

# INFLUENCE OF ELECTROMAGNETIC WAVES PRODUCED BY AN AMPLITUDE MODULATION RADIO ANTENNA ON THE ELECTRIC POWER DELIVERED BY A SILICON SOLAR CELL

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(Received 14 July 2014; Revision Accepted 5 September 2014)

## ABSTRACT

This article presents a one dimensional modeling of the influence of electromagnetic waves on the electric power delivered by a silicon solar cell under monochromatic illumination in steady state. The electromagnetic waves are produced by an amplitude modulation radio antenna of 2MW power of radiation and located at a variable distance of the solar cell  $[10m, +\infty[$ . The magnetotransport and continuity equations of excess minority carriers are solved with boundary conditions and led to new analytical expressions of minority carrier's density, photocurrent density, photovoltage and electric power depending on electromagnetic field intensity and wavelength  $\lambda$ . The dependence of the electromagnetic field and the incident light wavelength on photocurrent density, photovoltage and electric power is studied. The intensity of the electromagnetic field depends on the distance between the solar cell and the amplitude modulation radio antenna. We determine the peak power and the operating point of the solar cell according to distance or electromagnetic field intensity and also according to the wavelength of the monochromatic light.

**KEYWORDS:** 1- Amplitude modulation, 2- Radio antenna, 3- Electromagnetic waves, 4- Monochromatic illumination, 5- Solar cell

## INTRODUCTION

The efficiency of a solar cell is closely bound to its electronic properties but some external factors as magnetic field (Dieng et al., 2011; Zoungrana et al., 2011; Zoungrana et al., 2012), and external electric field (Zoungrana et al., 2012), can influence the solar cell quality. The magnetic field can have various origins: terrestrial magnetic field, magnetic component of the electromagnetic waves coming from radio transmitters, television transmitters and telecommunication transmitters, magnetic field coming from high voltage/low voltage transformer, etc. Also, we are interested in the effect of electromagnetic waves coming from radio transmitters and other telecommunication sources on silicon solar cell because whatever is their installation place, the silicon solar cells of photovoltaic panels by their principle of functioning (movement of electrons) can be influenced by the magnetic field as well as the electric field of the electromagnetic waves of the

different telecommunication sources that exist close to their installation place.

In previous works we studied the influence of electromagnetic waves produced by AM and FM radio antennas on silicon solar cell electronics and electrical parameters (Zerbo et al., 2011; Zerbo et al., 2012; Sow et al., 2012). In these works, the solar cell was illuminated by a multispectral light in steady state. In the present article, we study the effect of electromagnetic waves produced by an amplitude modulation radio antenna on the electric power delivered by a silicon solar cell illuminated by a monochromatic light. The AM radio 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 antenna is dependant of the power radiated by the antenna and the distance  $r$ . Therefore we will study the influence of electromagnetic field and wavelength on photocurrent density, photo voltage and electric power.

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2. Theory

2.1. Excess minority carriers' density  
Polycrystalline back surface field silicon solar

cell with n<sup>+</sup>-p-p<sup>+</sup> structure is studied under monochromatic illumination and under electromagnetic waves (figure 1)

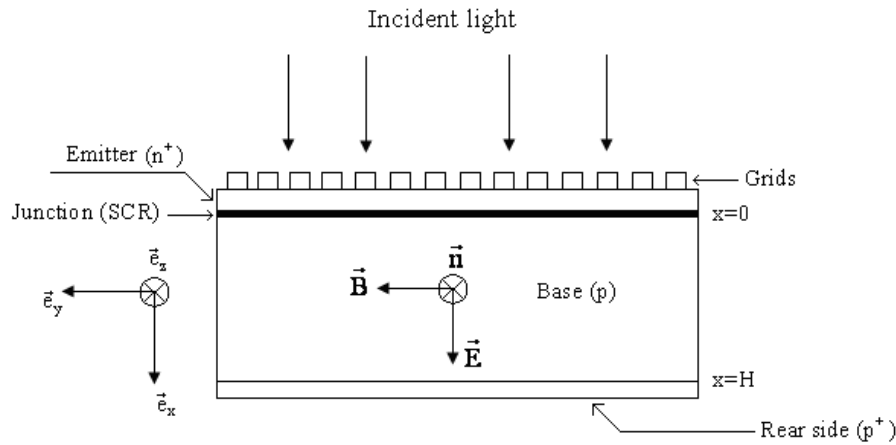


Figure 1: Silicon solar cell illuminated by monochromatic light and under electromagnetic waves influence

When the solar cell is illuminated with a monochromatic 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 (Zerbo et al., 2012; Sow et al., 2012)

$$\frac{\partial^2 \delta(x)}{\partial x^2} + \frac{L_E}{L_n^2} \cdot \frac{\partial \delta(x)}{\partial x} - \frac{\delta(x)}{L_n^{*2}} + \frac{G(x)}{D_n^*} = 0 \quad \text{-----} \quad (1)$$

