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3D NUMERICAL MODELING AND SIMULATION OF EFFECTS OF NON-UNIFORM IRRADIATION ON PERFORMANCE OF PHOTOVOLTAIC SOLAR CELLS

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Abstract- A wide range of studies treating the variation of solar cell performance is usually based on a simple approach that uses a uniform irradiation distribution. However, the flux arriving on the surfaces of solar cells is often not uniform, either because of obstacles (shading effect) or solar concentrators. In this paper, we will describe and study the effect of the non-uniformity of irradiation on the efficiency of a silicon photovoltaic cell. The numerical model used in this study is built based on the extended mathematical expression in three-dimensional for a P-N junction. The results from numerical modeling of Poisson and continuity equations (drift-diffusion model) show how the non-uniformity distribution of irradiation decreases the performance of a solar cell.

Keywords: Solar Cells, P-N Junction, Semiconductor, Non-Uniform Irradiation, 3D Modeling, Drift-Diffusion.

1. INTRODUCTION

The current world energy situation and its evolution in the future are significant issues that concern the whole of humanity [1]. The excessive use of fossil fuels (coal, oil, gas), whose reserves are limited, leads to the generation of carbon dioxide [2]. According to the international climate agreement signed at the end of COP 21 in Paris (2016) [3], researchers are pressured to find ways to make electricity that does not pollute the environment. This is because of the need to cut carbon dioxide, which worsens the greenhouse effect, and the amount of electricity used worldwide proliferates. These are precisely why renewable energies are considered promising with considerable future potential [4]. One of the most widely used renewable energies in the world, non-polluting, is photovoltaic energy [5]. It is based on the direct conversion of solar energy into electrical energy and has great potential among the various renewable energies [6]. Several efforts are made worldwide to optimize and reduce the cost of solar cells. On the material part, many research teams have been working for many years to obtain high efficiencies with low production costs [7]. On the conversion system part, the research can be summarized, generally, in two main points [8, 9]:

- The development of an accurate mathematical model that represents the actual photovoltaic cell and reflects the influence of different meteorological conditions on the parameters of the solar cell.
- The development of an efficient optimization method capable of determining the maximum power point of the cell's characteristic *I-V* for any irradiation and temperature condition, regardless of the nature of the change in these conditions, fast or slow.

The use of solar concentrators is one of the technologies that have shown an increase in the efficiency of solar cells. However, at the same time, they generate non-uniform irradiation on the surfaces of solar cells, resulting in a degradation of the electric power they produce. Although the use of solar concentrators can amplify the incident solar radiation on the photovoltaic cells several times, it always poses the problem of non-uniformity. This non-uniformity can be produced on a single PV cell or a module composed of many PV cells. In the case of non-uniform irradiation, some areas of the PV cell are highly illuminated, while others are less illuminated. The excessively illuminated regions generate a considerable current and get heated up. As a result, the electrical output of the PV cell is reduced, and the cross-current generated can cause damage to the cells.

In addition, there are other sources of irradiance non-uniformity, such as shading caused by obstacles like clouds, chimneys, trees, and nearby buildings. Although many good works on PV cell modeling have been presented, it is still necessary to investigate cell efficiency in greater detail for some particular purposes [10, 11].

This article presents a numerical modeling of a single junction PV cell under non-uniform irradiation using the three-dimensional Finite Difference Method (FDM). We developed a 3D model in MATLAB that is based on an extended mathematical expression, that we have developed, for a P-N junction under various non-uniform irradiation profiles. This paper's outline is organized as follows: The proposed three-dimensional physical and mathematical models are described in section 2. Moreover, we present the boundary conditions at various interfaces of the investigated P-N junction. Then, we describe in section 3 the numerical approach we used to solve the mathematical model obtained. Furthermore, we present in section 4 the Generation rate theory, which was applied to address the impact of non-uniform irradiation on the electrical parameters of solar cells. Section 5 presents the numerical results with analysis and discussion; finally, we summarize simulation results and draw some conclusions.

2. BASIC EQUATIONS

Our study used the drift-diffusion model. This model includes Poisson's equation, electron and hole continuity equations, and current relations. A set of nonlinear elliptic partial differentially coupled equations describes how electrons and holes behave in semiconductors. These equations may be generated from the Boltzmann transport equation or Maxwell's relations [12]. Both of these equation sets are available online.

