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New relationships of dark diffusion and recombination currents as a function of temperature for a crystalline cell photovoltaic

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The effects of temperature and solar radiation on the characteristic p-n junction solar cells are investigated theoretically. The two-diode model is represented in this paper. This model requires only five parameters (the photocurrent, the shunt resistance, the series resistances, the diffusion, and the recombination dark current). The analytical resolution of continuity equations in each region of a crystalline solar cell, including the intrinsic carrier concentration, the energy band gap and the thickness of space charge layer as function of temperature, allowed us to determine the expressions of diffusion and recombination dark currents. We propose new relationships giving the expressions of these currents as a function of their reference values which are determined from both the data provided by the manufacturer and the different temperature values. To validate the accuracy of the proposed model, we compared predicted current–voltage curves with model double-diode model of Ishaque *et al*. and experimental data from various manufactures for two different cell technologies (single crystalline, poly crystalline). We determine the maximum power calculated by our proposed model to compare by double-diode model of Ishaque *et al*. for two cell type at the five conditions of generation rate. Generally, our model shows a better agreement with the experimental data than the Ishaque one. Our proposed work is useful because it provides to manufacturers an easy and comprehensive study to know the variation of the maximum power delivered by the photovoltaic module as a function of temperature and generation rate.
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I. INTRODUCTION

Photovoltaic (PV) power generation has grown significantly since 1990. The annual photovoltaic market is about 3 GW in 2010 and is predicted between 9 and 21 GW by 2020.[1] To cope with this growth, the research is oriented on two main axes, which may seem opposite: increase cell efficiency, while reducing production costs.

Modeling and optimization of a solar cell are studied by different methods in order to improve conversion efficiency and lead to a short circuit current and open circuit voltage higher by identifying the optimal parameters circuit, namely, electrical and physical parameters of the cell in the different environmental conditions.

The single-diode, also known as the three-parameter model, is the most basic one. This model has been studied by many researchers[2–4] because it only requires three parameters in the current-voltage equation characterizing its electrical equivalent circuit such as short circuit

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current, the open circuit voltage, and ideality factor of the diode. The inclusion of a series resistance this model increases the number of parameters to four. This model, also named "model-R_s,"[5–7] is famous for its simplicity which led to its common use.[5] The addition of a parallel or shunt resistance R_{sh}, called "model-R_p"[8,9] resulted in the appearance of an improved version of this model. Despite the improvement, the increase in the number of parameters in this model to five meant more calculation effort. With the validity of high power today, more specific and complex models of photovoltaic modules are suggested as the "two-diode model"[10–12] which increased the parameters number to seven such as, the saturation currents I_{s1} and I_{s2}, ideality factors n_1 et n_2, the photo-current I_{ph}, and two resistors R_s and R_{sh}. Originally, the main purpose was to find an effective and fast method to calculate the values of all the parameters of this model based on external conditions such as temperature and irradiation. Various calculation methods are proposed,[13,14] and the new additional parameters are included in the equations which reduces the difficulty and complexity of the calculation, on the one hand, and the difficulty of determining the initial values of the parameters, on the other hand. To describe the two-diode model, some researchers[15,16] consider the shunt resistance is infinite, where the number of parameters to be determined is six parameters. To reduce the number of parameters to five, more than R_{sh} is infinite, the value of series resistance is equal to zero.[15,16]

This paper introduces a simulation method used to study the effect of temperature and generation rate on the P-V and I-V characteristics. In the first section, we present a theoretical study in order to determine the photocurrent, the diffusion and recombination dark currents by solving continuity equations in each region of an elementary solar cell. From the expressions of such currents and using the necessary approximations, we propose, in second section, a new relationships giving photocurrent, diffusion and recombination dark currents as a function of their reference values, the solar radiation and the different temperature values. We determine also the current-voltage characteristic of the considered cell based on the two diode electrical model for single and poly crystalline cell. In Sec. III, we validate our proposed relationships by comparing our results with those obtained by Ishaque model[17] and by the experimental data provided by manufacturer datasheets for two PV modules monocrystalline SQ150-PC PV and polycrystalline KC200-GT PV. Finally, we drew our conclusion in Sec. IV.

II. THEORETICAL STUDY

A. Physical model of the individual cell

In this paper, we consider a one-dimensional model to determine the dark currents in an n^+-p silicon solar cell, as shown in Figure 1. This model is extended in order to include the effects of temperature on the excess carrier lifetime, the diffusion constant, the diffusion length, the intrinsic carrier concentration, and the energy band gap. We consider the case of a uniform doping of n^+ and p regions of the cell.

B. Equivalent electrical model of a photovoltaic module

A solar cell is represented by an equivalent circuit composed of a current source, a double-parallel diode, a series resistance, and a shunt resistance, as shown in Figure 2. According to Kirchhoff's current, our proposed I-V characteristic equation is given by

$$I = I_{ph} - I_{d1} - I_{d2} - I_p, \tag{1}$$

where I_{ph} is the generated photo-current, I_{d1} is the dark diffusion current in n^+, and p region of the cell, I_{d2} is the dark recombination current in space charge layer, and I_p is the shunt current due to shunt resistor R_{sh} branch. Substituting relevant expression for I_{d1}, I_{d2}, and I_p, we get

$$I = I_{ph} - I_{sd} \times \left(\exp\left(\frac{V + R_s I}{n_1 N_s V_T}\right) - 1\right) - I_{sr} \times \left(\exp\left(\frac{V + R_s I}{n_2 N_s V_T}\right) - 1\right) - \frac{V + R_s I}{R_{sh}}, \tag{2}$$