In equation (1),  $L_E = \frac{\mu_n \cdot E_0 \cdot L_n^2}{D_n}$  is a coefficient that characterizes migration phenomena in solar cell base. In this expression,  $\mu_n$  is the electron mobility,  $E_0$  is the electric field intensity,  $L_n$  and  $D_n$  are the electron diffusion length and diffusion coefficient,  $L_n^*$  and  $D_n^*$  are the electron diffusion length and diffusion coefficient in the presence of magnetic field.  $\delta(x)$  and  $G(x)$  are respectively carriers' density and optic generation rate.

The term  $\frac{L_E}{L_n^2} \cdot \frac{\partial \delta(x)}{\partial x}$  of equation (1) 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 monochromatic incident light is given by

$$G(x) = \alpha(\lambda) \cdot \Phi_0 \cdot [1 - R(\lambda)] \cdot e^{-\alpha(\lambda)x} \quad \text{-----} \quad (2)$$

$\alpha(\lambda)$  and  $R(\lambda)$  are respectively absorption and reflection coefficient at the wavelength  $\lambda$  and  $\Phi_0$  is the incident photon flux.

The excess minority carriers (electrons) density, solution of equation (1) is completely determined using the two boundary conditions below:

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

$$\left. \frac{\partial \delta(x)}{\partial x} \right)_{x=0} = Sf \cdot \frac{\delta(0)}{D_n^*} \quad \text{-----} \quad (3)$$

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

$$\left. \frac{\partial \delta(x)}{\partial x} \right)_{x=H} = -Sb \cdot \frac{\delta(H)}{D_n^*} \quad \text{-----} \quad (4)$$

Sf is the sum of two contributions:  $Sf_0$  which is the intrinsic junction recombination velocity related to the losses of carriers at the junction interface and  $Sf_j$  which is the junction recombination velocity imposed by an external circuit and defines the operating point of the cell (Zerbo et al., 2012; Sow et al., 2012):

$$Sf = Sf_0 + Sf_j \quad \text{-----} \quad (5)$$

Sb is the effective back surface recombination velocity

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 (Freyer et al., 1994):

$$E_0 = \frac{1}{2 \cdot r} \cdot \sqrt{\frac{P_r \cdot Z_0}{\pi}} \quad \text{-----} \quad (6)$$

r being the distance that separates the source of radiation from the measurement point of electric field intensity E<sub>0</sub> and Z<sub>0</sub> is the characteristic impedance in free space.

**Table 1:** Information concerning electric and magnetic field intensities calculated for an AM radio antenna radiating power, Pr= 2 MW in free space, for different values of distance between the solar cell and the antenna using equation (6).

Alphabetic letter	Distance r (m)	E <sub>0</sub> (V/m)	B <sub>0</sub> (T)
A	10	774.3	2.581X10 <sup>-6</sup>
B	50	154.9	5.162 X10 <sup>-7</sup>
C	100	77.4	2.581 X10 <sup>-7</sup>
D	500	15.5	5.162 X10 <sup>-8</sup>
E	1000	7.7	2.581 X10 <sup>-8</sup>
F	r = +∞	0	0

**2.2. Photocurrent density**

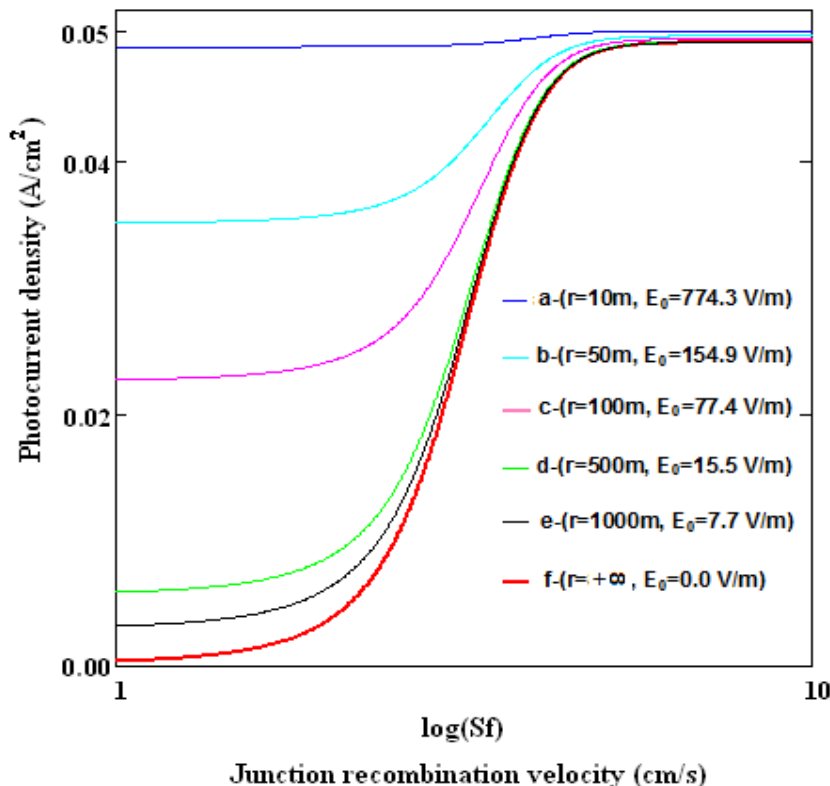
Applying Fick’s law at the solar cell junction, we get photocurrent density expression in the presence of electromagnetic field (Zerbo et al., 2012; Sow et al., 2012) as:

