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RESEARCH ARTICLE

TEMPPERATURE AND IRRADIANCE EFFECTS, IN QUASI-STATIC REGIME, ON THE CONVERSION EFFICIENCYOF A BIFACIAL SILICON SOLAR CELL UNDER POLYCHROMATIC ILLUMINATION

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Abstract

In this work, a theoretical study of the effects of temperature and irradiance on a bifacial silicon solar cell is presented. To achieve this, the bifacial solar cell placed under polychromatic illumination, is the site of a photocreation of minority carriers whose movement is governed by the continuity equation. Solving this continuity equation allowed us to determine the density of the minority carrier's photogenerated in the base of the cell as a function of temperature, irradiation and junction recombination velocity. From the expression of the minority carrier density, those of the photocurrent density, photovoltage, power and conversion efficiency have been deduced. When the ambient temperature of the medium varies from 290 K to 320 K, the power and efficiency of the solar cell decrease. On the other hand, for irradiance values between 100 W.m^{-2} and 400 W.m^{-2}, we see an increase in power and conversion efficiency.

Introduction:-

The study of solar cells involves several climatological parameters such as temperature and sunshine irradiance, whose effects are noted in the production of solar energy. The first monofacial monocrystalline and polychrystalline silicon solar cells achieved energy conversion efficiencies of 6% **[1]**. However, to improve the efficiency of solar cells, numerous research projects have led to the development of new bifacial solar cells **[2,3]**, with conversion efficiencies equal to or greater than 20% **[4]**. Solar irradiance is one of the main factors characterizing the electrical power and conversion efficiency of a silicon solar cell **[5, 6, 7]**. The low conversion efficiency of solar cells is strongly influenced by the ambient temperature of the medium **[8]**. The most reliable information on the efficiency of a solar cell in converting sunlight into electricity is provided by its current-voltage properties **[9, 10]**. It is therefore necessary to study the curve of the (I-V) characteristic to estimate the solar cell's electrical power in order to maximize conversion efficiency. From such a curve, it is possible to calculate and evaluate the influence of sunshine level and ambient temperature on power output **[11]** and the efficiency of photovoltaic systems **[12, 13]**.

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1. Theory

A simplified diagram of a bifacial n+-p-p+ silicon solar cell **[14, 15, 16, 17]** is shown in figure 1.

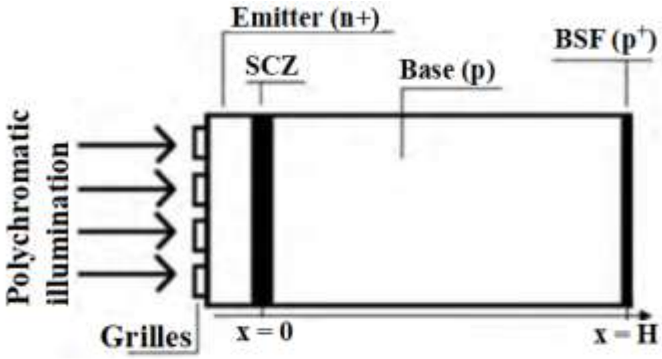

Figure 1:- Diagram of a bifacial solar cell under polychromatic illumination.

When the solar cell is illuminated, electron-hole pairs are created in the base. Photogenerated minority carriers may cross the space charge zone or undergo recombination in volume and at the surface. The density of excess minority charge carriers in the base is governed by the continuity equation **[4, 6]** :

$$\frac{\partial^2 \delta_n(x)}{\partial x^2} - \frac{\delta_n(x)}{L_n^2} = -\frac{G(x)}{D_n} \qquad (1)$$

Where $\delta_n(x)$ is the density of minority carriers (electrons) photogenerated in the base at a depth x ; D_n and Ln are the scattering coefficient and length respectively.
With G(x) is the minority carrier generation rate and its expression is given by **[18]** :

$$G(x) = n \sum_{i=1}^{3} a_i \, e^{-b_i x} \qquad (2)$$

Where a_i and b_i are coefficients tabulated in AM1.5 **[19]**.
The expression for the diffusion coefficient is given by the relation **[20]** :

$$D_n = \frac{\mu(T).K_b.T}{q} \qquad (3)$$

Where $\mu(T)$ is the electron mobility coefficient, q is the electron's elementary charge and Kb is Boltzmann's constant. Its expression is given by **[20]**.

