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SILICON SOLAR CELL UNDER ELECTROMAGNETIC WAVES IN STEADY STATE: ELECTRICAL PARAMETERS DETERMINATION USING THE I-V AND P-V CHARACTERISTICS

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Abstract. The principal effect that limits solar cell efficiency is the recombination of the photo generated charge carriers before they participate to energy current. These recombination are characterized by electronic (recombination) and electric interdependent parameters that influence the solar cell quality and conversion efficiency.

In previous works, we have studied the influence of telecommunication (AM radio antenna or a FM radio antenna) source's power of radiation on a silicon solar cell illuminated by a white light in steady state. We analyzed the effects of electromagnetic field on photo-current density, back surface recombination velocity, intrinsic junction recombination velocity, photo-voltage, maximum electric power and conversion efficiency by making vary the antenna power of radiation.

This article presents a one dimensional study in modeling of the influence of telecommunication source's power of radiation on silicon solar cell electric parameters (R_s, R_{sh}, J_p, V_p, P_p, FF, R_{pp}) using the I-V and P-V .characteristics. After the resolution of magneto transport equations in the base of the silicon solar cell under multispectral illumination, photo-current density and photo voltage are determined and the I-V and P-V curves are plotted. Two equivalent electric circuits of the solar cell in open and short circuit are proposed allowing us to deduce the shunt and series resistance. Using the I-V and P-V curves we determine the peak photo-current density, the peak photo voltage, the peak electric power, the fill factor and the load resistance at to the peak power point.

Keywords: Solar cell; 2- Electromagnetic waves; 3- Shunt resistance; 4- Series resistance; 5- Peak power , 6- Fill factor, 7- Load resistance.

1. Introduction

Works achieved by researchers put in evidence the effect of a magnetic field and an electric field on silicon solar cell [1-6]. It was evident from these studies that magnetic field values lower than 0,1 mT don't have any effect on silicon solar cell, on the other hand the magnetic field values superior to 0,1 mT have an ominous effect on silicon solar cell recombination parameters (carrier's diffusion length and lifetime). As for the electric field, according to its orientation it can have beneficial or ominous effects on silicon solar cell recombination parameters. The magnetic field can have various origins: terrestrial magnetic field, magnetic component of the electromagnetic wave coming from radio transmitters, television transmitters and telecommunication transmitters, magnetic field coming from the electric energy corporation distributor stations of transformers … Also, we were interested in the electromagnetic wave influence coming from radio transmitters and other telecommunication sources on silicon solar cell because whatever is their installation place, the silicon solar cell of photovoltaic systems by their principle of working (movement of electrons) can be influenced as well by the magnetic field and the electric field of the electromagnetic waves of the different telecommunication sources that exist close to their installation place. It is in this optics that first we studied the effects of electromagnetic waves on silicon solar cell recombination parameters by changing the distance between the 2 MW power of radiation AM antenna and the solar cell [7]. Secondly, we studied the influence of telecommunication (AM radio antenna or a FM radio antenna) source's power of radiation on a silicon solar cell illuminated by a white light in steady state. We analyzed the effects of electromagnetic field on photo-current density, back surface recombination velocity, intrinsic junction recombination velocity, photo-voltage, maximum electric power and conversion efficiency by making vary the antenna power of radiation [8]. In this present article we study the influence of telecommunication source's power of radiation on silicon solar cell electric parameters (R_s, R_{sh}, J_p, V_p, P_p, FF, R_{pp}) using the I-V and P-V .characteristics. This telecommunication antenna can be either a radio antenna functioning in frequency modulation FM or a radio antenna functioning in amplitude modulation AM. This radio station antenna is the source of production of progressive monochromatic plane electromagnetic waves linearly polarized whose electric field intensity measured at a distance r from the source is dependant on the power radiated by the source and the distance r. Therefore we will study the influence of electromagnetic field on shunt and series resistance, peak photo-current density, peak photo voltage, peak electric power, fill factor and peak power point's load resistance by varying the antenna power of radiation. We will relate the peak power point's load resistance to the junction recombination velocity calculated in the previous article.

2. Theory

2.1. Excess minority carriers' density

We consider a polycrystalline back surface field silicon solar cell with n^+-p-p^+ structure [9]. Since the base has a greater contribution to photo conversion than the emitter [10-12], the one-dimensional analysis will be developed only on this region using the Quasi-Neutral Base assumption. Moreover we are located in the quasi neutral basis hypothesis (Q.N.B) while neglecting the crystalline field that exists within the solar cell.