$$Jph(Sf) = q \cdot \left[ D_n^* \cdot \frac{\partial \delta(x)}{\partial x} \right]_{x=0} + \mu_n^* \cdot E_0 \cdot \delta(0) \quad \text{-----} \quad (7)$$

with  $D_n^* = \frac{D_n}{1 + (\mu_n \cdot B_0)^2}$  and  $\mu_n^* = \frac{\mu_n}{1 + (\mu_n \cdot B_0)^2}$  which are respectively electrons diffusion coefficient in the magnetic field and electrons mobility in the magnetic field

**2.2-1 Effect of electromagnetic field or distance on photo-current density**

The photo-current density versus junction recombination velocity curves are plotted on figure 2 for different values of electromagnetic field intensity or for different values of the distance between the AM radio antenna and the solar cell.



**Figure 2:** Photo-current density versus junction recombination velocity for different values of electromagnetic field or distance (L=0.02cm; H=0.03cm;D=26cm<sup>2</sup>/s;μ<sub>n</sub>=1000cm<sup>2</sup>/V.s, λ=0.68μm)

Curves of figure 2 show that the open circuit photo-current is null in the absence of electromagnetic field but not null in the presence of electromagnetic field. The open circuit photo-current or leakage current is proportional to the electromagnetic field intensity and stretches toward the value of short circuit photo-current for large values of electromagnetic field intensity. The short circuit photo-current and the leakage photo-current are increasing functions of electromagnetic field intensity.

The presence of photocurrent in the neighborhood of the open circuit explains the presence of leakage current at the solar cell junction. Indeed, while applying the boundary condition given by equation (3), equation (7) gives:

$$Jph(Sf) = q \cdot [Sf + \mu_n^* \cdot E_0] \cdot \delta(0) \quad \text{-----} \quad (8)$$

Rewriting equation (8) and taking equation (5) into account, one gets:

$$Jph(Sf) = q \cdot [Sf_0 + Sf_j + \mu_n^* \cdot E] \cdot \delta(0) \quad \text{-----} \quad (9)$$

The photocurrent can be divided in two components: a component that depends on the intrinsic junction recombination velocity  $Sf_0$  and the electromagnetic field applied at the solar cell  $Jph(Sf)_F$  and a second component that depends on the impedance of the external circuit and also the applied electromagnetic field  $Jph(Sf)_T$ .

$$Jph(Sf)_F = q \cdot [Sf_0 + \mu_n^* \cdot E_0] \cdot \delta(0) \text{ and } Jph(Sf)_T = q \cdot Sf_j \cdot \delta(0) \quad \text{-----} \quad (10)$$

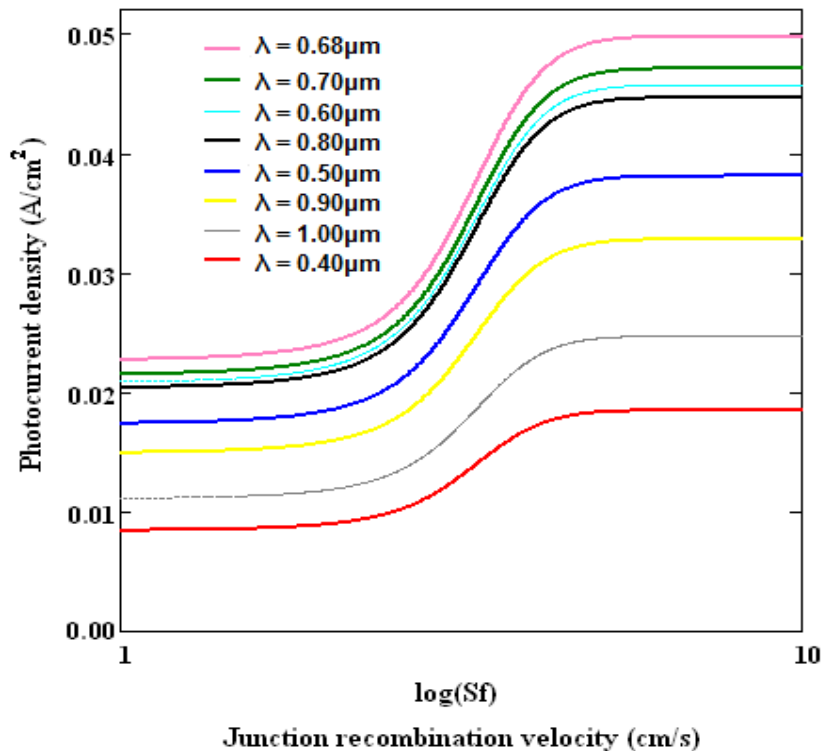
$Jph(Sf)_T$  is the photocurrent that crosses the external circuit and  $Jph(Sf)_F$  is the photocurrent that is lost because of interface phenomena and therefore  $Jph(Sf)_T$  is a leakage photocurrent.