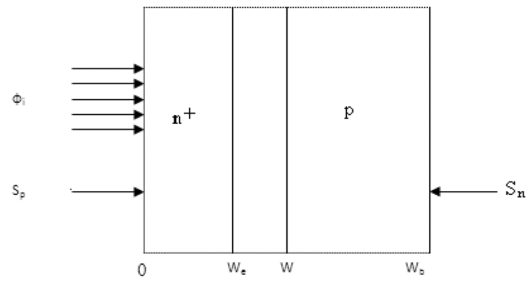

FIG. 1. Typical structure of an n^+-p solar cell.

where

$$V_T = \frac{kT}{q}, \tag{3}$$

where q is the electronic charge ($q = 1.602 \times 10^{-19}$ C), k is the Boltzmann constant ($k = 1.3806503 \times 10^{-23}$ J/K), T is the temperature of the cell, I_{sd} and I_{sr} correspond, respectively, to diffusion and recombination saturation dark current related to the carrier transported across the junction. The saturation current depends on the intrinsic properties of semiconductors, diffusion coefficient for the electron, lifetime and intrinsic carrier's densities.[9] The ideality factor of the diode is used as an adjustment parameter to account for a deviation of the ideal model ($n_1 = 1$). It is value depends on the current transport mechanism.[18] A unit value describes ideal electron transport across the PN junction while a value of 2 corresponds to the superposition of diffusion and recombination mechanisms. Value higher than two can be obtained in case of multi-recombination.[18]

Like the aforementioned models the ideality factors of the two diodes is assumed to be independent of temperature and irradiation in both operating conditions and Standard Rating Conditions (SRC)

$$n_1 = 1 \quad \text{and} \quad n_2 = 2. \tag{4}$$

The parallel leakage resistance or shunt resistance R_{sh} and series resistance are the last two unknown parameters in the solar cell model. Based on the experimental data from National Institute of Standards and Technology (NIST),[19] we note that the slope of the current–voltage characteristic close to short-circuit current decreases with the generation rate, De Soto *et al.*[19] used the following model relating the shunt resistance to irradiation at operating condition and SRC:

$$R_{sh} = R_{shref} \frac{G}{G_{ref}}. \tag{5}$$

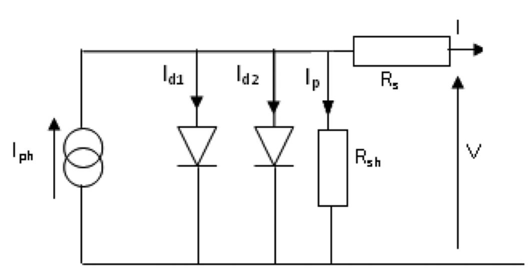

FIG. 2. Equivalent circuit of PV module.

As for the series resistance, several studies based on one or two diodes considered as temperature and irradiation independent at both operating conditions such as the five parameter method outlined by De Soto *et al.*[19] and Tian model.[20] However, we know that R_s depends on the temperature. We then propose the following expression:

$$R_s = \frac{T_{ref}}{T} R_{sref}. \tag{6}$$

C. Proposed photovoltaic module model

In the dark, the continuity equations in p and n^+ regions of the cell are, respectively, given by

$$\frac{\partial^2 \Delta n}{\partial z^2} - \frac{\Delta n}{L_n^2} = 0, \tag{7}$$

$$\frac{\partial^2 \Delta p}{\partial z^2} - \frac{\Delta p}{{L_p}^2} = 0. \tag{8}$$

In order to solve these equations, we consider the following boundary conditions:

$$\Delta n(z = W_e + W) = \frac{{n_i}^2}{N_a}\left(\exp\left(\frac{V_j}{V_t}\right) - 1\right), \tag{9}$$

$$D_n \frac{\partial \Delta n}{\partial z}\bigg|_{z=H} = -S_n \Delta n(z = H), \tag{10}$$

$$\Delta p(z = W_e) = \frac{{n_i}^2}{N_d}\left(\exp\left(\frac{V_j}{V_t}\right) - 1\right), \tag{11}$$

$$D_p \frac{\partial \Delta p}{\partial z}\bigg|_{z=0} = S_p \Delta p(z = 0). \tag{12}$$

Solving the previous system of equations, we can determine the saturation diffusion dark currents in the two regions of the cell

$$I_{n0} = -qD_n \frac{d\Delta n}{dz}\bigg|_{z=W+We} = \frac{-qD_n n_i^2}{L_n N_a} \frac{\left(\frac{S_n L_n}{D_n}\cosh(W_b/L_n) + \sinh(W_b/L_n)\right)}{\left(\frac{S_n L_n}{D_n}\sinh(W_b/L_n) + \cosh(W_b/L_n)\right)}, \tag{13}$$

$$I_{p0} = qD_p \frac{d\Delta p}{dz}\bigg|_{z=We} = \frac{qD_p n_i^2}{L_p N_d} \frac{\left(\frac{S_p L_p}{D_p}\cosh(W_e/L_p) + \sinh(W_e/L_p)\right)}{\left(\frac{S_p L_p}{D_p}\sinh(W_e/L_p) + \cosh(W_e/L_p)\right)}, \tag{14}$$

where n_i is the intrinsic carrier concentration of silicon solar cell. It is instrumental in determining the dark saturation current and hence the open circuit voltage of a solar cell. Its variation with temperature is given by[7]

$$n_i = 3.87 \times 10^{16} \times T^{\frac{3}{2}} \times \exp\left(-\frac{qE_g}{2KT}\right). \tag{15}$$