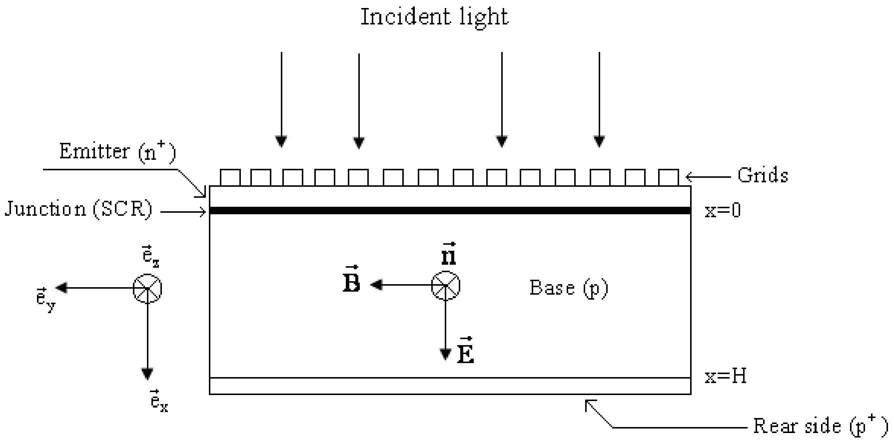

Figure 1: Silicon solar cell illuminated by white light and under electromagnetic waves influence

We suppose that the solar cell represented on **figure 1** above is submitted to the action of a progressive monochromatic plane wave linearly polarized, polarized in Ox direction and propagating in the sense of the increasing z.

$\vec{n}$ is the unit vector of the electromagnetic wave direction of propagation as the trihedral $(\vec{E},\vec{B},\vec{n})$ is direct.

The complex expression of the electric field is:

$$\vec{E} = E_0 \cdot \vec{e}_x \cdot \exp j(\omega \cdot t - k \cdot z) \tag{1.a}$$

either in real notation

$$\vec{E} = E_0 \cdot \vec{e}_x \cdot \cos(\omega \cdot t - k \cdot z) \tag{1.b}$$

The magnetic field of a progressive plane wave is obtained by the relation:

$$\vec{B} = \frac{\vec{e}_z \times \vec{E}}{c} \tag{2}$$

$$\vec{B} = B_0 \cdot \vec{e}_y \cdot \exp j(\omega \cdot t - k \cdot z) \tag{2.a}$$

either in real notation

$$\vec{B} = B_0 \cdot \vec{e}_y \cdot \cos(\omega \cdot t - k \cdot z) \quad (2.b)$$

We choose as origin of space and time the moment when the electromagnetic wave meets the solar cell. At t = 0, z = 0 so $\vec{E} = E_0 \cdot \vec{e}_x$ and $\vec{B} = B_0 \cdot \vec{e}_y$

E_0 and B_0 are respectively the amplitudes of electric and magnetic field.

In telecommunication, the level of reception in a given place of the signal radiated by a transmitter is measured through the intensity of electric field E_0 of this wave.

For an isotropic antenna radiating a power P_r (W) in free space, the electric field intensity E_0 (V /m) depending on the distance r (m) is given by the formula [13]:

$$E_0 = \frac{1}{2 \cdot r} \cdot \sqrt{\frac{P_r \cdot Z_0}{\pi}} \quad (3)$$

r being the distance that separates the source of radiation at the measurement point of electric field intensity E_0 and Z_0 is the characteristic impedance in free space.

When the solar cell is illuminated with a multi-spectral white light and submitted to the action of an electromagnetic field, the continuity equation relative to excess minority carriers (electrons) density photo generated in the base region can be written as [7,8]:

$$\frac{\partial^2 \delta(x)}{\partial x^2} + \frac{L_E}{L_n^2} \cdot \frac{\partial \delta(x)}{\partial x} - \frac{\delta(x)}{L_n^{*2}} + \frac{G(x)}{D_n^*} = 0 \quad (4)$$

In this expression $L_E = \frac{\mu_n \cdot E_0 \cdot L_n^2}{D_n}$ is a coefficient that accounts for the migration phenomena within the solar cell base, μ_n is the electrons mobility, E_0 is the electric field intensity, L_n the electrons diffusion length, L_n^* the electrons diffusion length in presence of magnetic field. $\delta(x)$ and $G(x)$ represent respectively carriers' density and the optic generation rate.