- In open circuit  $Sf_j \ll (Sf_0 + \mu_n^* \cdot E)$  and  $Jph(Sf) \approx Jph(Sf)_F$ , which means that the photocurrent is reduced to the leakage current.
- In short circuit  $Sf_j \gg (Sf_0 + \mu_n^* \cdot E)$  and  $Jph(Sf) \approx Jph(Sf)_T$ . In this functioning mode, the photocurrent is almost entirely delivered to an external circuit, the losses of current to the interfaces being weak.
- In an intermediate functioning mode, the recombination bound to interface effects and to the impedance of the external circuit are to be taken into account.

**2.2-1 Effect of incident monochromatic light wavelength on photo-current density**

The photo-current density curves versus the junction recombination velocity are plotted on figure 3 for

different wavelength of the incident monochromatic light and for a given electromagnetic field intensity or a fixed distance between the AM radio antenna and the solar cell.



**Figure 3:** Photo-current density versus junction recombination velocity for different values of incident monochromatic light wavelength (L=0.02 cm; H=0.03 cm; D=26 cm²/s;  $\mu_n=1000 \text{ cm}^2/\text{V.s}$ , r=100m )

The open circuit current is firstly weak and it increases with the increase of the wavelength. The open circuit current reaches a maximum for the wavelength  $\lambda = 0.68 \mu\text{m}$ . Then it becomes weaker if the wavelength

continues to increase: it appears then inversion phenomenon. The leakage current and the short circuit current increase with the wavelength to reach a maximum at the wave length  $\lambda = 0.68 \mu\text{m}$ .

**2.3. Effect of electromagnetic field or distance on photo-voltage**

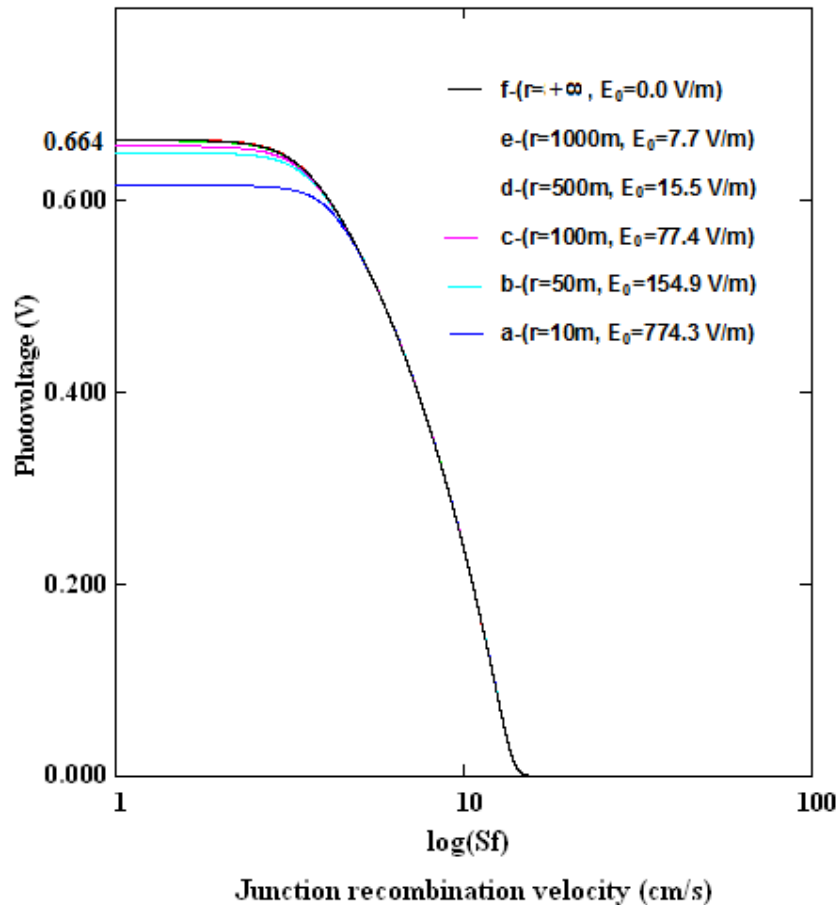
Using Boltzmann's relation (Zerbo *et al.*, 2012; Sow *et al.*, 2012) we can determine the solar cell junction photovoltage as:

$$V_{ph}(Sf) = V_T \cdot \ln\left(\frac{\delta(0)}{n_0} + 1\right) = \frac{k_B \cdot T}{q} \ln\left(\frac{\delta(0)}{n_0} + 1\right) \quad \text{-----} \quad (11)$$

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

**2.3-1 Effect of electromagnetic field or distance on photo-voltage**

We plot on **figure 4** below, photo-voltage versus junction recombination velocity curves for different values of electromagnetic field intensity or for different values of the distance between the AM radio antenna and the solar cell.



**Figure 4:** Photo-voltage versus junction recombination velocity for different values of electromagnetic field or distance (L=0.02 cm; H=0.03 cm; D=26 cm<sup>2</sup>/s;  $\mu_n=1000 \text{ cm}^2/\text{V}\cdot\text{s}$ ,  $\lambda=0.68 \mu\text{m}$ )

It appears on the curves of figure 4 that for large value of junction recombination velocity ( $Sf \geq 10^{10} \text{ cm}\cdot\text{s}^{-1}$ ), the photo voltage is null while for low value of junction recombination velocity ( $Sf \leq 10^2 \text{ cm}\cdot\text{s}^{-1}$ ) the open circuit voltage is maximal and depends of electromagnetic field intensity.

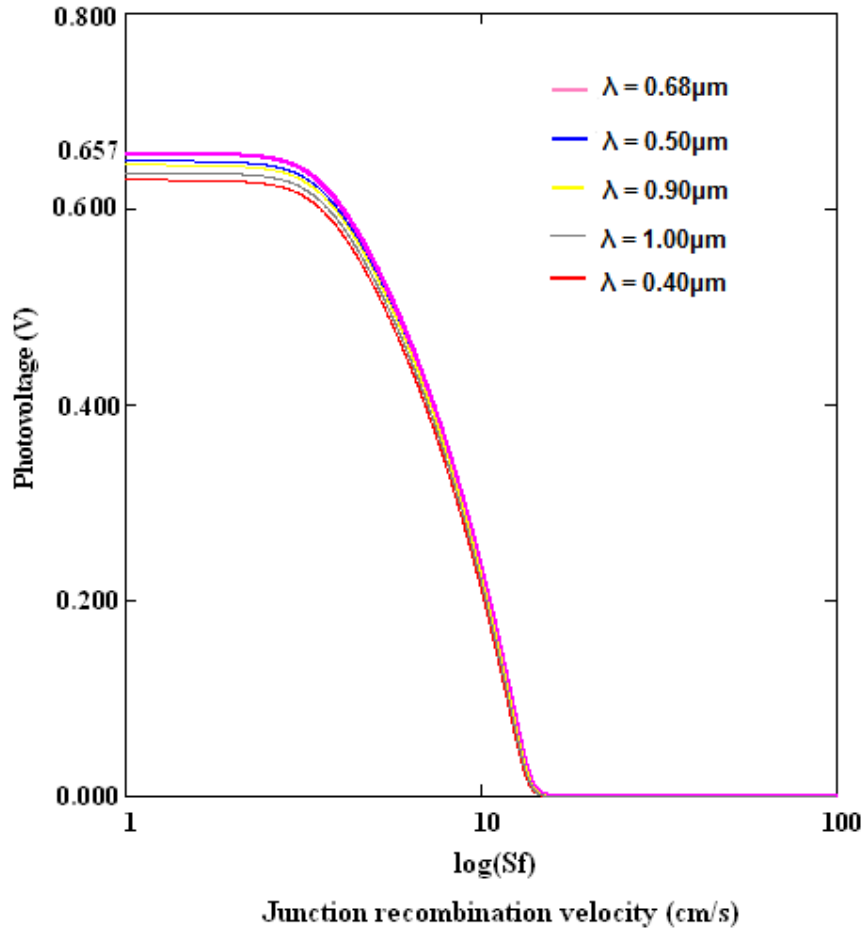
The open circuit voltage decreases while the electromagnetic field intensity increases.

Indeed, we have observed on the curves of figure 2 the existence of a current in open circuit named leakage current due to the passage of some carriers through the solar cell junction in open circuit. Thus, a

decrease of the open circuit voltage means a reduction of the quantity of carriers stocked at the junction. In fact, some carriers will cross the junction and produce a leakage current that will be quantified from a microscopic view point, by the intrinsic junction recombination velocity. A decrease of the open circuit voltage translates to an increase in the losses of carriers at the junction or even an increase of the intrinsic junction recombination velocity at the solar cell junction.