$$\mu(T) = 1350\left(\frac{T}{300}\right)^{-3/2} \qquad (4)$$

T is the temperature of the solar cell, which depends on the ambient temperature (Ta) of the environment and the amount of irradiance (E); it is given by the relationship **[21]** :

$$T = T_a + \frac{E}{800}(NOCT - T_{a,ref}) \qquad (5)$$

Where NOCT is the normal operating temperature of the solar cell; $T_{a,\,ref}$ is the reference temperature (25°C).
A general solution to equation (1) is given by :

$$\delta_n(x) = Ae^{-\frac{x}{Ln}} + Be^{\frac{x}{Ln}} + \sum_{i=1}^{3} K_i e^{-b_i x} \qquad (6)$$

Where Ki is given by :

$$K_i = \frac{nL_n^2}{D(1 - L_n^2 b_i^2)} a_i \qquad (7)$$

A and B are coefficients determined from the following boundary conditions **[22, 23, 24]** :

- at the junction (emitter-base), at x = 0 :

$$D_n.\frac{\partial^2\delta_n(x)}{\partial x^2}\bigg|_{X=O} = S_f.\delta_n(x)|_{x=0} \qquad (8)$$

- to the back side, at x = H :

$$D_n.\frac{\partial^2\delta_n(x)}{\partial x^2}\bigg|_{X=H} = -S_b.\delta_n(x)|_{x=H} \qquad (9)$$

With Sf and Sb being the recombination velocities at the junction and back surface respectively **[25].**

2.1. Expression of photocurrent density

The photocurrent density is obtained from the gradient of the minority carrier density at the junction. Its expression is **[21, 26]**:

$$J_{ph}(Sf,Ta,E,Sb) = q.D_n(Ta,E).\frac{\partial\delta_n(x,Sf,Ta,E)}{\partial x}\bigg|_{X=O} \qquad (10)$$

2.2. Expression of photovoltage

The photovoltage is given by Boltzmann's relation **[6, 26, 27]** :

$$Vph\ (Sf,Ta,E) = V_T.Ln\left[\frac{N_b}{ni^2(T,E)}\delta_n(0,Sf,Ta,E)+1\right] \qquad (11)$$

With $V_T = \frac{K_b}{q}T$ being the thermal voltage ; $\boldsymbol{N_b}$ is the doping rate of the acceptor atoms in the base; n_i is the intrinsic concentration of minority carriers, expressed as follows:

$$n_i(T,E) = \sqrt{2{,}86\times 1{,}04\times 10^{36}\left(\frac{T}{300}\right)^3\times exp^{\left(\frac{-Eg}{K\times T}\right)}} \qquad (12)$$

where Eg is the gap energy of the silicon used.

2.3. Expression of power

The electrical power supplied by the solar cell under illumination is obtained by the product of the photovoltage and the actual current collected from the external circuit **[28, 29]** :

$$P = V_{ph}.(J_{ph} - I_d) \qquad (13)$$

Where I_d is the diode current.

2.4. Expression of conversion efficiency

The conversion efficiency of the solar cell is the ratio of the maximum electrical power supplied to the incident power received by the solar cell **[30, 31]** :

$$\eta = \frac{P_{max}}{P_{inc}} \qquad (14)$$

Where P_{max} is the maximum power supplied to the external circuit and P_{inc} the incident power of the light received by the solar cell at A.M1.5 (P_{inc} = 1000W/m^2) **[32].**

3. Results and Discussion:-

3.1.Effect of temperature and sunlight on the characteristic J_{ph} - V_{ph}

The profile of the J_{ph}-V_{ph} characteristic, for different temperatures, is shown in figure 2-a :