E_g is the band gap energy. De Soto *et al.*[19] define the value for E_g for silicon to be

$$E_g = E_{gref} \times (1 - 0.0002677 \times (T - T_{ref})). \tag{16}$$

The saturation diffusion dark current is given by

$$I_{sd} = I_{n0} + I_{p0}. \tag{17}$$

The recombination dark current in the space charge layer is written by[22]

$$J_{r0} = J_{sr}\left[\exp\left(\frac{V_j}{2V_T}\right) - 1\right], \tag{18}$$

where J_{sr} is the saturation recombination current in the space charge layer given by[22]

$$J_{sr} = \frac{qWn_i}{\sqrt{\tau_n \tau_p}}, \tag{19}$$

where W is the width of the space charge region defined by

$$W = \sqrt{\frac{2\,\varepsilon\,\mathrm{K\,T}\ln\left(\frac{\mathrm{N_a\,N_d}}{n_i{}^2}\right)}{q^2 N_a}}. \tag{20}$$

The I-V characteristic of the considered solar cell shown in Fig. 2 depends on the internal characteristics of the cell (series and shunt resistance) and on external influences such as irradiation level and temperature. It is difficult to determine the light generated current (I_{ph}) of the elementary cell without the influence of the series and parallel resistance. Datasheets inform only the nominal short circuit current (I_{scn}), which the maximum current available at the terminals of the practical cell. The assumption $I_{sc} = I_{ph}$ is generally used in the modeling of PV device because, in practical devices, the series resistance is low and the parallel resistance is high.[9] The photocurrent I_{ph} depends on the solar irradiance G and the cell temperature T. The following expression is used to calculate the photocurrent as a function of these parameters proposed by many researchers.[8,20,21] Thus, we propose a new empirical relationship given by

$$I_{ph} = \left(\frac{G}{G_{ref}}\right) I_{phref} + \mu_{sc} \times (T - T_{ref}), \tag{21}$$

where I_{phref} is the light generated current at SRC (25 °C and 1000 W/m^2), μ_{sc} is a short circuit current temperature coefficient (A/K), T and T_{ref} being the actual and reference temperature, respectively (in Kelvin g), G is the irradiation on the device surface, and G_{ref} is the reference irradiation at SRC. Furthermore, many researchers have proposed the expression of saturation current as a function of the temperature cell for the single-diode[6,19] or for double-diode.[17,23] In this work, we express the diffusion and recombination dark currents as a function of their reference values which are determined from the data provided by the manufacturer and versus the temperature. We determined these expressions by substituting n_i, E_g, and W in Eqs. (13) and (14). Using the necessary approximations, the established relations are given by

$$I_{sd} = I_{sdref} \times \left(\frac{T}{T_{ref}}\right)^{\frac{7}{2}} \times \exp\left(\left(\frac{-\mathrm{q}}{\mathrm{K}}\right) \times \left(\frac{\mathrm{E_g}}{T} - \frac{\mathrm{E_{gref}}}{T_{ref}}\right)\right), \tag{22}$$

$$I_{sr} = I_{srref} \times \left(\frac{T}{T_{ref}}\right)^{2} \times \exp\left(\left(\frac{-\mathrm{q}}{2\mathrm{K}}\right) \times \left(\frac{\mathrm{E_g}}{T} - \frac{\mathrm{E_{gref}}}{T_{ref}}\right)\right), \tag{23}$$

where I_{sdref} and I_{srref} are the diffusion and recombination dark currents at reference conditions ($T_{ref} = 298$ K and $G_{ref} = 1000$ W m^{-2}).

D. The reference parameters

An explicit set of equations is written based on Eq. (2). In this equation, there are five unknown parameters: I_{ph},I_{sd}, I_{sr}, R_{sh}, and R_s. the resolution of these five parameters using the current-voltage relationship of our proposed two-diodes model and the traditional method of five parameter. In fact, the method is a system of five equations with five unknowns. Equation (2) is used to write down expressions for currents and voltages at each key point as it is shown in Fig. 3. They correspond to the following operational point conditions: the short-circuit point where $V = 0$ and $I = I_{sc}$ (Eq. (1)), the open circuit where $V = V_{oc}$, and $I = 0$ (Eq. (2)) and the maximum power point where $V = V_{mp}$ and $I = I_{mp}$ (Eq. (3)). In addition, we choose two other points corresponding to $I2 = I_{mp}/2$ and $V1 = V_{mp}/2$, in order to reduces the error on the reference parameters.

The first equation is derived from short-circuit conditions at SRC, where $I = I_{scref}$ and $V = 0$. Thus (2) becomes

$$\begin{aligned} I_{scref} = I_{phref} - I_{sdref} \times \left(\exp\left(\frac{R_{sref} I_{scref}}{NsV_T}\right) - 1\right) \\ - I_{srref} \times \left(\exp\left(\frac{R_{sref} I_{scref}}{2NsV_T}\right) - 1\right) - \frac{R_{sref} I_{scref}}{R_{shref}}. \end{aligned} \tag{24}$$

The second equation occurs at open circuit conditions at SRC, where $V = V_{ocref}$ and $I = 0$. Thus (2) becomes

$$0 = I_{phref} - I_{sdref} \times \left(\exp\left(\frac{V_{ocref}}{NsV_T}\right) - 1\right) - I_{srref} \times \left(\exp\left(\frac{V_{ocref}}{2NsV_T}\right) - 1\right) - \frac{V_{ocref}}{R_{shref}}. \tag{25}$$