**2.3-2 Effect of incident monochromatic light wavelength on photo-voltage**

The photo-voltage curves versus junction recombination velocity are plotted on figure 5 for different wavelength of the incident light and for a given electromagnetic field intensity or a fixed distance between the AM radio antenna and the solar cell



**Figure 5:** Photo-voltage versus junction recombination velocity for different values of incident monochromatic light wavelength (L=0.02cm; H=0.03cm; D=26 cm<sup>2</sup>/s; μ<sub>n</sub>=1000 cm<sup>2</sup>/V.s, r=100m)

The phenomenon of inversion observed on the curves of figure 3 appears also here. Indeed, the theoretical open circuit voltage increases while the wavelength, λ; increase and reach a maximum at λ=0.68μm. Beyond λ=0.68μm, the open circuit voltage decreases while the wavelength continues to increase.

**2.4. Solar cell electric power**

The electric power delivered by the solar cell base to an external load circuit is expressed using the equation (12) below:

$$P(Sf) = V_{ph}(Sf) \cdot J_{ph}(Sf)_T \tag{12}$$

In this expression,  $J_{ph}(Sf)_T$  is the photo-current that crosses the external load resistance ( $J_{ph}(Sf)_T = q \cdot Sf_j \cdot \delta(0)$ ).

2.4-1 Effect of electromagnetic field or distance on electric power

Electric power variations versus junction recombination velocity for different values of electromagnetic field intensity or for different values of the distance between the AM radio antenna and the solar cell are plotted on figure 6.

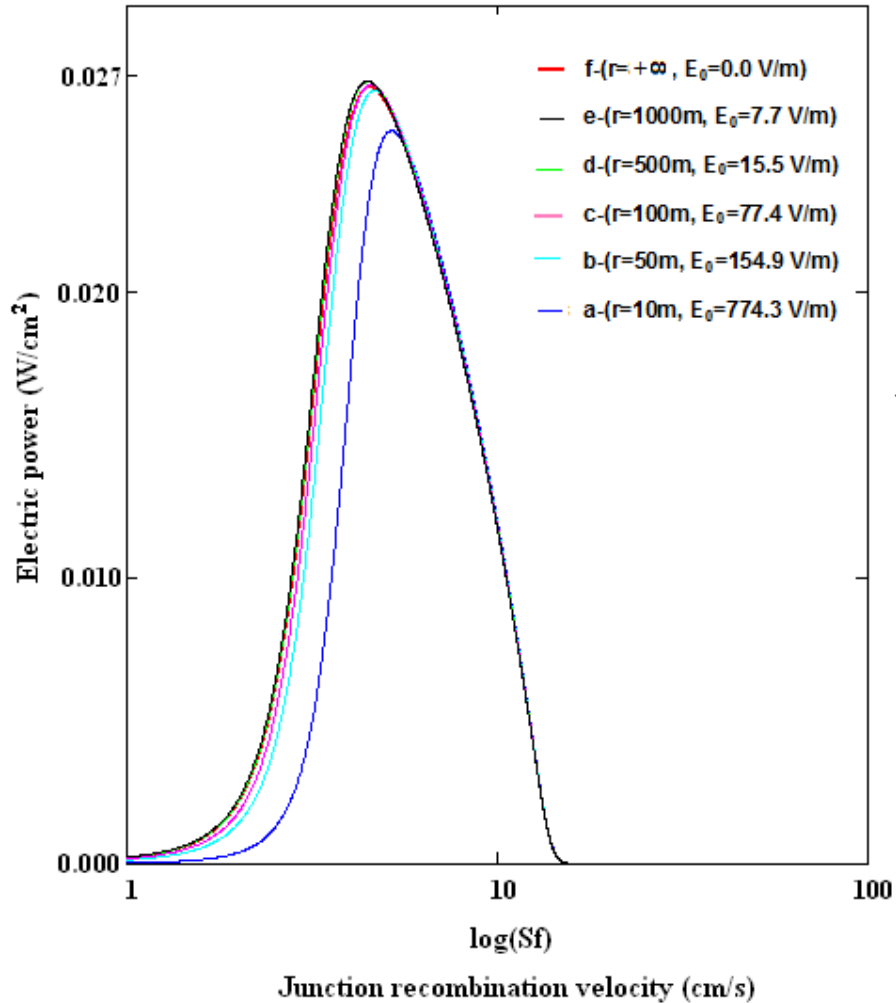


Figure 6: Electric power delivered by the solar cell versus junction recombination velocity for different values of electromagnetic field or distance (L=0.02cm; H=0.03cm; D=26cm<sup>2</sup>/s; μ<sub>n</sub>=1000 cm<sup>2</sup>/V.s, λ=0.68 μm)