The term $\frac{L_E}{L_n^2} \cdot \frac{\partial \delta(x)}{\partial x}$ of the previous equation being a first derivative in relation with position x, is similar to a term of damping.

The electrons-holes pair's optic generation rate for a multi-spectral incident light is given by [14]

$$G(x) = \sum_{i=1}^{3} a_i \cdot e^{-b_i \cdot x} \quad (5)$$

Parameters a_i and b_i are coefficients deduced from modelling of the generation rate considered for over all the solar radiation spectrum under Air Mass 1,5 standard conditions [15].

The excess minority carriers (electrons) density, solution of equation (9) is given by expression:

$$\delta(x) = e^{\alpha \cdot x} \cdot \left[A \cdot ch(\beta \cdot x) + B \cdot sh(\beta \cdot x)\right] - \sum_{i=1}^{3} K_i \cdot e^{-b_i \cdot X} \tag{6}$$

With $K_i = \dfrac{-a_i}{D_n^* \cdot \left[b_i^2 - \dfrac{1}{L_n^{*2}} - \dfrac{L_E \cdot b_i}{L_n^2}\right]}$, $\alpha = -\dfrac{L_E}{2 \cdot L_n^2}$ et $\beta = \dfrac{\left(L_E^2 + 4 \cdot L_n^2 \cdot \left[1 + (\mu_n \cdot B_0)^2\right]\right)^{1/2}}{2 \cdot L_n^2}$

Constants A and B are determined using the two boundary conditions below**:**

- At the junction emitter-base (x = 0)

$$\left.\frac{\partial \delta(x)}{\partial x}\right)_{x=0} = Sf \cdot \frac{\delta(0)}{D_n} \tag{7.a}$$

- At the rear side of the solar cell (x = H)

$$\left.\frac{\partial \delta(x)}{\partial x}\right)_{x=H} = -Sb \cdot \frac{\delta(H)}{D_n} \tag{7.b}$$

Sf is the sum of two contributions: Sf_0 which is the intrinsic junction recombination velocity induced by the shunt resistance and Sf_j which translates the current flow imposed by an external load and defines the operating point of the cell [16]:

$$Sf = Sf_0 + Sf_j \tag{8}$$

Sb is the effective back surface recombination velocity.

Table 1 gives information concerning the power of radiation of AM and FM radio antennas [13]

Table 1: Power of radiation of AM and FM radio antennas

Type of antenna	Power of radiation
FM antenna	50W - 5kW
AM antenna	500W - 2MW

The results of the previous work [7] showed that the solar cell conversion efficiency is much better as the distance that separates the solar cell of the antenna is weak. Consequently we will carry out the simulation by supposing that the solar cell is placed at 10 m from the electromagnetic waves transmitting antenna.

The **table 2** below gives information concerning the antenna power of radiation and the electric and magnetic fields intensity used in the numeric simulation for a distance solar cell-antenna r =10 m

Table 2: Electric and magnetic fields intensity versus power of radiation

Alphabetic letter	Power of radiation (W)	E_0 (V/m)	B_0 (T)
A	0	0	0
B	5000	38.7	$1.29.10^{-7}$
C	50000	122.4	$4.081.10^{-7}$
D	500000	387.1	$1.29.10^{-6}$
E	2000000	774.3	2.58110^{-6}

2.2. Photo-current density

While applying Fick's law at the solar cell junction, we get photocurrent density expression in presence of electromagnetic field:

$$Jph(Sf) = q \cdot \left[D_n \cdot \frac{\partial \delta(x)}{\partial x})_{x=0} + \frac{\mu_n \cdot E_0}{1 + (\mu_n \cdot B_0)^2} \cdot \delta(0) \right] \tag{9}$$

where q is the electronic charge.

2.3. Junction photo-voltage

The photo-voltage across the junction is expressed by means of excess minority carriers' density at the junction (x = 0) according to Boltzmann's relation:

$$Vph(Sf) = \frac{k_B \cdot T}{q} \cdot \ln\left(\frac{\delta(0)}{n_0} + 1 \right) \tag{14}$$

With $n_0 = n_i^{-2} \cdot N_B$ and $V_T = k_B \cdot T / q$ where n_i is the intrinsic carrier's density at thermal equilibrium, N_B the doping density of the base and V_T the thermal voltage.