2.1. Poisson's Equation

The Equation 1 allows to describe the distribution of the electrostatic potential ψ at any point of the material. It is deduced from Maxwell's first equation, and is therefore written in the form [13]:

$$\nabla^2\psi = -\rho / \varepsilon \tag{1}$$

where, ε is the dielectric permittivity of the semiconductor. In general, this permittivity is a tensor quantity that depends on the crystallographic directions of the material. In our case, we consider it homogeneous. The electric charge density ρ is given by Equation (2), where N_a^- and N_d^+ are the densities of ionized acceptor and donor dopants [14].

$$\rho = q\left(p - n + N_d^+ - N_a^-\right) \tag{2}$$

We consider that all states introduced by doping are ionized at the operating temperatures of the solar cells (i.e., $N_d^+ \approx N_d$ et $N_a^- \approx N_a$, where N_a and N_d are the initial acceptor and donor dopant densities, respectively). This is because both the donor and acceptor states are placed at energy levels that are very near their respective conduction bands and valence bands. Whereas the acceptor states are filled with electrons and have a negative charge, the donor states are unoccupied and have a positive charge [15].

2.2. Continuity Equations

The continuity equations of electrons Equation (3) and holes Equation (4) are derived directly from Maxwell's fourth equation, and they govern the dynamic equilibrium of charge carriers in a semiconductor. These equations relate the temporal variation of charge carrier densities n and p to recombination and generation rates R and G, as well as current densities J_n and J_p [16].

$$\frac{1}{q}\vec{\nabla}.\overrightarrow{J_n} + G - R = \frac{\partial n}{\partial t} \tag{3}$$

$$-\frac{1}{q}\vec{\nabla}.\overrightarrow{J_p} + G - R = \frac{\partial p}{\partial t} \tag{4}$$

The term R corresponds to the total recombination rate and G represents the optical generation rate of electron-hole pairs which will be discussed in detail in the Equation 4. J_p and J_n are the hole and electron current densities, respectively. By limiting oneself to the permanent regime ($\partial n / \partial t = 0$ and $\partial p / \partial t = 0$), and making the divergence operators explicit, Equations (3) and (4) [17] can thus be rewritten in the following:

$$\frac{1}{q}\left(\frac{\partial J_n}{\partial x} + \frac{\partial J_n}{\partial y} + \frac{\partial J_n}{\partial z}\right) + G - R = 0 \tag{5}$$

$$-\frac{1}{q}\left(\frac{\partial J_p}{\partial x} + \frac{\partial J_p}{\partial y} + \frac{\partial J_p}{\partial z}\right) + G - R = 0 \tag{6}$$

2.3. Charge Transport Equations

The current in a semiconductor is due to the displacement of charge carriers as a result of an electric field $\vec{E} = -\overrightarrow{\Delta\psi}$ (drift current) or to a gradient of concentration (diffusion current). The current densities of the electrons and holes are thus given, respectively, by the Equations (7, 8) [17].

$$\overrightarrow{J_n} = q.n.\mu_n.\vec{E} + q.D_n.\vec{\nabla}_n \tag{7}$$

$$\overrightarrow{J_p} = q.p.\mu_p.\vec{E} - q.D_p.\vec{\nabla}_p \tag{8}$$

In these equations, μ_n and μ_p represents the electron and hole mobilities, respectively. D_n and D_p are their coefficients of diffusion presented by the Einstein relation, Equation (9) [18].

$$D_{n,p} = \mu_{n,p}\frac{kT}{q} \tag{9}$$

2.3. Domains and Boundary Conditions

The boundary of the simulated structure is composed of two subdomains: the metal contacts on the one hand, in which the simple Dirichlet conditions are considered, and the rest of the boundary on the other hand, where homogeneous Neumann conditions are imposed [19].

A simple solar cell is composed, generally, of a P-N junction and two metal contacts, a first in front and a second in back. The conditions applied at these metal contacts are of Dirichlet type. In effect, the values of the potential ψ at each contact (forward or backward) are written as a function of the applied voltage V_a and the potential barrier ψ_{bi} between the metal and the semiconductor as Equation (10).

