

## A theoretical study of radio wave attenuation through a polycrystalline silicon solar cell

Adama OUEDRAOGO<sup>1</sup>, Vinci de Dieu Bokoyo BARANDJA<sup>1,2</sup>, Issa ZERBO<sup>1,\*</sup>,  
Martial ZOUNGRANA<sup>1</sup>, Emmanuel Wendsongré RAMDE<sup>3</sup>, Dieudonné Joseph BATHIEBO<sup>1</sup>

<sup>1</sup>Laboratory of Thermal and Renewable Energies, Department of Physics, Unit of Training and Research in Pure and Applied Sciences, University Ouaga I Prof. Joseph KI-ZERBO, Ouagadougou, Burkina Faso

<sup>2</sup>Department of Physics, University of Bangui, Bangui, Central African Republic

<sup>3</sup>Department of Mechanical Engineering, Kwame N’Krumah University of Science and Technology, Kumasi, Ghana

Received: 17.03.2017

Accepted/Published Online: 29.05.2017

Final Version: 05.09.2017

**Abstract:** One-dimensional study of both electronic and electrical parameters of a silicon solar cell in the presence or not of an electric field, a magnetic field, or an electromagnetic field does not take into account the grain size and the grain boundary recombination velocity. A three-dimensional study, on the contrary, takes those factors into account. However, the three-dimensional study poses the problem of the attenuation of the wave in the grain of the polycrystalline solar cell as well as the issue of finding the expressions of its components. This study aimed to solve these issues by considering radio waves, which are becoming more and more present in our environment via telecommunication masts. We first obtained the expressions of both the electric field and magnetic field in a grain of a polycrystalline silicon solar cell by solving the dispersion equation. Then we investigated the evolution of the radio wave into the grain by analyzing the behavior of the exponential coefficient that appeared in the expressions of both the electric field and the magnetic field. The study has shown that the attenuation of the radio wave can be neglected through the polycrystalline silicon solar grain and by extension through the polycrystalline silicon solar cell.

**Key words:** Attenuation, radio wave, polycrystalline silicon solar cell, equations of Maxwell, monochromatic illumination

### 1. Introduction

The spectrum of solar radiation extends from ultraviolet to infrared including the visible. The frequency ranges from  $3.4 \times 10^{16}$  Hz to  $3 \times 10^{11}$  Hz and the wavelength from  $0.01 \mu\text{m}$  to  $1 \text{mm}$ , but photovoltaic conversion takes place only between  $0.4 \mu\text{m}$  and  $1.1 \mu\text{m}$ .

It is worth noting that within the visible and the infrared range of the spectrum, the electric field oscillates at a very high frequency that is too fast to measure with any kind of instrument. It is rather possible to measure the power carried by the electromagnetic wave. On the other hand, it is technically possible to measure the electric field of an electromagnetic wave in the microwave and radio wave spectrum and even track its evolution with time [1]. Radio waves have frequencies lower than 300 GHz and wavelengths greater than 1 mm.

The boom of mobile phones and the proliferation of television and radio stations have led to the installation of telecommunication antennas in both urban and rural areas and every so often near solar photovoltaic

\*Correspondence: izerbo@hotmail.com

systems. These installations are sources of radio waves that may interact with solar photovoltaic installations, hence raising the issue of electromagnetic compliance [2].

In order to investigate the interaction between radio waves and solar cells, various researchers have used both experimental and theoretical methods under different conditions and arrived at different results.

Erel [3] conducted an experiment and studied simultaneously the effect of both electric and magnetic fields on the response of three different types of solar cells (monocrystal, polycrystal, and amorphous Si solar cells). Both fields were created separately and did not emanate from an electromagnetic wave. The cells were illuminated with LEDs. Erel concluded that the short-circuit current and the open-circuit voltage decreased under the simultaneous effects of both electric and magnetic fields. Drapalik et al. [2] studied crystalline photovoltaic cells as both receivers and emitters of electromagnetic waves. As receivers, they concluded that the reception of electromagnetic radiation depends linearly on the cell area, at least at low frequencies (below 10 MHz). They also used two antennas, namely dipole and patch antennas, to model the reception behavior of the solar cells. They concluded that the patch antenna may be used to roughly describe the reception behavior of the cells, much better compared to the dipole antenna.