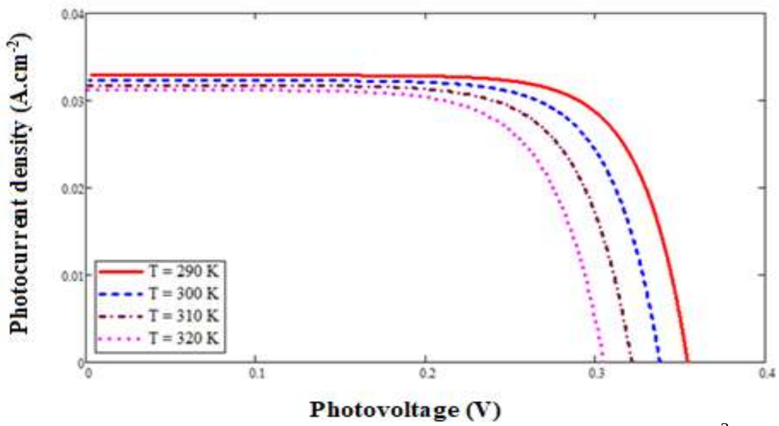

Figure 2-a:- Temperature Effect on J_{ph}-V_{ph} characteristic for E = 10^3 W.m^{-2}

In Figure 2-a, the profile of the photocurrent-photovoltage characteristic shows the same curves. For a given temperature, in a short-circuit situation, photocurrent density corresponds to its maximum value (J_{phcc}), while in an open-circuit situation, photocurrent density tends towards zero while photovoltage is equal to its maximum value (V_{phco}). As temperature increases, short-circuit photocurrent density and open-circuit photovoltage decrease in magnitude. Temperature increases the thermal agitation of photogenerated minority carriers: this decreases the diffusion rate of minority carriers, favoring their recombination in the volume and on the surface of the photocell.

In Figure 2-b, the profile of the characteristic J_{ph}-V_{ph} is represented for different values of arradiance :

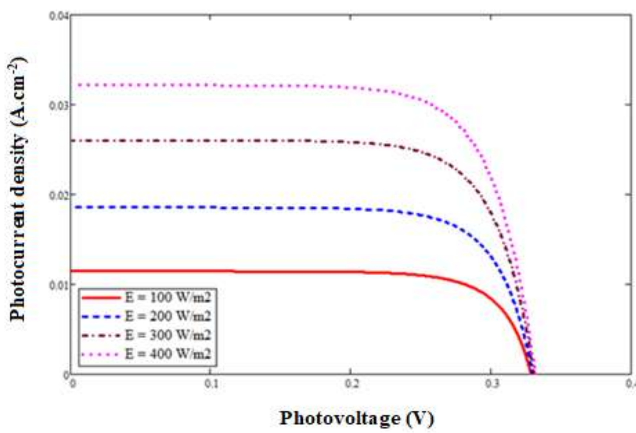

Figure 2-b:- Irradiance effect on J_{ph}-V_{ph} characteristic for Ta = 298 K

Figure 2-b shows that, at constant temperature, an increase in the level of sunlight leads to a significant increase in the photocurrent and a slight variation in the photovoltage. This is because the photocurrent generated by the solar cell is proportional to the flow of incident photons, which depends on the intensity of the level of sunlight. The short-circuit photocurrent increases sharply with light intensity, while the open-circuit photovoltage increases slightly with light intensity. The effect of irradiance on the electrical characteristics of the solar cell is much greater on the short-circuit current than on the open-circuit voltage.

3.2. Effect of temperature and irradiance on the characteristic (P- V_{ph})

The profile of electrical power as a function of photovoltage, for different temperatures, is shown in Figure 3:

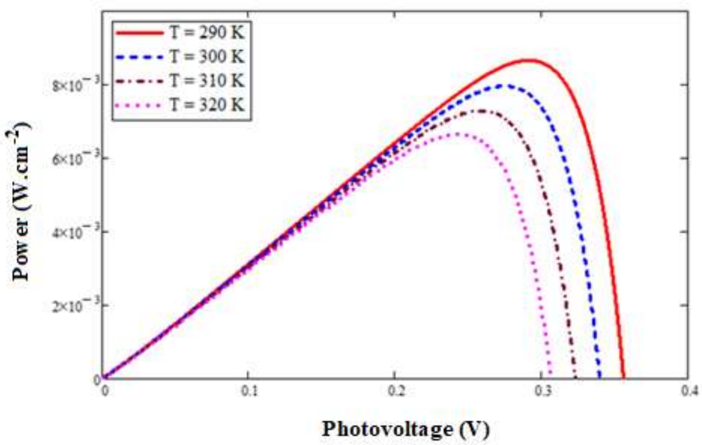

Figure 3:- Temperature effect on power-photovoltage characteristic for E = 10^3 W.m^{-2}