On the other hand, the current densities are equal to the recombination currents at the surfaces, given by Equations (11, 12). In these relations, S_p and S_n represent the surface recombination velocities of the holes and electron respectively. n_{eq}, p_{eq} are the concentrations of the electrons and holes at thermal equilibrium [20].

$$\psi = V_a + \psi_{bi} \tag{10}$$

$$J_n = S_n\left(n - n_{eq}\right) \tag{11}$$

$$J_p = S_p\left(p - p_{eq}\right) \tag{12}$$

At the lateral surfaces, we apply Neumann-type conditions, given by Equations (13)-(15), [21, 22]. These conditions can be explained by the fact that there is no flow of charge carriers to the outside environment via the lateral surfaces.

$$\vec{\Delta}\psi.\overrightarrow{n_{\perp}} = 0 \tag{13}$$

$$\overrightarrow{J_n}.\overrightarrow{n_{\perp}} = 0 \tag{14}$$

$$\overrightarrow{J_p}.\overrightarrow{n_{\perp}} = 0 \tag{15}$$

where, $\overrightarrow{n_{\perp}}$ is a unit vector normal to the surfaces and oriented to the interior of the structure.

The Equations (1), (5)-(8) form a system of nonlinear elliptic partial differential coupled equations. This system is defined in a three-dimensional space in steady state. Since the analytical solution is not possible, we resort to numerical methods.

3. NUMERICAL APPROACH

In the last part of this chapter, we discussed the mathematical model used to simulate a solar cell. In this part, we will discuss the method of numerical simulation that we have devised and put into practice for a P-N junction, the fundamental component of a solar cell, in both equilibrium and non-equilibrium thermodynamics. This process was developed by us and implemented by us. This software is a simulation in three dimensions of the flow of electrical charge across a P-N junction [23].

In fact, there are several methods and numerical techniques to solve our system of equations. The choice of the method used in this study is mainly based on the structure of the cell to be simulated; since we worked on a simple parallelepiped shape, we used the FDM to discretize the deferential equations [24]. In addition, it was necessary to develop an adaptive three-dimensional Schaftter-Gummel scheme to linearize the obtained model [25].

After discretization, we obtained a large system of equations that we solved with the Newton Raphson method using preconditioning so that the method used converges more rapidly. We use the initial hypothetical (X_0=(ψ_{analy}+$\varphi_{n,eq}$+$\varphi_{p,eq}$)) as a starting point for the method of Newton-Raphson, to find the numerical solution of reduced system (X_{eq}=(ψ_{eq}+$\varphi_{n,eq}$+$\varphi_{p,eq}$)).

Next, our computer software figures out the exact answer for each polarization by starting with this equilibrium solution and using a method based on half-intervals to move forward. This process continues until the desired polarization condition is achieved.

We use the same method for each polarization to introduce the half-interval lighting conditions until we reach the value set up front. This process continues until we reach the value. The process that must be carried out to disrupt the system is shown in Figure 1, a schematic.

Although it may appear long, this process is very efficient such that it allows for a rapid convergence to find the values of the state variables at each operating point (characterized by a given bias and/or irradiation). The details of the development of the three-dimensional simulator of charge transport in semiconductors at equilibrium and out of equilibrium can be done by following the strategy given by the organizational charts in Figures 2 and 3.

In addition to the adequate choice of the system excitation strategy to accelerate the calculation. The precision also depends on the discretization step, since the FDM is used, it will be larger as the step is smaller, while a larger step allows a faster calculation. In effect, the program allows different steps to be chosen depending on the region. To have a calculation as fast and as accurate as possible, the compromise is to choose a fairly large step, when the variables vary slowly with position, usually in the center of the layers far from the junction, and to choose a smaller step in the regions around this junction, where the variables vary rapidly.