Other researchers also conducted theoretical modeling of the effect of the electromagnetic field on the properties of solar cells. Zerbo et al. used a one-dimensional steady-state approach to study the recombination properties of silicon solar cells [4]. The electromagnetic field considered in their study was that produced by an amplitude modulation (AM) radio antenna of a given radiation power. For a given orientation of the electromagnetic field, they varied the distance between the solar cells and the radio antenna while the cells were being illuminated by a multispectral light. The study showed that the magnetic field component of the electromagnetic wave has negligible effect on the cells while its electric component influences the cells. They also observed an increase of the short-circuit photocurrent density and the leakage photocurrent density but a decrease of the open circuit voltage. In a related study, Zerbo et al. [5] studied the effect of the electromagnetic field on the power output and conversion efficiency of a silicon solar cell. The study conditions were the same as in [4], except that this time the cells were illuminated by monochromatic light. Their study revealed that for a given wavelength of the monochromatic light, the open-circuit voltage decreases while the short-circuit photocurrent density and the leakage photocurrent density are increasing as the intensity of the electromagnetic field increases. A comparative study of the influence of the electromagnetic field coming from AM and FM radio antennas on the power output and conversion efficiency of a silicon solar cell was conducted by Zerbo et al. [6]. For a given type of radio antenna, they obtained the same conclusion as in previous studies [4,5], but their study revealed that the FM radio antennas, which produce low values of electromagnetic field, have less influence on the solar cell than AM radio antennas.

The theoretical studies mentioned above were all conducted using one-dimensional approaches. However, one-dimensional study does not take into account the grain size, the grain boundary recombination velocity, and the flow of lateral current, which may counterbalance the longitudinal current. A three-dimensional study, on the contrary, takes those factors into account. However, three-dimensional study poses the problem of the attenuation of the wave in the grain of the solar cell as well as the issue of finding the expressions of its components. This study attempts to address these issues by considering radio waves, which are often generated by radio transmitters and other telecommunication transmitters. The study considers a polycrystalline silicon solar cell under monochromatic illumination and investigates the attenuation of radio waves in a grain of the cell. In addition, it finds the expressions of both the electric field and the magnetic field within this grain.

When an electromagnetic wave penetrates a good electric conductor, it vanishes during its propagation;

this phenomenon of attenuation of the electromagnetic wave is called the Kelvin effect or skin effect. In contrast, when it is a good insulating medium (dielectric), the electromagnetic wave crosses it without attenuation. The electric conductivity of a semiconductor lies between that of an electric conductor and that of an insulator. Furthermore, a solar cell, which is a semiconductor, behaves like an electric conductor when illuminated by an incident light, but like an insulator when not.

## 2. Methodology

### 2.1. Description of the solar cell

The structure of the polycrystalline silicon solar cell considered is  $n^+ - p - p^+$  [6]. On this solar cell the distribution of the grain is random and we assume a harmonious division. In this assumption, the grain has the same structural characteristics ( $n^+ - p - p^+$ ) as the solar cell. The grain also has the same electronic and electrical characteristics as the solar cell because the grain is considered as a unit structure composing the solar cell. Consequently, the polycrystalline solar cell is considered as a regular array of many units cells connected in parallel [7,8]. That allowed us to conduct the study on a grain and then extrapolate the results to a solar cell. Moreover, the assumption of a harmonious division allows us to choose a parallelepipedic form for each grain. The grain boundaries are perpendicular to the junction and their effective recombination velocity  $S_{gb}$  is constant along the grain boundaries and independent of illumination up to AM 1 [9]. In this study, we extend this assumption up to AM 1.5, which is the average air mass at our latitude [10]. The grain boundary is the surface interfacing two grains [11]. This assumption leads the carriers to move to the junction following the (Oz) axis as shown in Figure 1.

The illumination is uniform and the generation rate depends only on the depth of the base  $z$  [12,13] and the wavelength  $\lambda$  [14].

The analysis was developed only in the base region of the grain [12] using the quasineutral base hypothesis while neglecting the crystalline field that exists within the solar cell [6]. The solar cell structure and thus the unit structure under consideration have the space charge region between the highly doped  $n^+$  and relatively low doped  $p$ -type layer, also called the base region of the solar cell. The doping density of the base region is  $N_B = 10^{17} \text{ cm}^{-3}$ , and consequently the modeling of radio wave attenuation in the polycrystalline silicon grain was conducted with the assumption of low-level injection.