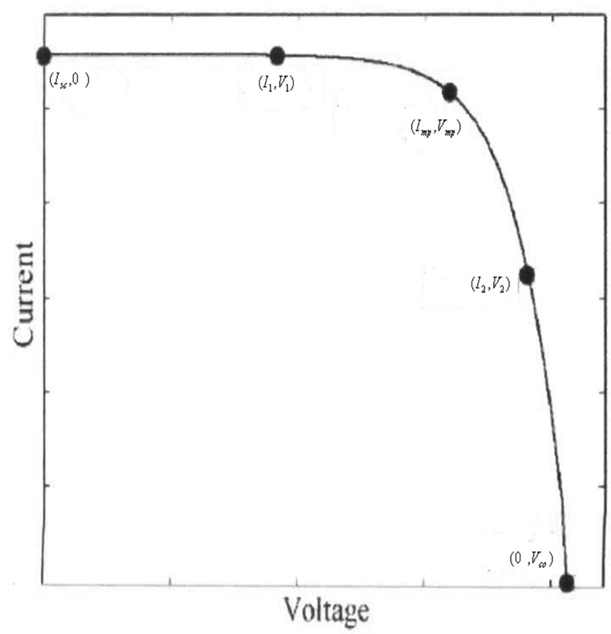

FIG. 3. The five points of the IV characteristic used in our proposed model.

The measured current-voltage pair at the maximum power point under SRC can be substituted into (2) to obtain the third equation where $I = I_{mpref}$ and $V = V_{mpref}$,

$$I_{mpref} = I_{phref} - I_{sdref} \times \left(\exp\left(\frac{V_{mpref} + R_{sref} I_{mpred}}{V_T}\right) - 1\right) - I_{srref} \times \left(\exp\left(\frac{V_{mpref} + R_{sref} I_{mpref}}{2V_T}\right) - 1\right) - \frac{V_{mpref} + R_{sref} I_{mpref}}{R_{shref}}. \tag{26}$$

At current equal I_1 and voltage equal V_1,

$$I_1 = I_{phref} - I_{sdref} \times \left(\exp\left(\frac{V_1 + R_{sref} I_1}{V_T}\right) - 1\right) - I_{srref} \times \left(\exp\left(\frac{V_1 + R_{sref} I_1}{2V_T}\right) - 1\right) - \frac{V_1 + R_{sref} I_1}{R_{shref}}. \tag{27}$$

At current equal I_2 and voltage equal V_2,

$$I_2 = Iphref - I_{sdref} \times \left(\exp\left(\frac{V_2 + R_{sref} I_2}{V_T}\right) - 1\right) - I_{sr} \times \left(\exp\left(\frac{V_2 + R_{sref} I_2}{2V_T}\right) - 1\right) - \frac{V_2 + R_{sref} I_2}{R_{shref}}. \tag{28}$$

Thus, Eqs. (24)–(28) can be solved simultaneously with the five points at reference conditions (Table I). The resolution is done using the nonlinear equation solver fsolve in Maple.

III. VALIDATION OF OUR PROPOSED MODEL

To predict the conversion efficiency of the PV module, a good knowledge of the effect of temperature and generation rate on the IV characteristic is essential for photovoltaic installations. By substituting the different currents I_{ph}, I_{sd}, and I_{sr} with their expressions in the IV characteristic equation (2), we obtain a transcendental equation giving the current and voltage of the PV module as a function of temperature and generation rate. The two-diode model described in this paper is validated by a double-diodes proposed by Ishaque *et al.*[17] and the measured parameters of selected PV modules for two different cell technologies. The experimental (V,I) data are extracted from the manufactures datasheets.

Two modules are used for verification for two different cell technologies (single crystalline and poly crystalline) SQ150PC mono-crystalline PV module and KC200GT poly-crystalline. The specifications of the modules are listed in Table I.

Based on the specifications of the modules, the references parameters calculated by our proposed model and Ishaque model are illustrated in Tables II and III, respectively.

TABLE I. Specifications of two modules used in the experiment.

Parameters	Mono-crystalline: Shell SQ150-PC	Polycrystalline: Kyocera KC200GT
I_{scref} (A)	4.8	8.2
V_{ocref} (V)	43.4	32.9
I_{mpef} (A)	4.4	7.61
V_{mpref} (V)	34	26.3
μ_{sc} (mA/°C)	1.4	3.18
N_s	72	54

TABLE II. Parameters of our proposed model.

Parameters	Monocrystalline: Shell SQ150-PC	Polycrystalline: Kyocera KG200GT
I_{scref} (A)	4.8	8.2
V_{ocref} (V)	43.4	32.9
I_{mpref} (A)	4.4	7.61
V_{mpref} (V)	34	26.3
I_{srref} (A)	1.11×10^{-5}	3.33×10^{-5}
I_{sdref} (A)	2.24×10^{-10}	1.79×10^{-10}
I_{phref} (A)	4.8	8.2
R_{shref} (Ω)	1277.7	702.9
R_{sref} (Ω)	0.72	O.O6

Table II displays the references parameters for our proposed two-diode model, although the model has more variables, the actual number of parameters is five (I_{ph}, I_{sd}, I_{sr}, R_s, and R_{sh}).

Table III shows the parameters used for the "Ishaque model." The authors consider that reverse saturation currents I_{01} and I_{02} are set to be equal. For the series and shunt resistance are calculated by the iteration method.