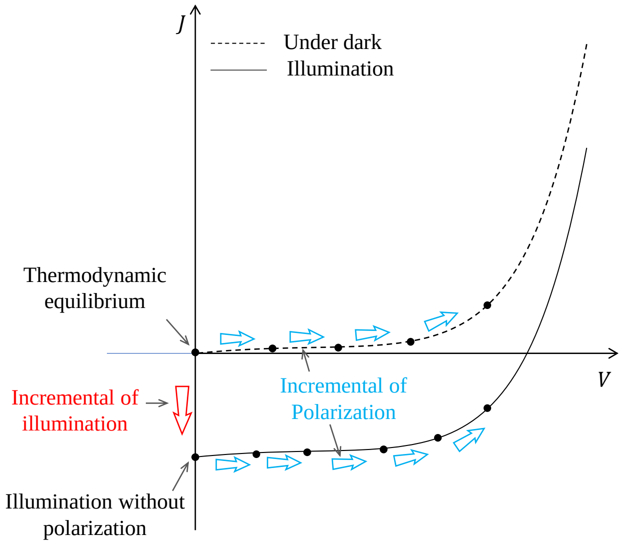

Figure 1. The technique followed to solve our system of equation under operating conditions (polarization and/or illumination)

4. MODELING OF NON-UNIFORM ILLUMINATION

The amount of light that hits the active surface of a solar cell has a clear and vital effect on how well that cell works. The efficiency of a PV solar cell also according to how that illumination is distributed across the cell's surface, which is mathematically represented by the corrective function f_c (y; z). Indeed, the creation of free carriers by the absorption of solar radiation is given by the optical generation rate G (cm^{-3} s^{-1}), which is found in the continuity equations. This term depends on the flux ϕ_λ of the radiation penetrating the solar cell [26, 27].

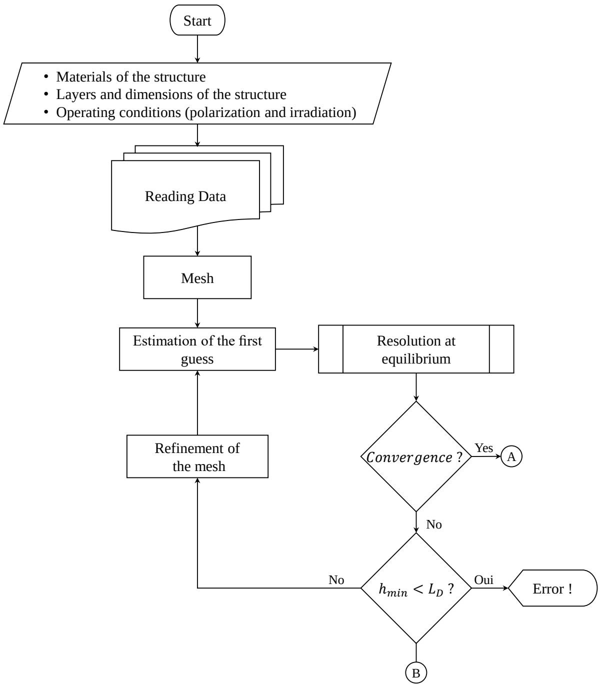

Figure 2. Procedure for the simulation of a solar cell at thermodynamic equilibrium

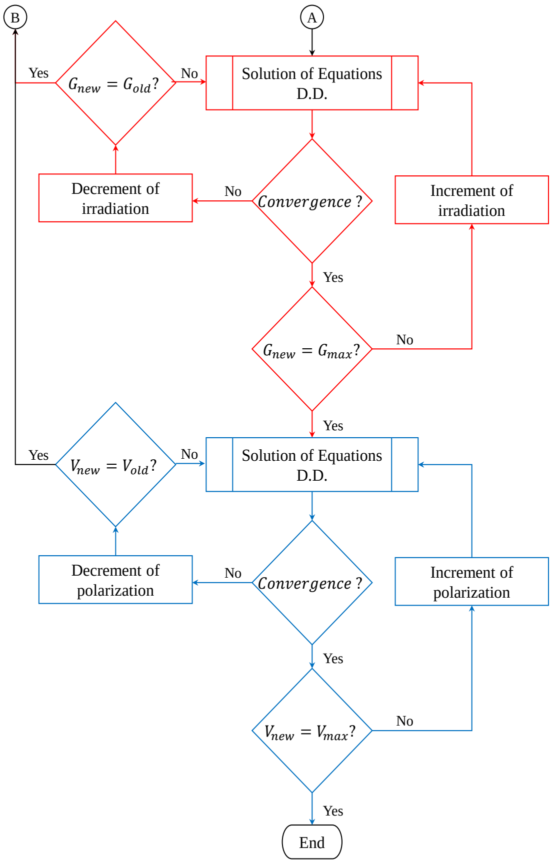

Figure 3. Organizational charts for solving the equation system at non-equilibrium thermodynamics, introducing polarization and irradiation in series