In the next section, the dispersion equation is established and solved.

### 2.2. Dispersion equation and its resolution

Figure 2 illustrates an isolated grain from a polycrystalline silicon solar cell. In this figure, the grain and by extrapolation the polycrystalline silicon solar cell are illuminated with an incident monochromatic light.

It is also subjected to the action of a progressive monochromatic plane wave linearly polarized in the (Oz) direction and propagating in the increasing  $x$  direction [6].

We assume that the electromagnetic wave meets the grain of the polycrystalline solar cell at position  $z$  in the base region such as  $0 < z < H$ . Consequently, the attenuation of the electromagnetic wave is not studied at the junction ( $z = 0$ ) and the rear side ( $z = H$ ) of the polycrystalline silicon grain.

In Figure 2,  $\vec{k} = k\vec{e}_x$  is the wave vector of the electromagnetic wave direction of propagation as the trihedral  $(\vec{k}, \vec{E}, \vec{B})$  is direct.

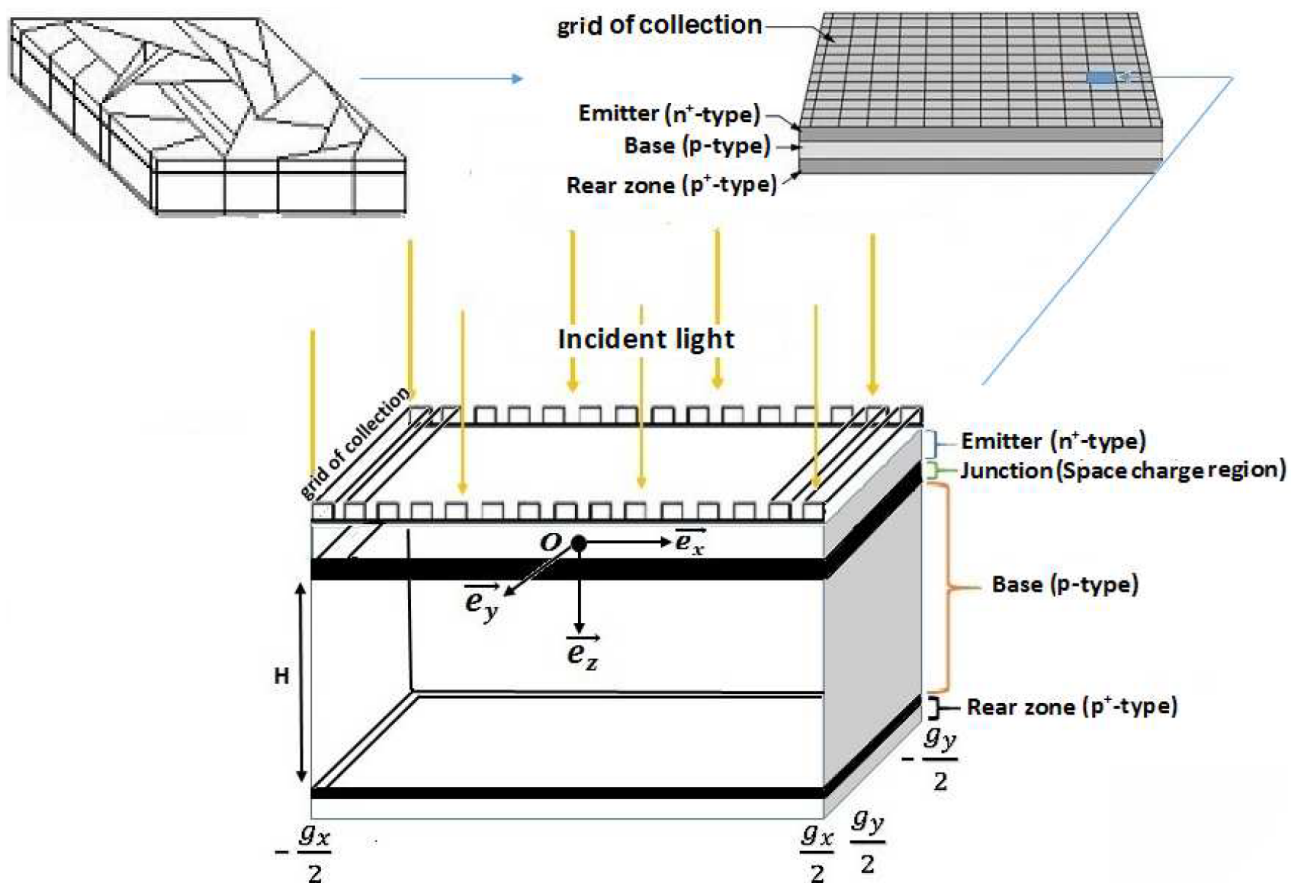


Figure 1. Extraction of grain in parallelepipedic form.