2.4. Photo-current density - photo-voltage characteristic (Jph-Vph)

The photocurrent density and the photo-voltage depend on the junction recombination velocity Sf. While taking like parameter the junction recombination velocity, we plot on **figure 2** the solar cell Jph-Vph characteristic curves for different values of electromagnetic field intensity or for different values of the power radiated by the antenna.

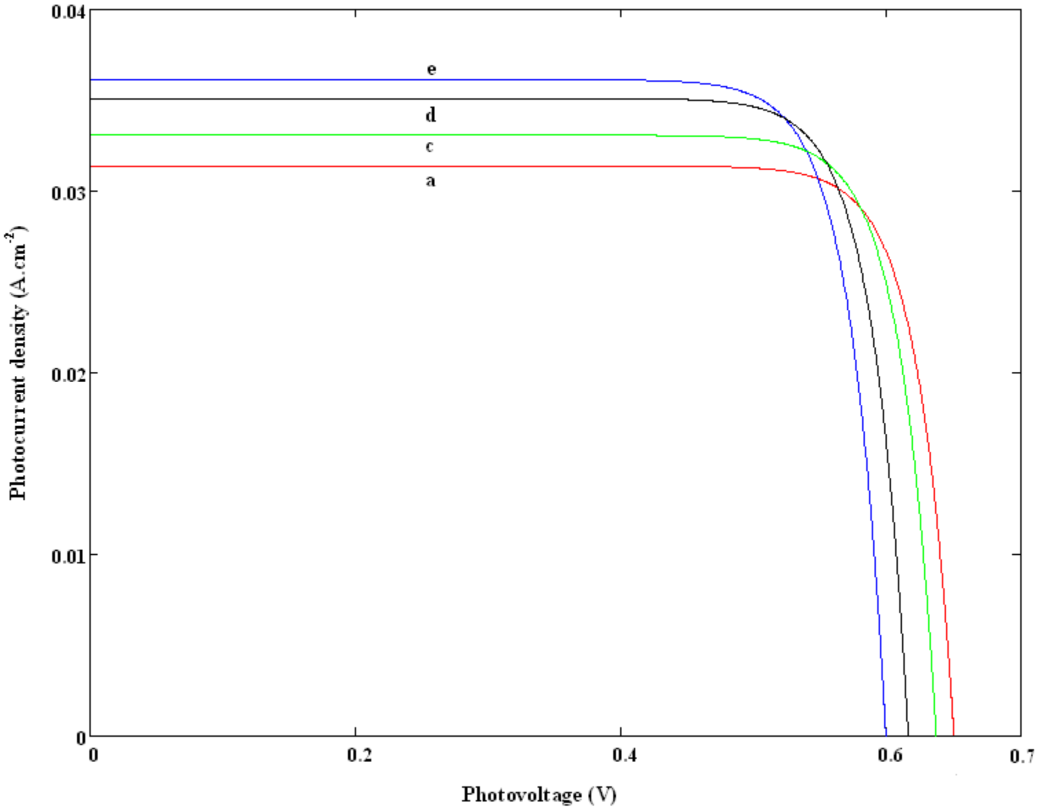

Figure 2: Photocurrent density-photo voltage characteristic for different power of radiation (L=0.02 cm; H=0.03 cm; D=26 cm^2/s; μ_n=1350 cm^2/V.s)

Curves of **figure 2** show that the short circuit photo-current is an increasing function of the antenna power of radiation while the open circuit photo voltage is a decreasing function of the same antenna power of radiation. In a previous work [8], we explain the increasing values of the short circuit photocurrent by the fact that the electric field of the electromagnetic wave, which is an increasing function of the antenna power of radiation, intensifies carriers' migration toward the solar cell junction. And the consequence of this migration phenomenon is the increase of the short circuit photo-current. As for the decrease of open circuit photo voltage with the antenna power of radiation, it is explains by an increase of the losses of carriers at the solar cell junction.