The optical generation rate G at an abscissa x inside the material is obtained by the relation 16:

$$G(x,y,z) = \alpha \times \phi_\lambda(x) \times f_c(y;z) \tag{16}$$

For any structure composed of multiple layers, as shown in the Figure 4, the expression of the flux in a layer j, between the abscissas x_i and $x_i + d_j$ of absorption coefficient α_λ^j, after crossing the previous layers of respective thicknesses $d_1, d_2, \ldots, d_{j-1}$, is given by the Equation (17).

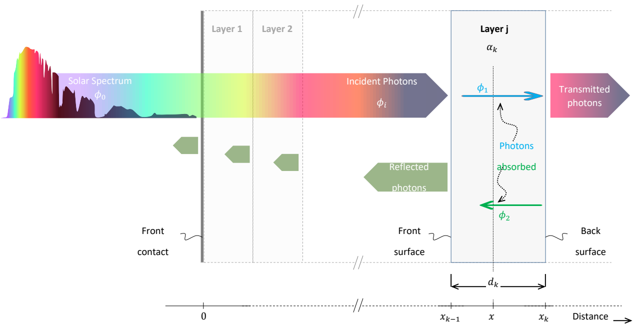

Figure 4. Source side voltage and current of phase (2) Absorption of white light by a solar cell composed of multiple layers

$$\phi_\lambda(x) = \left(1 - R_f\right)\phi_{\lambda i}\prod_{i=1}^{j-1}\left(1 - R_{i/i+1}\right)\exp\left(\sum_{i=1}^{j-1}\left(\alpha_\lambda^j - \alpha_\lambda^i\right)\right)\times$$
$$\times\exp\left(\left(-\alpha_\lambda^j x\right) + R_{j/j+1}\exp\left(-\alpha_\lambda^j\left(2x_{j+1} - x\right)\right)\right) \tag{17}$$

In the case of polychromatic radiation characterized by the incident flux $\phi_i = \sum \delta\phi_{\lambda,i}\delta\lambda$, with $\delta\phi_{\lambda,i}$ is the value of the flux of photons per unit wavelength, in the spectral band [λ, $\lambda+\delta\lambda$], the optical generation rate in layer j then becomes (Equation (17)):

$$G(x,y,z) = \left(1 - R_f\right)\phi_{\lambda i}\prod_{i=1}^{j-1}\left(1 - R_{i/i+1}\right)\sum \delta\phi_{\lambda,i}\delta\lambda\exp\left(\sum_{i=1}^{j-1}\left(\alpha_\lambda^j - \alpha_\lambda^i\right)\right)\times$$
$$\times\alpha_\lambda^j\exp\left(\left(-\alpha_\lambda^j x\right) - R_{j/j+1}\exp\left(-\alpha_\lambda^j\left(2x_{j+1} - x\right)\right)\right) \tag{18}$$

5. RESULTS AND DISCUSSION

The numerical techniques described above allow us to calculate the values of the selected state variables at each point of the device, namely the electrostatic potential $\psi(x, y, z)$, the electron and hole Fermi quasi-potentials $\varphi_p(x, y, z)$ and $\varphi_n(x, y, z)$, respectively. The program calculates all other quantities and their spatial variations from these three variables. It also calculates the electrical I-V characteristics for a given polarization and/or irradiation conditions. In this paper, we will present three studies: the effect of light intensity for non-uniform irradiation, the effect of the percentage of non-uniformity, and the effect of the distribution of non-uniformity.