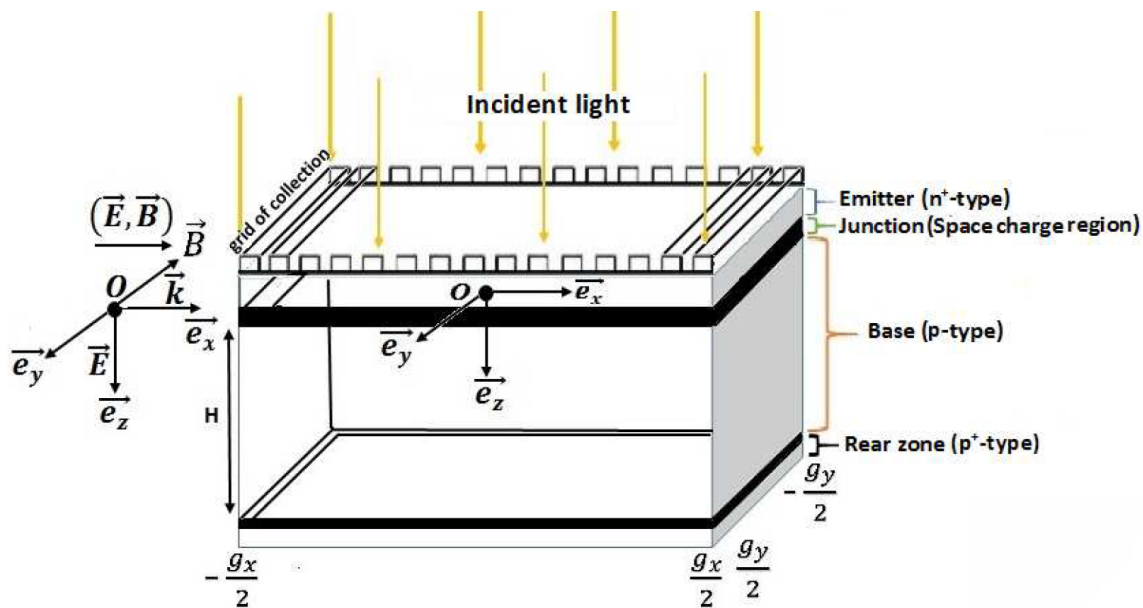


Figure 2. Silicon grain under electromagnetic wave and under monochromatic illumination.

The complex expressions of the electric field and magnetic field for a progressive plane wave, in free space, are given in Eqs. (1a) and (1b), respectively [6]:

$$\vec{E} = E_0 \vec{e}_z \exp j(kx - \omega t) \quad (1a)$$

$$\vec{B} = -B_0 \vec{e}_y \exp j(kx - \omega t) \quad (1b)$$

The dispersion equation uses the four equations of Maxwell, which describe the propagation of the electromagnetic wave in the grain of the polycrystalline silicon solar cell. The first equation, Eq. (2a), is the Maxwell–Gauss equation, which allows us to obtain a relationship between the effects (electric field) and the causes (electric charges):

$$\text{div}(\vec{E}) = \frac{\rho}{\varepsilon} \quad (2a)$$

In this equation  $\rho$  is the volume density of the electric charge. The permittivity of the silicon can be obtained by the following relationship:  $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$ , where the air or space permittivity is  $\varepsilon_0$  and  $\varepsilon_r$  is the relative permittivity.