In Figure 3, the power versus photovoltage curves show the same trends for the different temperatures. For a given temperature, power output and photovoltage increase at the same time until they reach maximum power (P_{max}) and optimum photovoltage ($V_{ph,op}$) values respectively. Beyond maximum power and optimum photovoltage, power decreases as photovoltage approaches its open-circuit value. An increase in temperature leads to a decrease in the amplitude of the power and photovoltage. Similarly, as the temperature increases, the points of maximum power and optimum photovoltage decrease because thermal agitation can lead to losses by recombination of photogenerated minority carriers.

Figure 4 shows the profile of electrical power as a function of photovoltage for different values of solar irradiance:

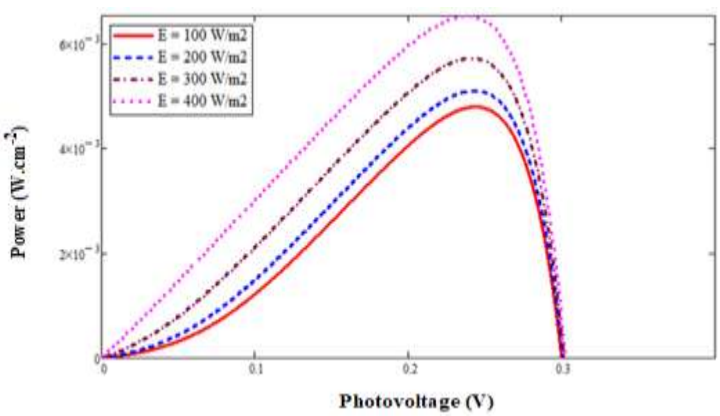

Figure 4:- Irradiance effect on power-photovoltage characteristic for Ta = 298 K

In Figure 4, for a given curve, power increases with photovoltage until reaching a maximum value corresponding to optimum photovoltage. However, beyond the maximum power and optimum photovoltage, the power decreases and the solar cell operates in an open-circuit situation. As the amount of sunlight increases, the amplitude of the power increases, including the maximum power, but the optimum photovoltage is almost insensitive to irradiation.

3.3. Effect of temperature and arradiance on energy conversion efficiency

The conversion efficiency profile as a function of the junction recombination velocity, for different temperatures, is shown in Figure 5 :

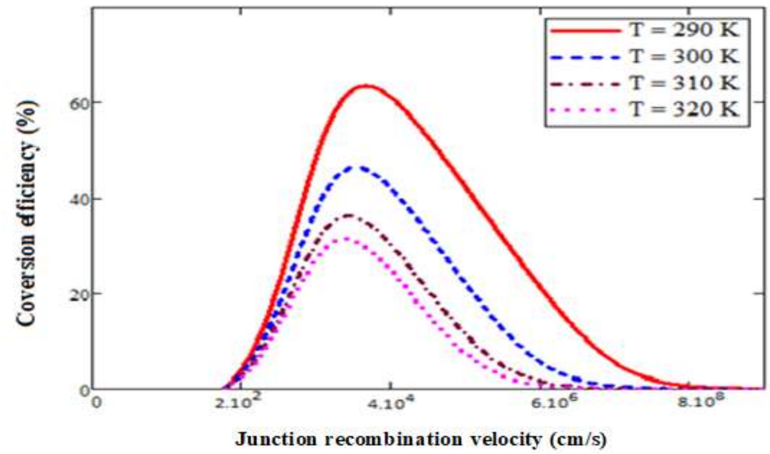

Figure 5:- Temperature effect on conversion efficiency as a function of junction recombination vilocity for E=1000W/m^2