Each curve is characterized by three remarkable points: the short circuit photocurrent J_{sc}, the open circuit photo voltage V_{oc} and a point named "knee" or peak power point. The coordinates of the peak power point are J_p and V_p and the product of the two terms gives the peak power $P_P = J_P.V_P$. The peak power is the maximum electric power delivered by the solar cell to an external load; so the peak power point defines the operating point of the solar cell. We note that the peak power point is also an increasing function of the antenna's power of radiation and that corresponds to a displacement of the solar cell's operating point so a decrease of the peak power point's load resistance.

2.5. Solar cell shunt and series resistance

Series and shunt resistances are electrical parameters and their determination can be done by using many methods [17-19].

The series resistance is caused by the movement of electrons through the emitter and base of the solar cell, the contact resistance between the metal contact and the silicon and the resistance of metal grids at the front and the rear of the solar cell [17-19].

The shunt resistance is due to manufacturing defects and also lightly by poor solar cell design. It corresponds to an alternate current path for the photocurrent [17-19].

It appears on the curves of **figure 2** that near the short circuit the solar cell behaves like an ideal current generator (horizontal characteristic) and near the open circuit the solar cell behaves like an ideal voltage generator (vertical characteristic). However, in experimental I-V curves, one can observe that beyond the short circuit, the photocurrent decrease with the increase of the photo voltage and beyond the open circuit, the I-V characteristic is not vertical but oblique. Thus, to the neighborhood of the open circuit (low values of Sf, $Sf<10^2$ $cm.s^{-1}$) the solar cell behaves like a real voltage generator i.e. a voltage source in series with the solar cell series resistance (**figure 3.a**) [20, 21]. On the other hand, to the neighborhood of the short circuit (large values of Sf, $Sf>10^4$ $cm.s^{-1}$), the solar cell behaves like a real current generator i.e a current source in parallel with the solar cell shunt resistance (**figure 3.b**) [20, 21]

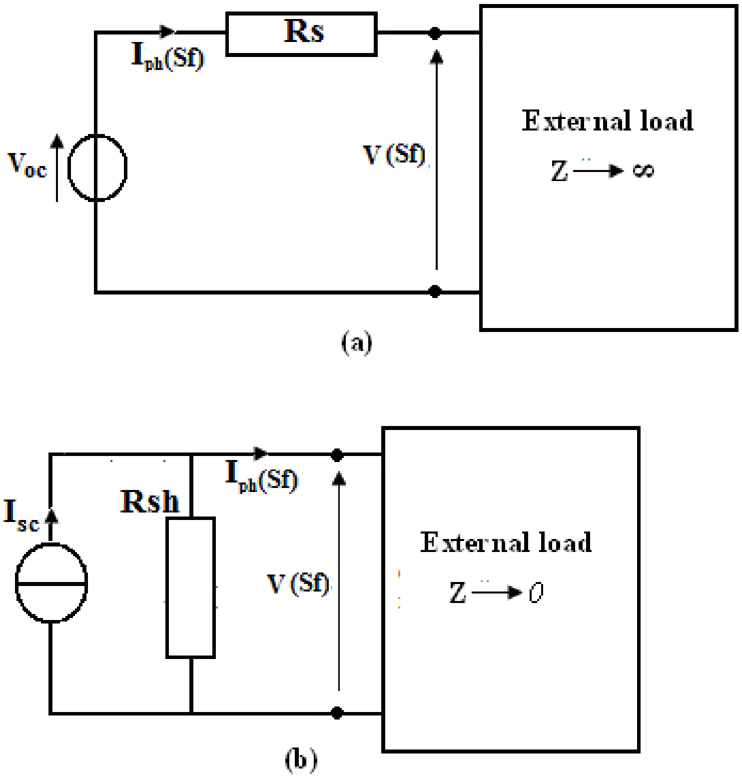

Figure 3: Equivalent electric circuit of the solar cell

(a) solar cell as a real voltage generator; **(b)** solar cell as a real current generator

Using the circuits of **figure 3,** the series and shunt resistances can be respectively expressed:

$$R_s = \frac{V_{oc} - V_{ph}}{J_{ph}} \tag{15}$$

$$R_{sh} = \frac{V_{ph}}{J_{sc} - J_{ph}} \tag{16}$$

We note that the series and shunt resistance depend on the same parameter than the photovoltage and the photocurrent density; the junction recombination velocity Sf and the electromagnetic field intensity.