The conductive region of a semiconductor can be assumed the same as in an electric neutrality regime [8,13] and so  $\rho = 0$ . The Maxwell–Gauss equation becomes:

$$\text{div}(\vec{E}) = 0 \quad (2b)$$

Eq. (3), which is the second Maxwell equation, expresses the conservation of the magnetic flux in the matter.

$$\text{div}(\vec{B}) = 0 \quad (3)$$

The third equation of Maxwell is called the Maxwell–Faraday equation. This equation connects the electric field to the magnetic field and is given by Eq. (4).

$$\vec{\text{rot}}(\vec{E}) = -\frac{\partial \vec{B}}{\partial t} \quad (4)$$

The signification of this equation is that the variation of the magnetic field with time can produce an electric field. The Maxwell–Faraday equation expresses the induction phenomenon.

The last equation of Maxwell is called the Maxwell–Ampere equation and is given by Eq. (5):

$$\vec{\text{rot}}(\vec{B}) = \mu \vec{J}_c + \mu \varepsilon \frac{\partial \vec{E}}{\partial t} \quad (5)$$

Here  $\vec{J}_c = \gamma \vec{E}$ , where  $\gamma$  is the silicon conductivity depending on the density of the minority charge carriers.

The combination of the four equations of Maxwell gives Eq. (6), which is the dispersion equation:

$$\underline{k}^2 = \mu \omega (\varepsilon \omega + j \gamma) \quad (6)$$

The solution of Eq. (6) after all combinations and by assuming  $k = a + ib$  is given by Eq. (7):

$$\begin{cases} a = \omega \sqrt{\mu \varepsilon} \left(1 + \left(\frac{\gamma}{\omega \varepsilon}\right)^2\right)^{\frac{1}{4}} \frac{1}{\sqrt{2}} \left[1 + \frac{1}{\sqrt{1 + \left(\frac{\gamma}{\omega \varepsilon}\right)^2}}\right]^{\frac{1}{2}} \\ b = \omega \sqrt{\mu \varepsilon} \left(1 + \left(\frac{\gamma}{\omega \varepsilon}\right)^2\right)^{\frac{1}{4}} \frac{1}{\sqrt{2}} \left[1 - \frac{1}{\sqrt{1 + \left(\frac{\gamma}{\omega \varepsilon}\right)^2}}\right]^{\frac{1}{2}} \end{cases} \quad (7)$$

Note that Eq. (6) gives both a negative solution and a positive solution. We keep the positive solution because this case is indicative of a plane progressive monochromatic wave propagating in the positive direction of (Ox) axis.

The matter of the semiconductor (silicon) is not a good electric conductor [15] so  $\varepsilon\omega \gg \gamma$ , implying that Eq. (7) becomes Eq. (8a):

$$\begin{cases} a = \omega\sqrt{\varepsilon\mu} \\ b = \frac{\gamma}{2}\sqrt{\frac{\mu}{\varepsilon}} \end{cases} \quad (8a)$$

Consequently we get:

$$\underline{k} = \omega\sqrt{\varepsilon\mu} + j\frac{1}{\ell_p} \quad (8b)$$

Here  $\ell_p = \frac{2}{\gamma}\sqrt{\frac{\varepsilon}{\mu}}$  defines the characteristic length of the penetration of the electromagnetic wave through the silicon grain.

$\gamma = e\mu_n\delta(x, y, z)$  is the conductivity of silicon, which depends on the density of the excess minority carriers (electrons) photogenerated in the base region of the grain in the absence of an electromagnetic wave.

The exponential form of Eq. (8b) is given in Eq. (8c):

$$\underline{k} = \omega\sqrt{\mu\varepsilon} \cdot \underline{e}_x \exp j\left(\frac{\gamma}{2\varepsilon\omega}\right) \quad (8c)$$

Eq. (9) is the complex expression of the electric field in the grain of the polycrystalline silicon solar cell. It is obtained by combining Eq. (8b) and Eq. (1a):

$$\underline{E}(x, t) = E_0\underline{e}_z \exp(-x/l_p) \exp j(\omega\sqrt{\varepsilon\mu}x - \omega t) \quad (9)$$

The complex expression of the magnetic field, in the grain of the polycrystalline silicon solar cell, is obtained by solving the Maxwell–Faraday equation in complex form:

$$\underline{B} = \frac{1}{\omega}\underline{k} \times \underline{E} \quad (10a)$$