2.1. Effect of Light Intensity

The non-uniform irradiation in this section has a rectangular-shaped distribution [28] and is applied to 25% of the total cell area. The rest of this area is illuminated by uniform irradiation. The Figures 5 and 6 represents the I-V and Power-voltage characteristics of a solar cell illuminated in a uniform and non-uniform manner, respectively. We can see that there is no significative difference between the two curves. Therefore, we can conclude that when the concentration ratio is low, non-uniform irradiation has almost no effect on the *I*-*V* characteristic. This can be explained by the fact that at low concentrations of the flux of light, the effect of the parallel resistance, which results from non-uniform irradiation, is negligible [29].

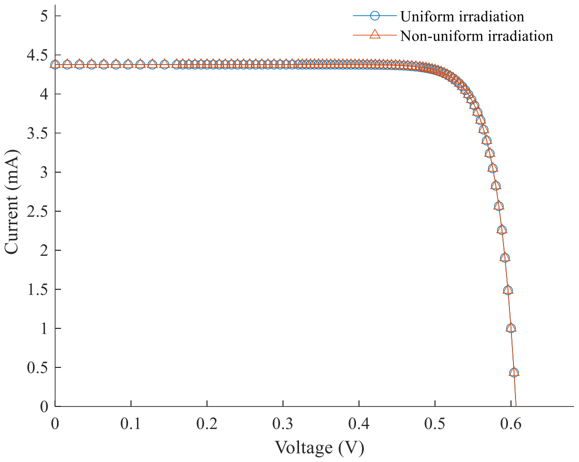

Figure 5. Current-voltage *I*-*V* characteristics of a low-concentration (500 W/m^2) solar cell under uniform and non-uniform irradiation

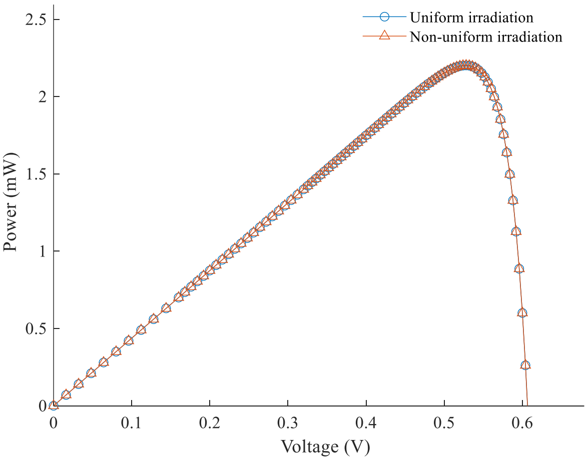

Figure 6. Power-voltage *P*-*V* characteristics of a low-concentration (500 W/m^2) solar cell under uniform and non-uniform irradiation

Table 1 groups the values of the different solar cell parameters for uniform and non-uniform irradiations. We find that the open-circuit voltage V_{oc}, the short-circuit current I_{sc}, the maximum power Pmax, the fill factor *FF*, and the efficiency η did not change much for both types of irradiations. In effect, the voltage V_{oc} is still the same in both cases because it does not depend on the distribution of the light flux but only on the saturation current and the photocurrent [30].

Table 1. Values of a PV solar cell with uniform and non-uniform irradiation with a concentration of 500 W/m², Values of a solar cell under uniform and non-uniform irradiation with a concentration of 500 W/m²

Irradiation	I_{sc} (A)	V_{oc} (V)	*FF*	η (%)
Uniform	4.375	0.610	0.840	18.427
Non- uniform	4.312	0.610	0.852	18.427

Given that the temperature of the photovoltaic cell is maintained as constant, and knowing that the cell receives the same amount of energy in both cases (uniform and non-uniform irradiations), the currents I_{sc} generated by the photovoltaic cell are the same. Moreover, due to the low concentration of the light flux and the choice of the ohmic contact, the effect of the internal series resistance on these variables is negligible. The same can be noticed for the fill factor *FF* and the conversion efficiency η, which is defined as the maximum power ratio by the power input.

