta\delta n(x,y,z)}{dz^2}-\frac{\Delta\delta n(x,y,z)}{L_n^2}+\frac{G_n(\lambda,z)}{D_n}=0 \quad (1)$$

$\Delta\delta n$ is the electron density in the p-layer.

L_n and D_n are the length and transition coefficient, respectively, of p-layer electrons across the n$^+$/p transition zone.

The solar cell is illuminated from the side covered by an anti-reflective layer, and the expression of the generation rate $G_n(z)$ is:

$$G_n(\lambda,z)=\alpha(\lambda)\left[1-R(\lambda)\right]\phi(\lambda)e^{-\alpha(\lambda)Z} \quad (2)$$

z is the depth of light penetration into the p-layer, and $\Delta\delta n(x, y, z)$ is the charge density generated.

The solution to equation (1) is [5]:

$$\Delta\delta n(x,y,z)=\sum_k\sum_j \Delta Z_{kj}(z)\cos(c_{nk}x)\cos(c_{nj}y) \quad (3)$$

c_{nk} and c_{nj} demonstrate the capture effect at the interface between two crystals.

Injecting equation (3) into (1), we have:

$$\frac{\partial^2\Delta Z_{kj}}{\partial z^2}-\frac{1}{Ln_{kj}^2}\Delta Z_{kj}(z)=-\frac{1}{D_{kj}}G_n(z) \quad (4)$$

where Ln_{kj} and Dn_{kj} are the effective diffusion length and the effective diffusion coefficient, respectively.

Sf and Sb are respectively the recombination velocities at the junction and at the back face. In this work, we have fixed them at 10^3 cm^{-3} for Sf and 10^2 cm^{-3} for Sb [5].

Determining external quantum efficiency

We use the following relationship [9]-[11]:

$$EQE=\frac{J_{CC}}{q\phi(\lambda)} \quad (5)$$

With J_{CC} is the short-circuit current, q is the load, and $\phi(\lambda)$ is the incident flux as a function of wavelength.

Determining spectral sensitivity

Starting from the expression of the external quantum yield, we have expressed the spectral sensitivity as follows:

$$S(\lambda) = \frac{\lambda}{1243} EQE \tag{6}$$

3. Results and Discussion

Analysis of the impact of temperature and crystal size on external quantum efficiency

For a crystal illuminated from its front face, the variation of EQE as a function of wavelength for different temperatures and crystal dimensions is shown in **Figure 2**.

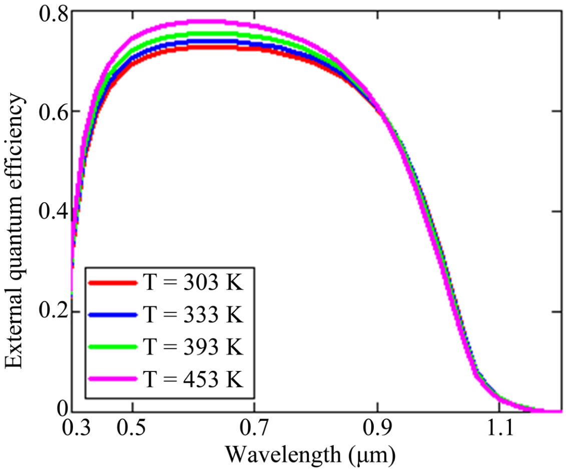

Figure 2. External quantum efficiency as a function of wavelength for different values of crystal size: g = 55 µm, Sf = 3000 cm/s, Sb = 200 cm/s.