For SQ150PC mono-crystalline module, Fig. 4 presents the I-V curves at a fixed cell temperature of 25 °C and different irradiation levels. A good agreement between this curves calculated by our proposed two diodes model and the Ishaque model with experimental data.

In addition, Fig. 5 illustrates the P-V curves for SQ150-PC PV module for different irradiation levels at a constant cell temperature. The maximum power point for each condition is given on each curve and the numerical results are published in Table IV. Comparison between the calculated maximum power point values and those published by the manufacturer reveals a good agreement.

Figs. 6 and 7 present the I-V and P-V curves produced from our proposed two-diode model (cross), Ishaque model (diamond) and experimental data (circle) for SQ150PC module at the same irradiation level of 1000 W/m^2, for different cell temperatures: 20 °C; 40 °C; and 60 °C. The results of the proposed model and those of the experimental data are closed mainly for the low values of temperature.

The maximum power values calculated by our proposed two-diode model to Ishaque-model and SQ150PC mono-crystalline module, at the 3 operating conditions temperatures are shown in Table V. We give a comparison between these values obtained by our proposed model and those calculated by Ishaque-model. Therefore, these two models give close values through this comparison.

TABLE III. Ishaque model parameters.

Parameters	Monocrystalline: Shell SQ150-PC	Polycrystalline: Kyocera KG200GT
I_{scref} (A)	4.8	8.2
V_{ocref} (V)	43.4	32.9
I_{mpef} (A)	4.4	7.61
V_{mpref} (V)	34	26.3
$I_{01} = I_{02}$ (A)	3.10×10^{-10}	4.21×10^{-10}
I_{phref}	4.8	8.21
R_{sh}	275	160.5
R_s	0.9	0.32

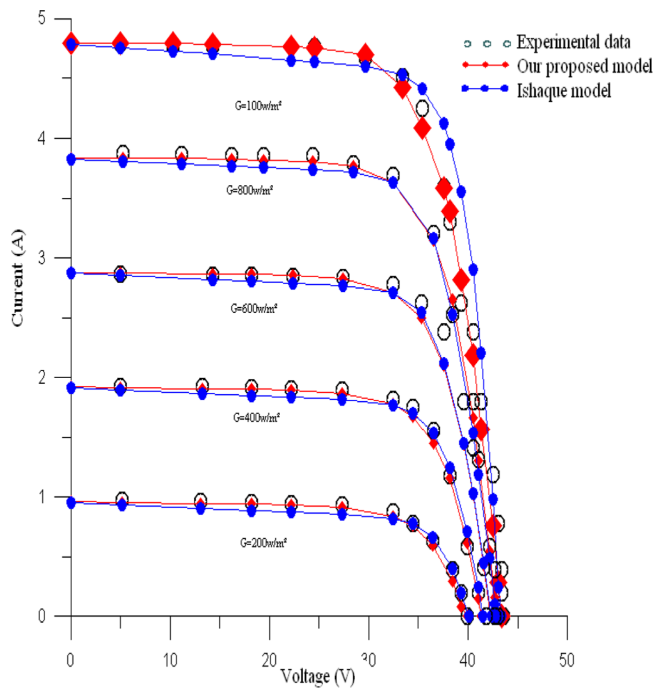

FIG. 4. I-V curves of Ishaque model and our proposed model of the SQ150-PC PV module for several irradiation levels at 25 °C.

Figure 8 shows the relative error at P_{mp} and V_{oc} for SQ150-PC PV module for different irradiation levels, on the one hand, and for different temperatures, on the other hand. As function of solar radiation, the relative error, of the maximum power does not exceed 3.5% in our proposed model while it exceeds 5% for Ishaque model. Regarding the V_{oc} value, relative error reaches 1.17% for our model and it is less than 1% for Ishaque model.

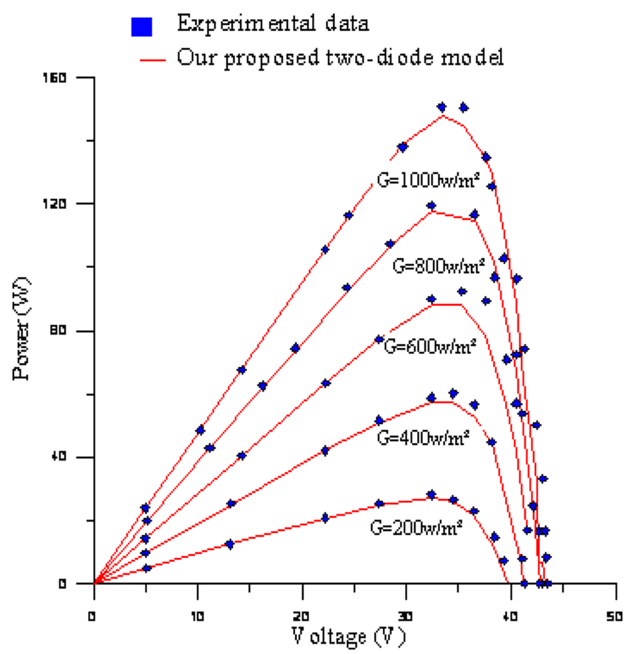

FIG. 5. P-V Curves of our proposed model of the SQ150-PC PV module for several irradiation levels at 25 °C.

TABLE IV. Predicted maximum power values and published results for SQ150-PC PV at a cell temperatures of 25 °C.