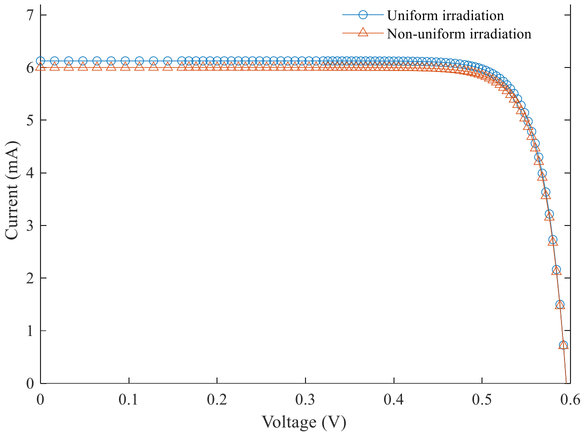

Figure 7. Solar cell current-voltage *I*-*V* characteristics under standard intensity (1000 W/m^2) uniform and non-uniform irradiation

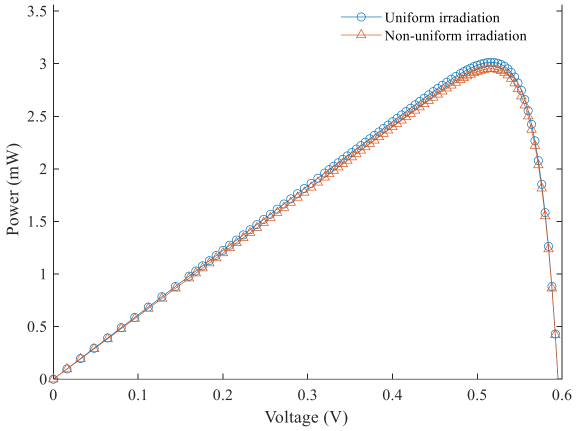

Figure 8. Power-voltage *P*-*V* characteristics of a PV solar cell with uniform and non-uniform irradiation of standard intensity (1000 W/m^2)

In contrast to the low irradiation case (500 W/m^2), the standard flux (1000 W/m^2) shows more effect on the *I*-*V* and *P*-*V* characteristics as shown in Figures 7 and 8, respectively.

As shown in Figures 9 and 10, the effect of irradiation non uniformity becomes more significant at high intensities (1500 W/m^2). This effect appears for all electrical parameters of the cell, except that for the open-circuit voltage which is not much influenced.

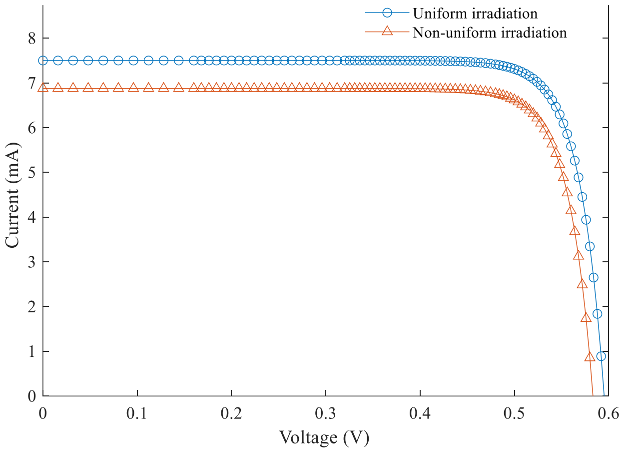

Figure 9. Solar cell (*I-V*) parameters under uniform and non-uniform high-intensity (1500 W/m^2) irradiation

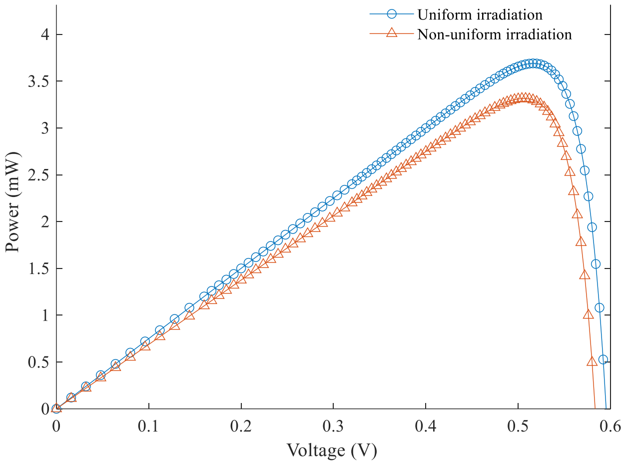

Figure 10. A solar cell's power-voltage *P-V* characteristics under high-intensity (1500 W/m^2) uniform and non-uniform irradiation

2.1. Effect of Percentage of Non-Uniformity

In this analysis, we investigate a light flux that is not uniform across three brightness levels and alters the degree of its irregularity across these levels. Figure 11 shows how the efficiency of solar cells drops proportionally at this level of degradation. We see a general trend of decreasing efficiency when the light flow increases. As a result, even for small percentages of non-uniformity, the efficiency loss is almost linear for high-intensity flux. However, for significant percentages of non-uniformity, the degradation is highly considered for low and standard-intensity fluxes.