The curves of series and shunt resistance versus junction recombination velocity are plotted respectively in **figure 4** and **5.**

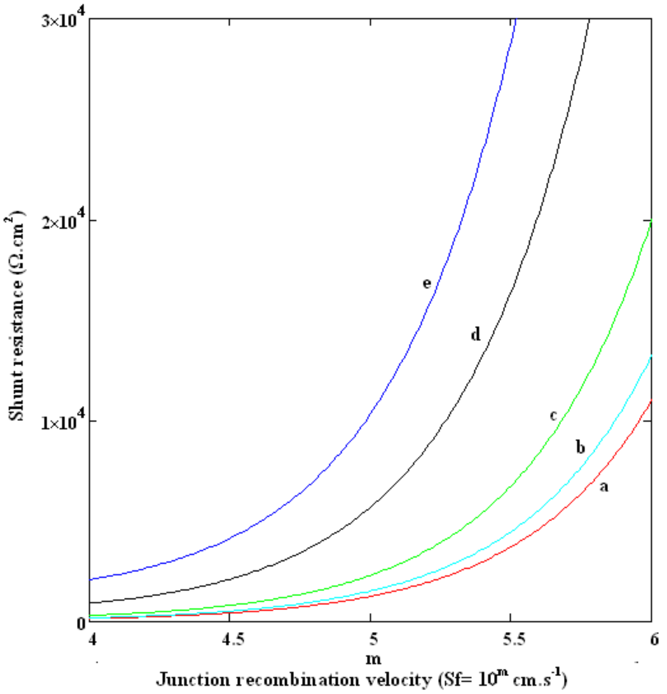

Figure 5: Shunt resistance versus junction recombination velocity
(L=0.02 cm; H=0.03 cm; D=26 cm^2/s; μ_n=1350 $cm^2/V.s$)

The shape of the different curves shows that the shunt resistance is an increasing function of junction recombination velocity and the power radiated by the antenna. The increase of shunt resistance with the increase of junction recombination velocity and the power radiated by the antenna has for consequence the increase of photocurrent density delivered by the solar cell to an external load. The increase of junction recombination velocity corresponds to an increase of carriers (electrons) crossing the junction to participate to the photocurrent [8]. One also notes from the equivalent circuit of the solar cell (**figure 3.a)** that an increase of shunt resistance permits to reduce the leak current tin this resistance (shunt resistance) and therefore permits to get an important photocurrent.

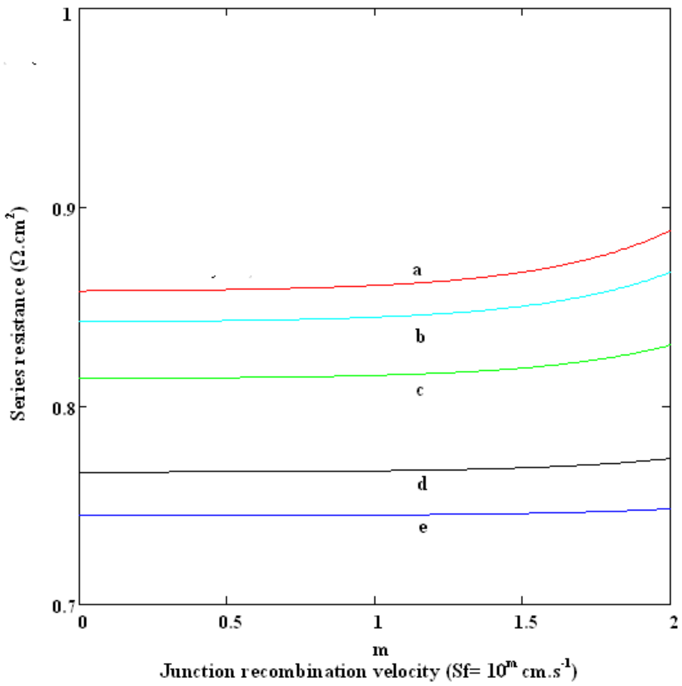

Figure 6: Series resistance versus junction recombination velocity
(L=0.02 cm; H=0.03 cm; D=26 cm^2/s; μ_n=1350 cm^2/V.s)

Curves of **figure 6** are increasing function of junction recombination velocity and a decreasing function of the antenna power of radiation. The decrease of series resistance with the antenna power of radiation has for consequence a reduction of ohmic fall voltage so an increase of photo voltage delivered to an external load as the circuit of **figure 3.b** shows it.