The complex expression of the magnetic field, in the grain of the polycrystalline silicon solar cell, is given in Eq. (10b):

$$\underline{B}(x, t) = -\frac{\sqrt{\mu_r\varepsilon_r}E_0}{c}\underline{e}_y \exp(-x/l_p) \exp j\left(\omega\sqrt{\varepsilon\mu}x + \frac{\gamma}{2\varepsilon\omega} - \omega t\right) \quad (10b)$$

Taking into account the fact that  $\varepsilon\omega \gg \gamma$  or  $(\gamma/\varepsilon\omega) \ll 1$ , Eq. (10b) becomes Eq. (10c):

$$\underline{B}(x, t) = -\frac{\sqrt{\mu_r\varepsilon_r}E_0}{c}\underline{e}_y \exp(-x/l_p) \exp j(\omega\sqrt{\varepsilon\mu}x - \omega t) \quad (10c)$$

In Eqs. (9) and (10c), x varies according to the grain size in the present situation.

It appears through Eqs. (9) and (10c) that the expressions of the electric field and the magnetic field into the grain are different from those obtained in free space. One can also note the appearance of an exponential coefficient, expressed by Eq. (10d):

$$\exp(-x/l_p) \quad (10d)$$

The behavior of Eq. (10d) characterizes the electric field and the magnetic field of the electromagnetic wave evolution into the polycrystalline silicon grain. In Eq. (10d), the characteristic length of the penetration of the electromagnetic wave through the silicon grain appears. That characteristic length is a function of the silicon conductivity  $\gamma$ , which in turn is a function of the density of the excess minority carriers, photogenerated in the grain:  $\gamma(x, y, z) = e\mu_n\delta(x, y, z)$ .

The expression of the density of the excess minority carriers photogenerated in the base of the polycrystalline silicon solar cell under constant monochromatic illumination was suggested by Mbodji et al. [14]:

$$\delta(x, y, z) = \sum_j \sum_k \left[ A_{j,k} \cdot \cosh\left(\frac{z}{L_{j,k}}\right) + B_{j,k} \cdot \sinh\left(\frac{z}{L_{j,k}}\right) + K_{j,k} \cdot e^{-\alpha(\lambda) \cdot z} \right] \cdot \cos(C_{xj}x) \cdot \cos(C_{yk}y), \quad (11)$$

with  $\frac{1}{L_{j,k}^2} = \frac{1}{L_n^2} + C_{yk}^2 + C_{xj}^2$ ,  $K_{j,k} = -\frac{\alpha(\lambda)\varphi_0[1-R(\lambda)]}{D_{j,k}[L_{j,k}^{-2} + \alpha^2(\lambda)]}$ , and  $\frac{1}{D_{j,k}} = \frac{16 \cdot \sin(C_{xj} \frac{g_x}{2}) \cdot \sin(C_{yk} \frac{g_y}{2})}{D_n \cdot [\sin(C_{xj} g_x) + C_{xj} g_x] \cdot [\sin(C_{yk} g_y) + C_{yk} g_y]}$ .

$D_n$  and  $L_n$  are respectively the diffusion constant and the diffusion length of the excess minority carriers. The optical parameters are  $\Phi_0$ ,  $\alpha(\lambda)$ , and  $R(\lambda)$  and respectively the incident photon flux, the absorption, and the reflection coefficients of silicon at wavelength  $\lambda$ . In this paper we used the experimental values of the optical parameters of intrinsic silicon at 300 K [16]. Coefficients  $C_{xj}$  and  $C_{yk}$  are found using the grain boundary conditions [9,12,13] while coefficients  $A_{j,k}$  and  $B_{j,k}$  are solved for using the boundary conditions of the solar cell [9,12,13].

When the value of the characteristic length of the electromagnetic wave  $\ell_p$  in Eq. (10d) is greater than the grain size ( $\exp(-g_x/l_p) \rightarrow 1$ ), the electromagnetic wave crosses, without attenuation, the grain as an insulator. In the opposite case of ( $\exp(-g_x/l_p) \rightarrow 0$ ), the electromagnetic wave vanishes in the grain as a good electric conductor: it is the phenomenon of attenuation of the electromagnetic wave called skin effect. It is, however, necessary to study the behavior of the electromagnetic wave to clarify this situation.

### 3. Results and discussion

In order to investigate the evolution of the electromagnetic field into the grain of the polycrystalline silicon solar cell, we proceeded in analyzing Eq. (10d), taking the variable  $x$  equal to the grain size  $g_x$ .