2.1. Effect of the Non-Uniformity Distribution

Here, we show the results of a simulation run on a solar cell subjected to non-uniform irradiation of both the rectangular and Gaussian varieties. The electrical properties of the model cell subjected to these various radiation levels are shown in Figure 12. We see that the solar cell's performance is more affected by a Gaussian distribution of no uniformity than by a rectangular distribution.

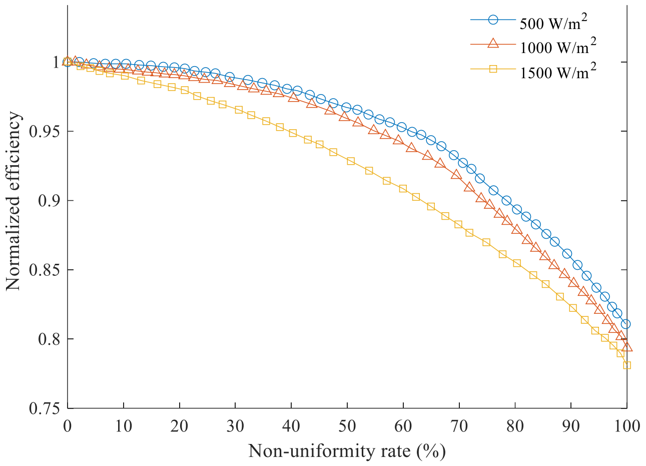

Figure 11. Solar cell efficiency varies non-uniformly with surface irradiation

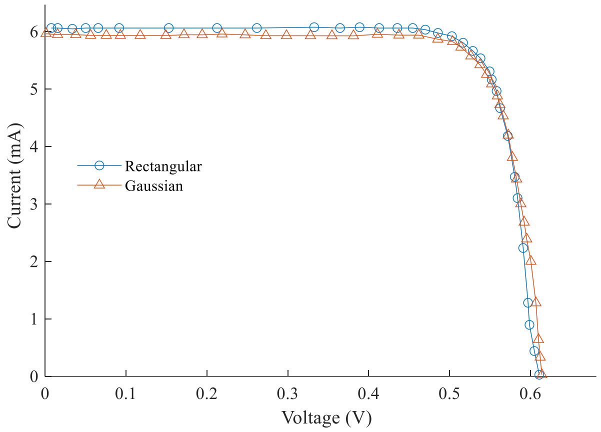

Figure 12. *I-V* characteristic of a solar cell submitted to a standard non-uniform irradiation, with rectangular and Gaussian distributions

6. CONCLUSIONS

Modeling and simulating a P-N junction, a crucial component of PV solar cells, under uniform and non-uniform irradiation was the goal of this work. We employed the finite difference approach to discretize and linearize the differential equations supplied by the drift-diffusion model. In addition, we extended the Scharfetter-Gummel scheme to three dimensions. We demonstrated the simulation results comparing the performance of a solar cell subject to uniform irradiation with solar cells subjected to low, medium, and high light flux intensities. A solar cell's *I-V* characteristic is unaffected by low-intensity non-uniform irradiation. This is because the flowing current through the PV solar cell is not affected by the parallel and series resistances caused by the non-uniform irradiation. Additionally, in the case of rectangular distribution, the impact of non-uniform irradiation on a solar cell's performance is reduced. At a light flow of medium or high intensity, however, the impact of non-uniform irradiation on solar cell characteristics becomes noticeable.

NOMENCLATURES

Acronyms

PV	Photovoltaic
P-N	P-type and N-type semiconductors.
COP	Conference of Parties
DD	Drift-Diffusion

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