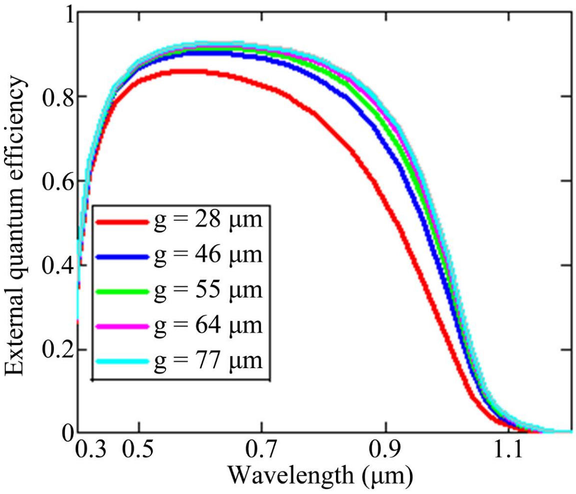

Figure 3. External quantum efficiency as a function of wavelength, respectively, for different values of crystal size and temperature: Sf = 3000 cm/s, Sb = 200 cm/s, T = 333 K.

EQE increases with temperature for wavelengths between 0.35 µm and 0.8 µm Figure 2. The solar spectrum comprises three zones: from infrared to visible, then to ultraviolet. The impact of temperature is most noticeable in the visible range. Temperature has a significant impact on the external quantum efficiency (EQE), affecting both the shape and intensity of the spectrum. A rise in temperature leads to a broadening of spectral bands and a shift to shorter wavelengths from infrared to visible, then to ultraviolet Figure 2. This effect is linked to the increased kinetic energy of molecules, which leads to more frequent collisions and a greater probability of absorption or emission of photons of different energies. Like temperature, increasing crystal size leads to an increase in EQE.

Polycrystalline silicon crystal size has a significant impact on EQE Figure 3. In particular, smaller crystals result in lower light absorption. They therefore affect the efficiency of the photovoltaic cell. Crystallographic defects at crystal interfaces, more common in small-crystal materials, also disrupt charger transport and reduce external quantum efficiency.

Analysis of the impact of temperature and crystal size on spectral sensitivity

For a front-illuminated crystal, the variation in spectral sensitivity as a function of wavelength for different temperatures and crystal sizes is shown in Figure 4 and Figure 5.

The figures below show that spectral sensitivity increases with temperature (Figure 4) and crystal size (Figure 5), respectively. The effect of temperature on the spectral sensitivity of polycrystalline silicon manifests itself in a drop in output power and a change in open-circuit voltage and short-circuit current. Increasing temperature leads to a reduction in open-circuit voltage and an increase in short-circuit current, which in turn reduces maximum output power.

A solar cell does not absorb all the radiation emitted by the sun. It is sensitive to only part of the sun's rays, with remarkable differences depending on the technology used.

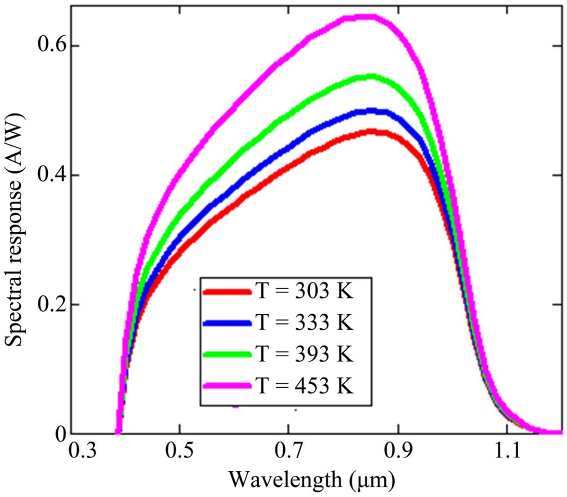

Figure 4. Spectral sensitivity as a function of wavelength for different values of temperature: g = 55 µm, $\lambda = 0.7$ µm, Sf = 3000 cm/s, Sb = 200 cm/s.