The analysis of the different curves shows that the electric power delivered by the solar cell base is null near the open circuit and the short circuit. It passes by a maximum that is located at an intermediate operating point. This operating point for which the electric power is maximal moves toward the short circuit (large values of Sf) when the distance between solar cell and electromagnetic source reduces (electromagnetic field intensity increases). We observe also on this figure that the maximum electric power is obtained in absence of electromagnetic field (large distance between the AM radio antenna and the solar cell) because from 0.4μm to

0.8μm, carriers are generated near the junction and the electromagnetic field has no effect on them. Conversely, from 0.8μm to 1μm, excess minority carriers are generated inside the base (far from the junction) and the electromagnetic field has a great effect on their mobility.

We determined the values of maximum electric power delivered by the solar cell to an external circuit and the values of corresponding junction recombination velocity, for different values of electromagnetic field intensity and for an incident monochromatic light wavelength, λ=0.68μm. These results are consigned in table 2 below.

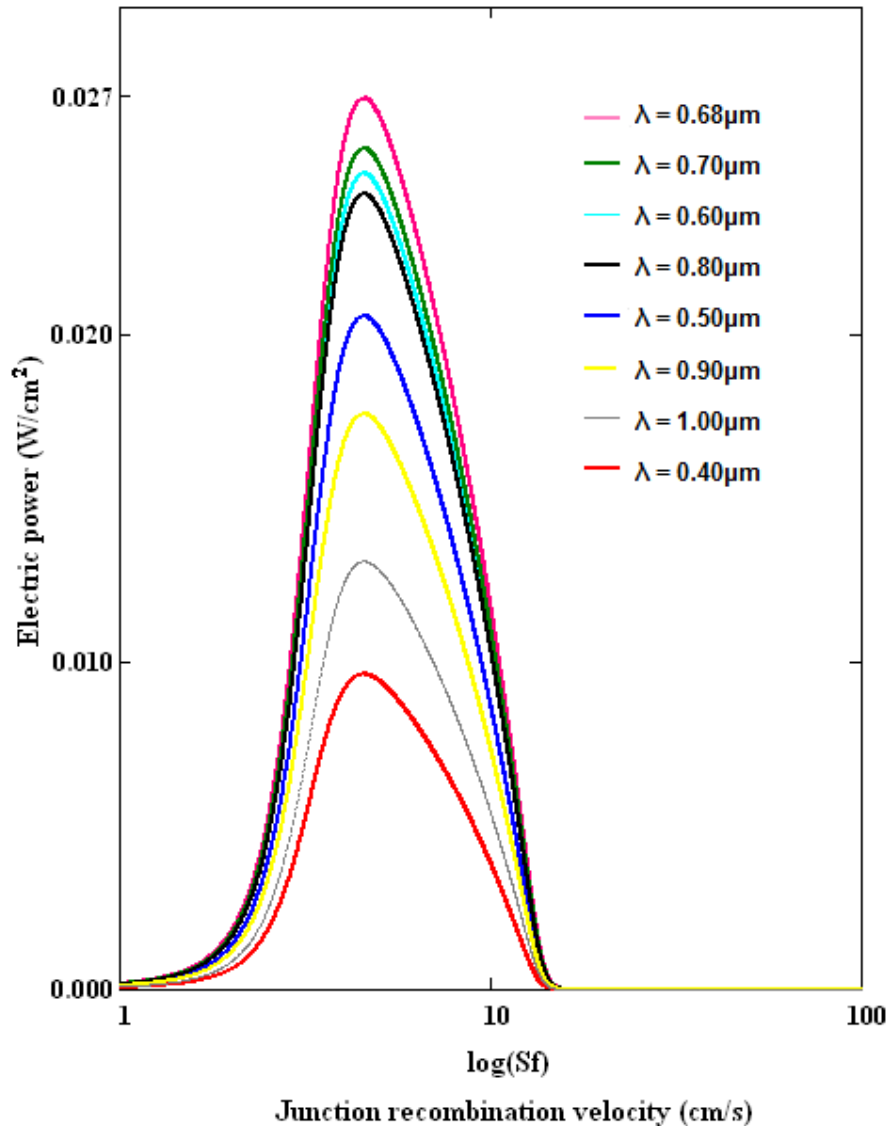
Table 2: Maximum electric power and corresponding junction recombination velocity for different values of electromagnetic field intensity for incident monochromatic light wavelength λ=0.68μm.