Solar (W/m^2)	SQ150-PC datasheet	Maximum power (W/m^2)	
		Our proposed model	Ishaque model
1000	150.81	149.57	149.60
800	119.67	119.69	120.21
600	92.49	89.24	89.80
400	60.17	58.47	58.54
200	28.34	27.86	26.83

As function of different temperatures at P_{mp}, the relative error is reaches 3.4% for our proposed model and it is reaches 3.73% for Ishaque model. It is less than 3% for our model and 2% for Ishaque model at V_{oc}.

Figure 9 presents the I-V curves obtained from our proposed model, Ishaque model and experimental data for KC200GT poly-crystalline module as a function of different level of irradiation and versus value of temperature. The comparison between these models shows an excellent agreement with experimental data.

Numerical values of maximum power calculated by our proposed model, Ishaque model and those published by the KC200GT PV module are shown in Tables VI and VII. Comparison between these values gives a good agreement mainly as a function of different values of temperatures. To prove this result, the relative error at P_{mp}, V_{oc} for the KC200GT PV module is less than 0.7% for all values of temperature and less than 1% at short-circuit current I_{sc} for our proposed model and Ishaque model as shown in Fig. 10.

This figure shows the relative error for KC200GT PV module as a function of different level irradiations. Our proposed model gives a better result than Ishaque model because the relative error is less than 8% at P_{mp}, 3.5% at I_{sc} and 1.8% at V_{oc} while for Ishaque model it is more than 12% at P_{mp}, it reaches 3.5% at I_{sc} and it is less than 1.8% at V_{oc}.

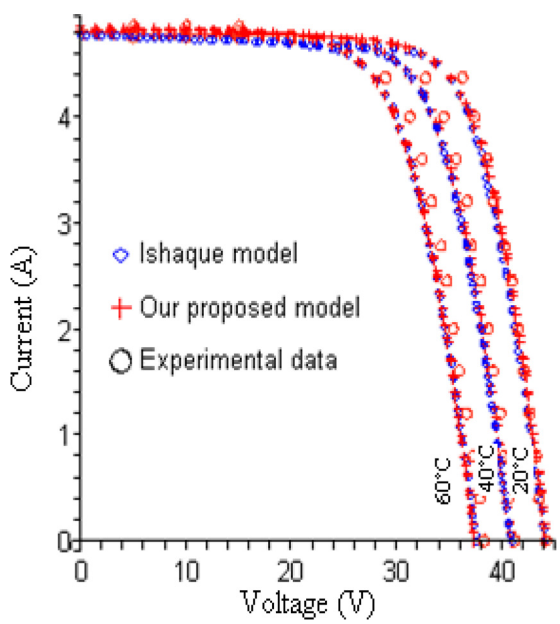

FIG. 6. I-V curves of Ishaque model and proposed two-model of the SQ150-PC PV module for several temperatures at 1000 W/m^2.

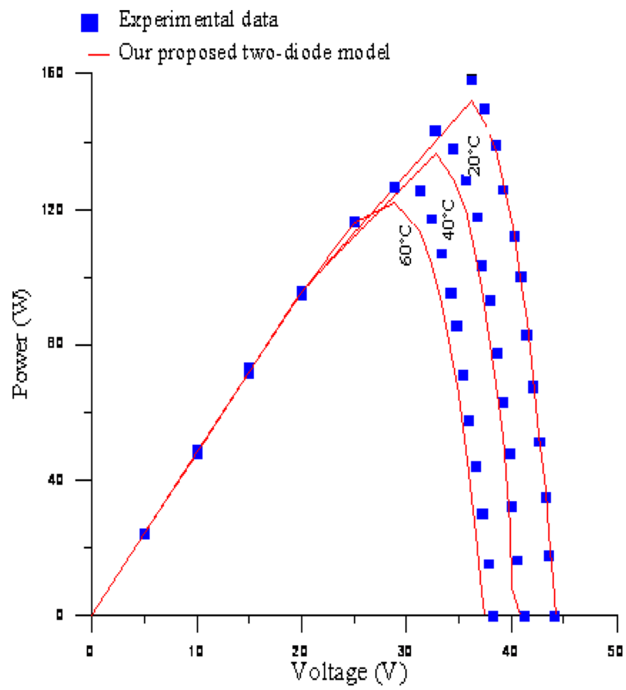

FIG. 7. P-V Curves of our proposed model of the SQ150-PC PV module for several temperatures at 1000 W/m^2.

IV. CONCLUSION

In this paper, a two-diode model was proposed. We developed an analytical resolution of the continuity equations in each region of considered cell, to establish new expressions of diffusion and recombination dark currents as a function of temperature and the values of these currents at the reference conditions. We have determined the I-V characteristic, P-V curves of the considered photovoltaic module, the maximal power, the open-circuit voltage V_{oc}, and the short-circuit current I_{sc} for five illumination conditions at 25 °C, on the one hand, and, on other hand, for three different values of temperatures at 1000 W/m^2,for two different technologies mono-crystalline and poly-crystalline. The comparative study proves that the results of our model are in good agreement with the experimental data provided by two PV modules KC200GT and SQ150 PC. Indeed, the relative error on the maximum power delivered by the PV module for single and polycrystalline cell is less than 4% for different illumination conditions. It is less than 0.7% for different temperatures for KC200GT pv module and less than 3.5% for SQ150 PC PV. As regards V_{co}, it is less than 1.8% for different irradiation solar for KC200GT pv module and it is, less than 1.2% for SQ150 PC PV. Compared to the Ishaque model, our model is easier and gives closer results to experimental data.