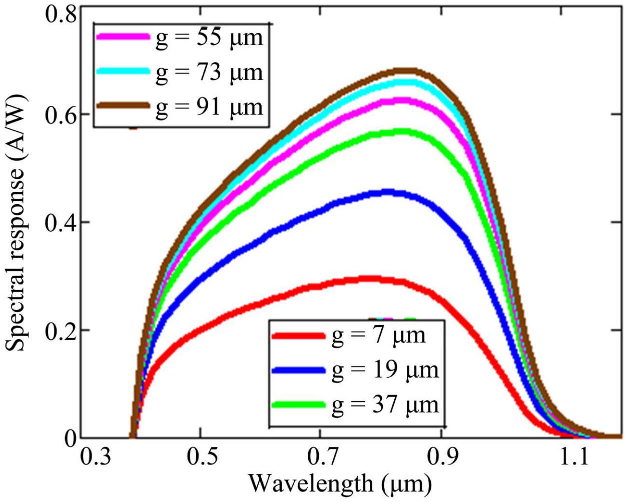

Figure 5. Spectral sensitivity as a function of wavelength for different values of crystal size: $\lambda = 0.7$ µm, Sf = 3000 cm/s, Sb = 200 cm/s, T = 333 K.

Spectral sensitivity increases slightly as temperature rises **Figure 4**. This is due to a higher probability of generating electron-hole pairs if not all the optical power is absorbed by the semiconductor material.

Photovoltaic cells work by absorbing light and generating electrons. A material's ability to absorb light depends on its crystalline structure. In polycrystalline silicon, crystal boundaries act as traps for charge carriers, reducing the number of electrons generated. Smaller crystal size and greater defect density lead to a reduction in spectral response, particularly in spectral regions where light is normally well absorbed.

Polycrystalline solar cell manufacturers strive to optimize grain size to maximize electricity production. We note that larger crystals (not too large) offer better efficiency than smaller ones **Figure 5**.

Determination of the effective diffusion length using the inverse of the external quantum yield as a function of the inverse of the absorption coefficient under temperature

The short-circuit photocurrent, measured at different wavelengths, makes it possible to determine the minority carrier diffusion length *Ln* (or *Lp*) by knowing the values of the absorption coefficient $\alpha(\lambda)$.

However, the following conditions must be met:

- The thickness of the sample *H* must be large in front of *Ln* (or *Lp*) ($H \geq 4.\mathrm{Ln}$).
- The values of the product $\alpha(\lambda)\ H$ must be large in front of the unit.
- The depth of the emitter and the RCE must be small in front of *H* so that the short-circuit photo current is essentially produced in the base of the cell.

We then obtain:

$$J_{CC} = q\left(1-R(\lambda)\right)\phi(\lambda)\left(\frac{Ln_{kj}}{Ln_{kj}+\dfrac{1}{\alpha(\lambda)}}\right) unite\ A/cm^2 \tag{6}$$

The cell's external quantum efficiency (EQE(λ)) = number of charges collected/number of photons incident is given by the relation:

$$EQE = \frac{J_{CC}}{q\phi(\lambda)} \approx \frac{\alpha(\lambda)Ln}{\alpha(\lambda)Ln+1} \tag{7}$$

We obtain:

$$\frac{1}{EQE(\lambda)} \approx \frac{\alpha(\lambda)Ln_{kj}+1}{\alpha(\lambda)Ln_{kj}} = 1+\frac{1}{Ln_{kj}}\frac{1}{\alpha(\lambda)} \tag{8}$$

The above relationship is the equation of a straight line:

$$Y = AX + 1 \tag{9}$$

With:

$$Y = \frac{1}{EQE(\lambda)} \tag{10}$$

$$X = \frac{1}{\alpha(\lambda)} \tag{11}$$

$$\text{And} \quad A = Ln_{kj}^{-1} \tag{12}$$

Determining the effective diffusion length by this method requires very precise knowledge of the evolution of $\frac{1}{EQE(\lambda)} = f\left(\frac{1}{\alpha(\lambda)}\right)$. For an extended domain of λ, we obtain the following plots (**Figure 6**, **Figure 7**).