Distance (m)	10	50	100	500	1000	absence of antenna
E <sub>0</sub> (V/m)	774.3	154.9	77.4	15.5	7.7	0
B <sub>0</sub> (T)	2.581X10 <sup>-6</sup>	5.162 X10 <sup>-7</sup>	2.581 X10 <sup>-7</sup>	5.162 X10 <sup>-8</sup>	2.581 X10 <sup>-8</sup>	0
P <sub>max</sub> (W/cm <sup>2</sup> )	0.025582	0.027031	0.027224	0.027229	0.027358	0.027358
Sf (10 <sup>4</sup> cm/s)	19.05460	5.12861	3.98107	3.71535	3.01995	3.0199517

The results consigned in table 2 confirm the above ones of figure 6. Indeed, it appears that the maximum electric power delivered by the solar cell base to an external circuit increases while electromagnetic field intensity decreases. We also note that the intense values of electromagnetic field intensity leads to weak values of maximum electric power for large values of junction recombination velocity. This phenomenon can be interpreted as an increase of carriers' losses at solar cell junction (intrinsic junction recombination velocity increase).

#### 2.4-2 Effect of incident light wavelength on electric power

Electric power variations versus junction recombination velocity for different wavelength of the incident monochromatic light and for a given electromagnetic field intensity or distance between the AM radio antenna and the solar cell are plotted on figure 7.



**Figure 7:** Electric power delivered by the solar cell versus junction recombination velocity for different values of incident light wavelength ( $L=0.02$  cm;  $H=0.03$  cm;  $D=26$  cm<sup>2</sup>/s;  $\mu_n=1000$  cm<sup>2</sup>/V.s,  $r=100$  m)

It appears from this figure that for each curve, the electric power passes by a maximum that is located in an intermediate operating point. We observe also that the maximum electric power increases with the increase in wavelength until  $\lambda=0.68\mu\text{m}$ . Beyond  $\lambda=0.68\mu\text{m}$ , the phenomenon of inversion observed while studying photocurrent density and photo voltage appears also.

In table 3 below, we give the maximum electric power delivered by the solar cell to an external circuit and the corresponding junction recombination velocity value for different wavelengths and for a given electromagnetic field intensity.



**Table 3:** Maximum electric power and corresponding junction recombination velocity for different wavelength and for a given electromagnetic field intensity

Wavelength $\lambda$ ( $\mu\text{m}$ )	$P_{\text{max}}$ ( $\text{W}/\text{cm}^2$ )	$Sf$ ( $10^4 \text{ cm}/\text{s}$ )
0.40	0.0096398	3.63078
0.50	0.020573	3.98107
0.60	0.024926	3.89045
0.68	0.027224	3.98107
0.70	0.025695	3.98107
0.80	0.024303	3.89045
0.90	0.017581	3.98107
1.00	0.01308	3.71535

The results of table 3 confirm the above ones of figure 7. We also note that the maximum electric power is obtained almost at the same intermediate operating point for all wavelengths ( $Sf = 3.9 \times 10^4 \text{ cm} \cdot \text{s}^{-1}$ ).

**CONCLUSION**

A theoretical study of amplitude modulation radio waves effects on silicon solar cell electric power is presented. The study of photo current density shows that for a given wavelength, the short circuit photo-current and the open circuit photo-current or leakage current are increasing functions of electromagnetic field intensity. Then, for a given electromagnetic field intensity, the leakage current and the short circuit current increase with the wavelength to reach a maximum at the wavelength  $\lambda = 0.68 \mu\text{m}$ ; and they decrease, while the wavelength continues to increase: this is the phenomenon of inversion. As for the photo voltage, for a given wavelength, the open circuit voltage is a decreasing function of electromagnetic field intensity. We also note that, for a given electromagnetic field intensity, the open circuit voltage increases with the wavelength to reach a maximum at the wavelength  $\lambda = 0.68 \mu\text{m}$  and decreases while the wavelength continues to increase.

The numeric calculations, deduced from the analysis of electric power curves, show increase in the maximum electric power delivered by the solar cell, with decrease in electromagnetic field intensity at an intermediate operating point for a given wavelength. For a given electromagnetic field intensity, the electric power manifests the phenomenon of inversion, after the wavelength,  $\lambda = 0.68 \mu\text{m}$ , where it is maximal. This inversion presents a similarity with the spectral inversion of solar radiation with a wavelength gap of a few hundred nanometers between the maximum points. In fact, the point of maximum power for the cell is not achieved for the equivalent wavelength of maximum solar radiation, as it is known that this value is reached for wavelength, ranging from 475 to 500nm (Beichner *et al.*, 2000). For all wavelengths, the electric power is almost maximal at the same intermediate operating point ( $Sf = 3.9 \times 10^4 \text{ cm} \cdot \text{s}^{-1}$ ).

It appears in this study that solar cells are influenced none the less by the electromagnetic waves produced by AM and FM radio antennas but also by light of high wave lengths. So it confirms that it would be judicious to take into account these parameters when installing silicon solar cells photovoltaic panels to optimize their efficiencies.

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