In Figure 5, the efficiency curves as a function of the junction recombination velocity show the same trends. For a given curve and temperature, there are three zones : i) in an open circuit situation, i.e. in the range [0 $cm.s^{-1}$; 2.10^2 $cm.s^{-1}$[, where the photogenerated minority carriers, which have almost no kinetic energy, are stored in the vicinity of the junction ; which results in almost zero conversion efficiency ; ii) in a short-circuit situation, in the interval [6.10^6 $cm.s^{-1}$; 8.10^8 $cm.s^{-1}$], the photogenerated minority carriers have sufficient kinetic energy to cross the junction ; this results in zero photovoltage, as there are no more minority carriers stored in the vicinity of the junction. In this case, the conversion efficiency is almost zero ; iii) at an operating point in the interval [2.10^2 $cm.s^{-1}$; 6.10^6 $cm.s^{-1}$[, the conversion efficiency varies with the recombination vilocity at the junction. The optimum junction recombination velocity $S_{f.op}$ = 3.8. 10^3 $cm.s^{-1}$, can be used to determine the maximum conversion efficiency at a given operating point. In the interval [2.10^2 $cm.s^{-1}$; 3.8. 10^3 $cm.s^{-1}$], the efficiency increases with the junction recombination velocity. On the other hand, in the interval [3.8. 10^3 $cm.s^{-1}$; 6.10^6 $cm.s^{-1}$], the efficiency decreases as the junction recombination velocity increases since we are tending towards the short-circuit situation. As the temperature rises, the range of efficiency decreases, as does the maximum efficiency, because an increase in temperature can lead to heating of the solar cell as a result of thermalization of the photogenerated minority carriers.

Figure 6 shows the conversion efficiency profile as a function of the recombination vilocity at the junction, for different solar irradiance values:

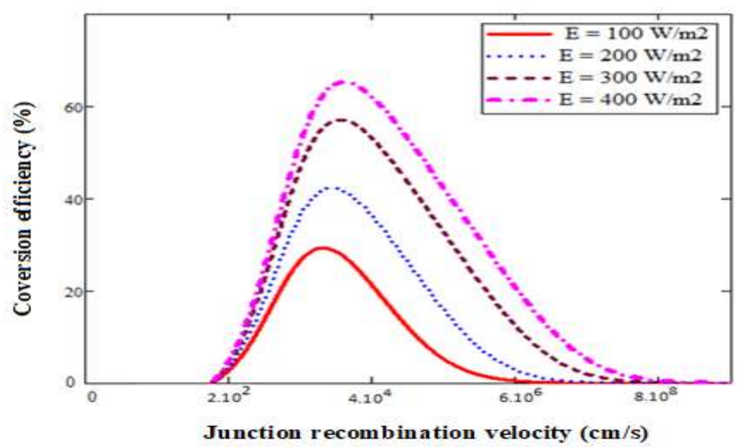

Figure 6:- Irradiance effect on conversion efficiency as a function of junction recombination vilocity for Ta = 298K

The same efficiency curves as a function of the junction recombination velocity, for different values of solar irradiance, are obtained in Figure 6. In both open-circuit and short-circuit conditions, the efficiency is almost zero. For a given curve, in the range [2.10^2 $cm.s^{-1}$; 3.8. 10^3 $cm.s^{-1}$], the conversion efficiency increases with junction recombination velocity. However, in the interval [3.8. $10^3$$cm.s^{-1}$; 6.10^6 $cm.s^{-1}$], the efficiency decreases with the junction recombination vilocity. As the amount of sunlight increases, the amplitude of the efficiency and its maximum value increase as a result of the increase in power delivered by the solar cell.

4.Conclusion:-

A theoretical study of a bifacial silicon solar cell under polychromatic illumination has been carried out. Profiles of the J_{ph}-V_{ph} characteristic and electrical power as a function of photovoltage were plotted for different values of temperature and irradiance. The conversion efficiency of the solar cell was plotted as a function of the recombination vilocity at the junction for different temperature and irradiance values. By setting the irradiance at 1000W/m^2, we found that increasing the temperature causes a decrease in the open-circuit photovoltage, maximum power and conversion efficiency of the solar cell. However, by keeping the temperature constant at 298 K, we found that increasing the solar irradiance also leads to an increase in the short-circuit photocurrent, maximum power and conversion efficiency of the solar cell. This increase in efficiency is observed for junction recombination vilocity close to Sf,op, with efficiencies ranging from 25%, 40%, 55% to over 60% for respective irradiances of 100W/m^2, 200W/m^2, 300W/m^2 and 400W/m^2. In this study, we have not taken into account the enlargement of the space charge zone, and have neglected the contribution of the emitter, the variation in the gap energy of the silicon.

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