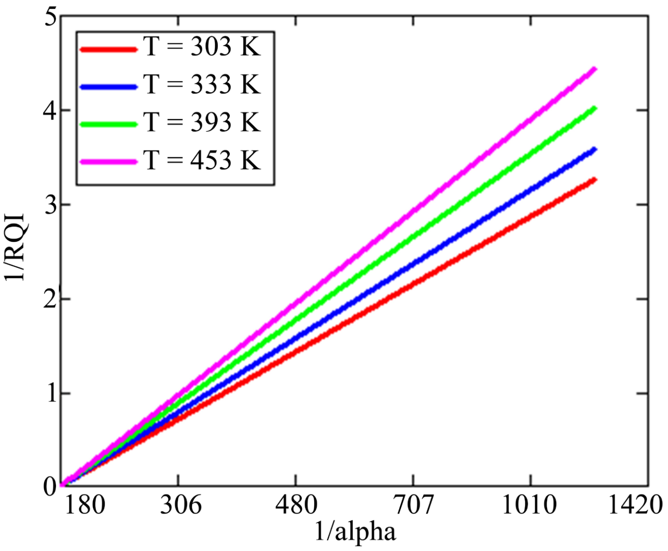

Figure 6. Inverse of the external quantum yield as a function of the inverse of the absorption coefficient for different values of crystal size and temperature, respectively: g = 55 μm, Sf = 3000 cm/s, Sb = 200 cm/s, Sg = 3000 cm/s.

From the curves in **Figure 6**, we obtained the numerical values given in **Table 1**.

Table 1. Impact of temperature on effective diffusion length.

Temperature (K)	303	333	393	453
Effective diffusion length (µm)	89.5	75.9	69.7	64.7

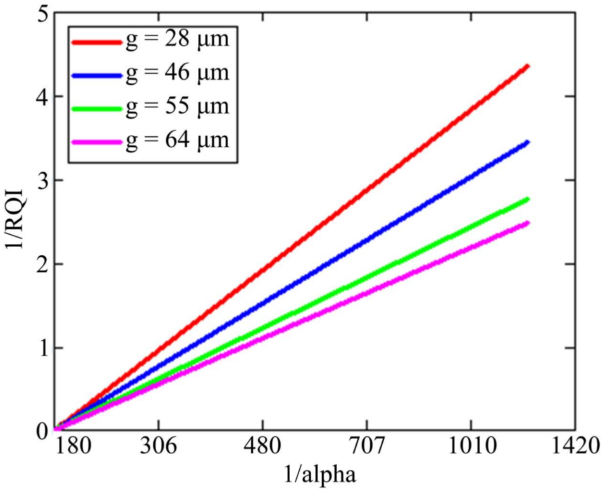

Figure 7. Inverse of the external quantum yield as a function of the inverse of the absorption coefficient for different values of crystal size and temperature, respectively: Sf = 3000 cm/s, Sb = 200 cm/s, T = 333 K, Sg = 3000 cm/s.

From the curves in Figure 7, we obtained the numerical values given in Table 2.

Table 2. Impact of crystal size on effective diffusion length.

Crystal size (µm)	7	19	37	55
Effective diffusion length (µm)	50.62	89.52	100	130

Table 1 shows a decrease in the effective diffusion length as a function of temperature, while Table 2 shows that the effective diffusion length increases with crystal size. So, the low effective diffusion length is due to very high temperatures and small crystal sizes. The diffusion length, being the distance travelled by the carriers before recombining, had to be large to expect a good yield.

4. Conclusions

Increasing temperature raises the kinetic energy of molecules, leading to more frequent collisions and a greater probability of absorption or emission of photons of different energies. This broadens spectral bands and shifts them towards shorter wavelengths, from infrared to visible, then to ultraviolet.

Spectral sensitivity increases slightly as temperature rises. This is due to the greater probability of electron-hole pair generation.

Crystalline defects at crystal interfaces, which are more numerous in small-crystal materials, also disrupt charge transport and reduce external quantum efficiency.

The low effective diffusion length is due to very high temperatures and small crystal size. For a country like Guinea, the Labé region is the most favorable for good polycrystalline silicon solar cell performance, based solely on the study of the effect of temperature. This is because higher temperatures reduce the cell's overall energy yield.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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