2.5. Solar cell electric power

The electric power delivered by the solar cell base to an external load circuit is expressed using the equation (14) below [7, 8]:

$$P(Sf) = Vph(Sf) \cdot Jph(Sf)_T \qquad (17)$$

With $Jph(Sf)_T = q \cdot Sf_j \cdot \delta(0)$

$Jph(Sf)_T$ is the photo-current that crosses the external load resistance.

Electric power variations versus photo-voltage for different values of the electromagnetic waves transmitting antenna power of radiation are plotted on **figure 6**.

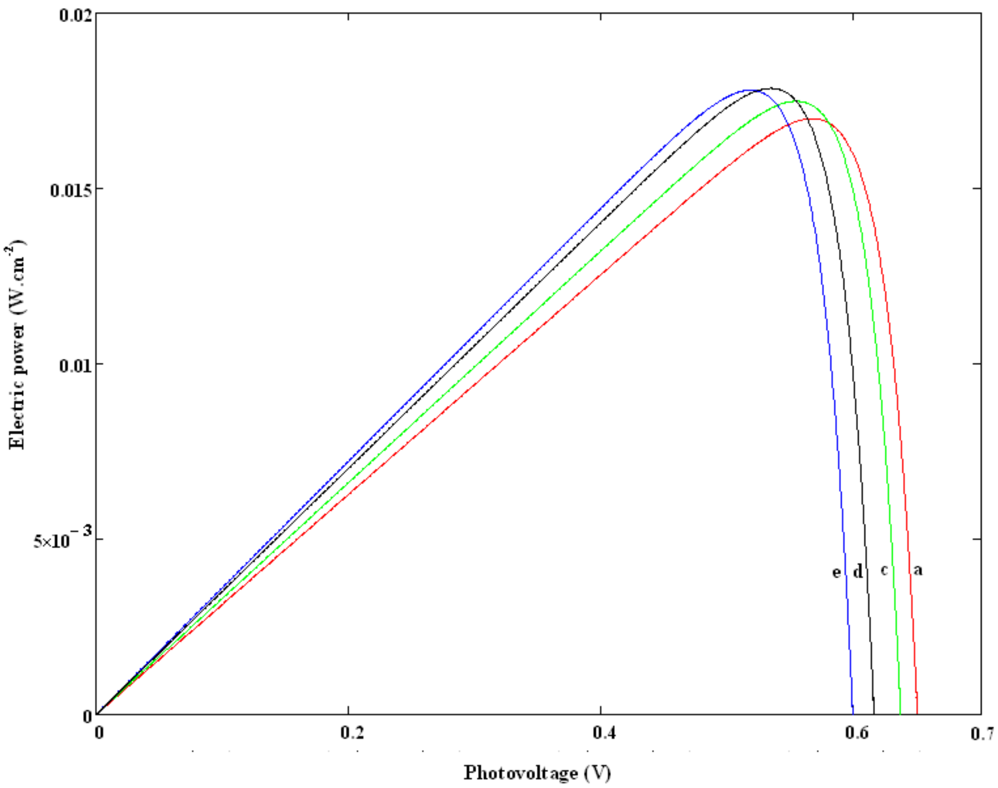

Figure 6: Electric power-photovoltage characteristic for different power of radiation ($L=0.02$ cm; $H=0.03$ cm; $D=26$ cm^2/s; $\mu_n=1350$ cm^2/V.s)

We note also on curves of **figure 6** that the peak power is an increasing function of the antenna's power of radiation and that corresponds to a displacement of the solar cell's operating point so a decrease of the peak power point's load resistance.

Using the P-V characteristic, we determined the values of maximum electric power (peak power) delivered by the solar cell to an external circuit and the values of photo-voltage corresponding (peak voltage). Then, using now the Jph-Vph characteristic we determine the peak photocurrent corresponding to the peak photo-voltage determined previously and we determine also the short circuit density photocurrent and the open circuit photo voltage. Then we calculated the solar cell fill factor (FF) using the formula below:

$$FF = \frac{V_p \cdot J_p}{V_{oc} \cdot J_{sc}} \quad (18)$$

We calculated also the load resistance corresponding to the peak power point using Ohm's law:

$$R_{pp} = \frac{V_p}{J_p} \tag{19}$$

These results are consigned in the **table 3** below.