TABLE V. Predicted maximum power point values and published results for SQ150-PC PV for different cell temperatures at 1000 W/m^2.

Temperature (°C)	SQ150-PC datasheet	Maximum power (W/m^2)	
		Our proposed model	Ishaque model
20	158.65	153.74	153.49
40	143.30	138.43	137.95
60	126.67	123.51	122.51

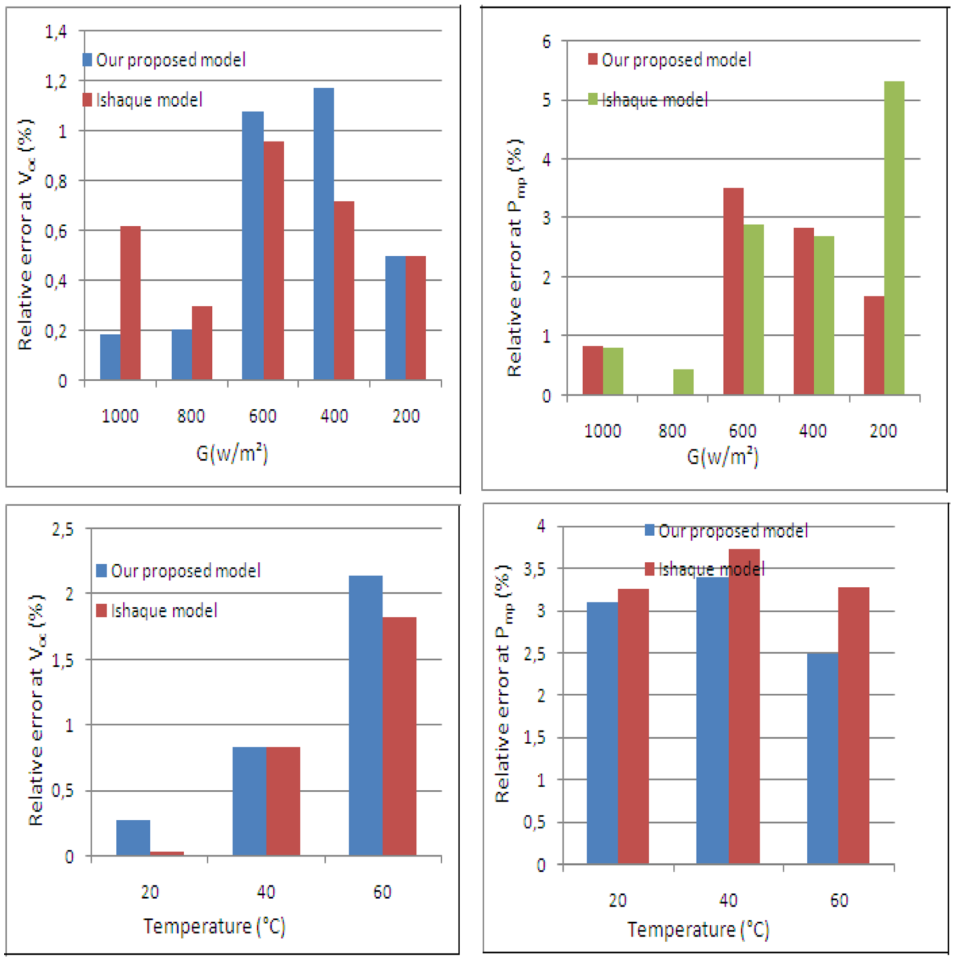

FIG. 8. Relative error for V_{oc} and P_{mp}, for Ishaque model and our proposed model for SQ150-PC PV module.

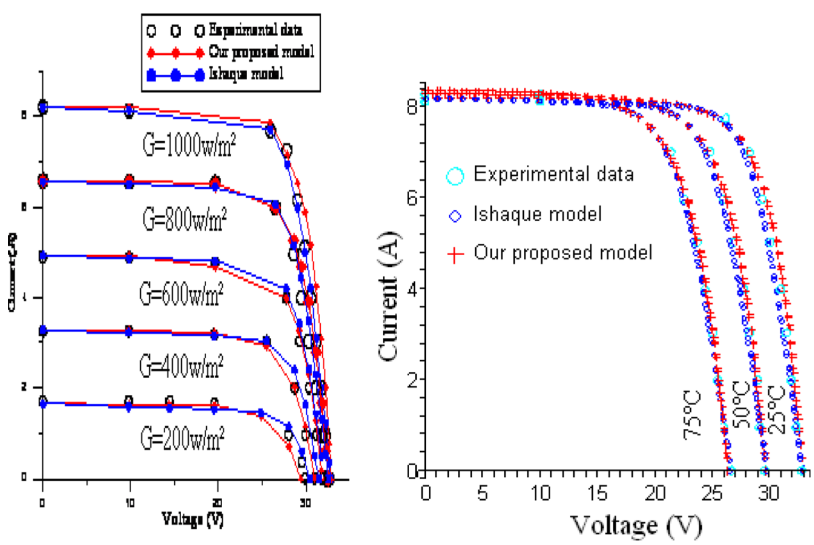

FIG. 9. I-V curves of Ishaque model and proposed two-model of the KC200GT PV module for several irradiation levels at 25 °C and for different temperature at 1000 W/m^2.

TABLE VI. Predicted maximum power values and published results for KC200GT PV for different generation rate at 25 °C.

Solar (W/m^2)	KC200GT datasheet	Maximum power (W/m^2)	
		Our proposed model	Ishaque model
1000	201.52	200.82	200.19
800	158.64	157.82	160.40
600	110.70	115.46	119.64
400	77.22	74.09	78.13
200	32.34	34.45	36.33

TABLE VII. Predicted maximum power values and published results for KC200GT PV for different cell temperatures at 1000 W/m^2.

Temperature (°C)	KC200GT datasheet	Maximum power (W/m^2)	
		Our proposed model	Ishaque model
25	201.01	200.82	200.19
50	173.85	174.97	174.48
75	149.92	149.23	149.01

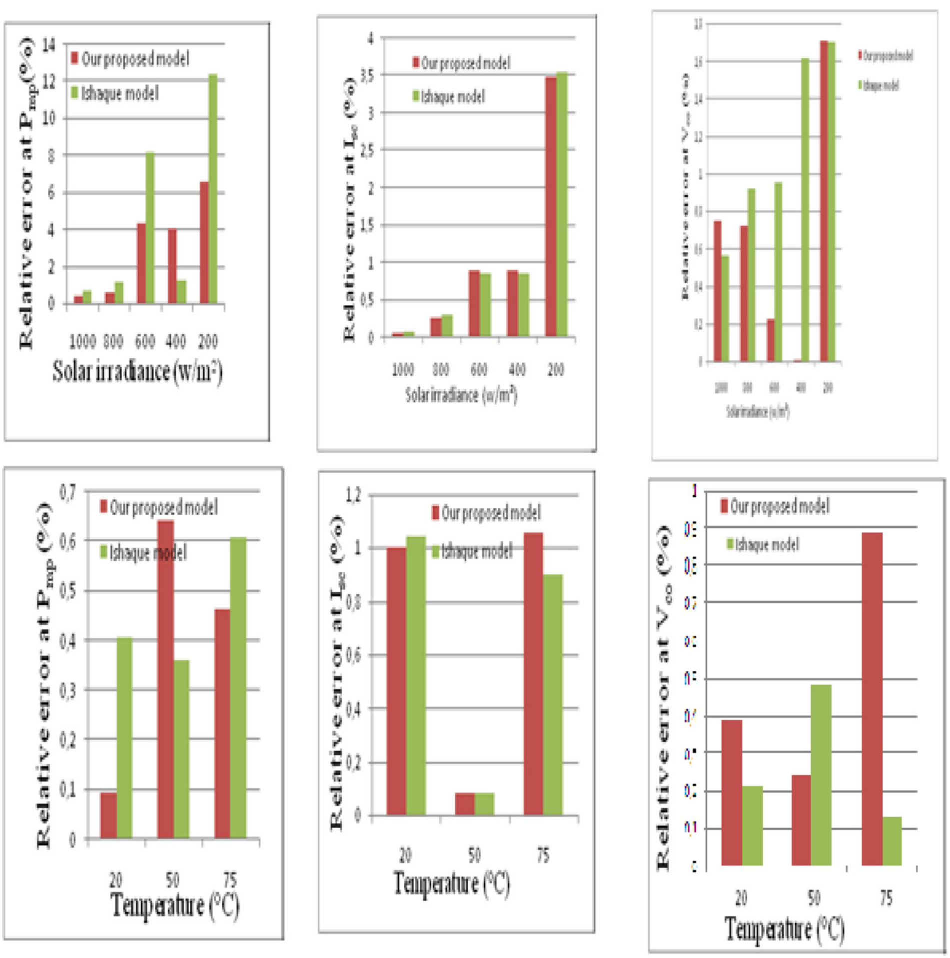

FIG. 10. Relative error for P_{mp}, I_{sc}, and V_{co} for Ishaque model and our proposed model for KC200GT PV module.

NOMENCLATURE

D_n	diffusion constant of n^+ region of the cell
D_p	diffusion constant of P region of the cell
E_g	energy band gap (eV)
E_{gref}	reference energy band gap (1.121 eV from silicon)
G	generation rate (W/m^2)
G_{ref}	reference generation rate (1000 W/m^2)
H	total thickness of the cell
I_{ph}	photocurrent (A)
I_{phref}	photocurrent at SRC (A)
I_{sd}	diffusion dark current (A)
I_{sdref}	diffusion dark current at SRC (A)
I_{sr}	recombination dark current (A)
I_{srref}	recombination dark current at SRC (A)
K	Boltzmann constant (1.38066×10^{-23} J/K)
L_n	diffusion length of n^+ region of the cell
L_p	diffusion length of P region of the cell
n_i	intrinsic level density of silicon
N_a	doping density in P region of the cell
N_d	doping density in n^+ region of the cell
N_s	number of cells in series (72)
NOCT	nominal operating cell temperature (316.85 K)
n_1	ideality factor of diode one
n_2	ideality factor of diode two
q	electron charge (1.60218×10^{-19} C)
R_s	serie resistance (Ω)
R_{sch}	shunt resistance (Ω)
R_{shref}	shunt resistance at SRC (Ω)
R_{sref}	serie resistance at SRC (Ω)
S	effective area of the solar cell (m^2)
S_n	recombination velocity at the rear contact of the cell
S_p	recombination velocity at the frontal surface of the cell
T	temperature of PV module (K)
T_{ref}	reference temperature of PV module (298 K)
V_T	thermal voltage constant
W	thickness of space-charge layer
W_b	thickness of P region
W_e	thickness of n^+ region
μ_{sc}	temperature coefficient for short circuit current (A/K)
ξ	permittivity of silicon
τ_n	lifetime of n^+ region of the cell
τ_p	lifetime of P region of the cell

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