Table 3: Solar cell electric parameters for different power of radiation

Power of radiation (W)	0 (absence of antenna)	5000	50000	500000	2000000
J_p (A.cm^{-2})	0,030023	0,030516	0,031586	0,033432	0,034396
V_p (V)	0,56588	0,5626	0,55361	0,53407	0,51748
J_{sc} (A.cm^{-2})	0,031389	0,031963	0,033081	0,035111	0,036143
V_{oc} (V)	0,65024	0,64588	0,6369	0,61584	0,59897
P_p (W.cm^{-2})	0,01699	0,017168	0,017486	0,017855	0,017799
FF	0,8324	0,8316	0,830	0,826	0,822
R_{pp} (Ω.cm^2)	18,848	18,436	17,527	15,975	15,048

The results consigned in table 3 shows that the peak photocurrent density and the short circuit photocurrent density increase with the power radiated by the antenna while the peak photo voltage and the open circuit photo voltage decrease. These results have been observed on the Jph-Vph characteristic. The peak power values increase with the antenna power of radiation while the fill factor decreases. One notes a reduction of the load resistance according to the antenna power of radiation corresponding thus to a change of the solar cell's operating point. Thus, so that the solar cell delivers the maximum power to an external load, it is necessary to proceed to an impedance adaptation.

In **table 4** below, we give the values of maximum electric power delivered by the solar cell to an external circuit and the values of junction recombination velocity corresponding [8]. We also give the values of the peak power and the corresponding peak power point's load resistance, determined in the present work.

Table 4: Solar cell recombination and electric parameters for different power of radiation

Power of radiation (W)	0 (absence of antenna)	5000	50000	500000	2000000
$P_{max}(W.cm^{-2})$ [8]	0,017000	0,017167	0,017486	0,017854	0,017798
Sf $(cm.s^{-1})$ [8]	$2,884.10^4$	$3,236.10^4$	$5,129.10^4$	$1,047.10^5$	$1,95.10^5$
P_p $(W.cm^{-2})$	0,01699	0,017168	0,017486	0,017855	0,017799
R_{pp} $(\Omega.cm^2)$	18,848	18,436	17,527	15,975	15,048

We note that the maximum electric power determined in a previous article [8] is in the same order of size that the peak power determined in this present article. We also note that the junction recombination velocity and the peak power point's load resistance evolve the other way around. Indeed, when the junction recombination velocity becomes small one stretches toward the open circuit and the load resistance becomes big. On the other hand, when the junction recombination velocity becomes big, one stretches toward the short circuit and the load resistance small. Finally, Sf appears as effective characteristics of the junction and is related to the solar cell technological parameters (base doping, base width) and to the operating conditions (junction polarization) [21].

3. Conclusion

In this work, we have presented a theoretical study of electromagnetic waves power of radiation influence on silicon solar cell electric parameters. Taking as parameter the junction recombination velocity, we plot on the solar cell Jph-Vph characteristic and we proposed two equivalent electric circuits. In open circuit conditions corresponding to low values of Sf ($Sf<10^2$ $cm.s^{-1}$) the solar cell behaves as a real voltage generator and in short circuit condition corresponding to large values of Sf ($Sf>10^4$ $cm.s^{-1}$), the solar cell behaves like a real current generator. Using the real generator voltage, we determined the solar cell series resistance and using the real current generator, we determined the solar cell shunt resistance. The series resistance is a decreasing function of the antenna power of radiation while the shunt resistance is an increasing function of the same parameter. The peak powers, the peak voltage, the peak photo current, the short circuit density photocurrent and the open circuit photo voltage are determined by means of the Jph-Vph and P- Vph characteristic. Then we calculated the solar cell fill factor (FF) and the load resistance corresponding to the peak power point using Ohm's law.

The numeric calculations put in evidence a decrease of the fill factor and the peak power point's load resistance with the increase of the antenna power of radiation. We interpreted the variation of the peak power point's load resistance as being an adaptation of impedance to the boundary-marks of the solar cell following a variation of the solar cell's operating point. The peak power point's load resistance has been related to the junction recombination velocity determined in a previous work. We noted that the junction recombination velocity and the peak power point's load resistance evolve the other way around. This last analysis put in evidence that the junction recombination velocity defines effectively the solar cell operating point.

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