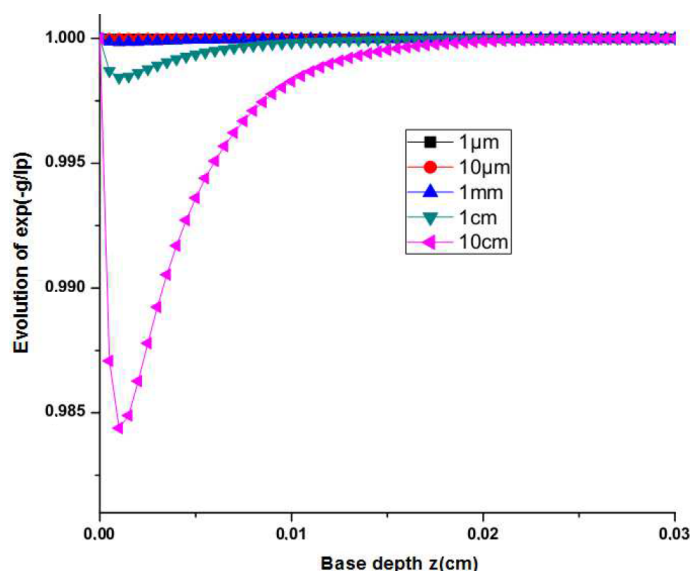
The silicon conductivity as the excess minority carriers' density photogenerated in the grain depends on the grain size, the grain boundary recombination velocity, and the incident light wavelength. Therefore, Eq. (10d) depends also on the same parameters. It is important to know how the electromagnetic wave crosses the grain in varying the grain size and the wavelength of the monochromatic illumination.

We have also used the classification of grain size presented in the Table [17].

**Table.** Classification of the different grains.

Crystalline type	Symbol	Grain size
Microcrystalline	$\mu\text{c-Si}$	$g_x \leq 1\mu\text{m}$
Polycrystalline	$\text{pc-Si}$	$1\mu\text{m} \leq g_x \leq 1\text{mm}$
Multicrystalline	$\text{mc-Si}$	$1\text{mm} \leq g_x \leq 10\text{cm}$
Single crystalline	$\text{sc-Si}$	$g_x \geq 10\text{cm}$

Figure 3 plots the curves of evolution of the electromagnetic field into the base depth of different crystalline types of silicon solar cell according to different grain sizes in short-circuit condition.



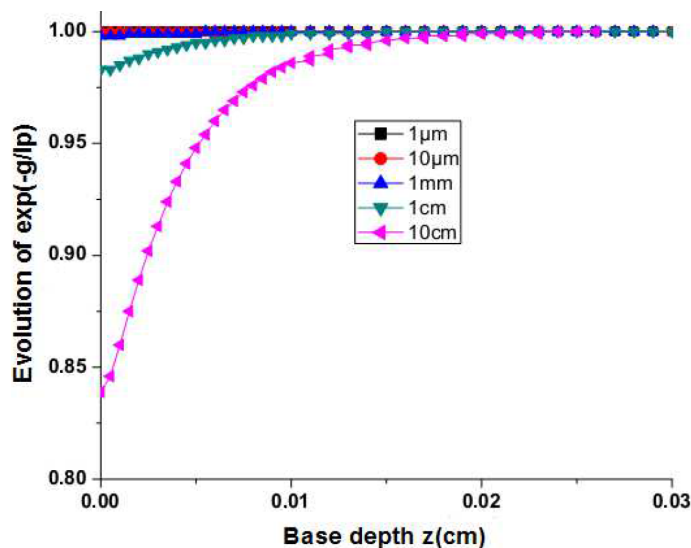
**Figure 3.** Evolution of the electromagnetic field versus base depth for different grain sizes in short circuit ( $D_n = 26 \text{ cm}^2 \text{ s}^{-1}$ ;  $\lambda = 0.70 \text{ } \mu\text{m}$ ,  $S_{gb} = 10^3 \text{ cm s}^{-1}$ ,  $S_b = 10^4 \text{ cm s}^{-1}$ ,  $L_n = 0.015 \text{ cm}$ ,  $S_f = 10^8 \text{ cm s}^{-1}$ ;  $H = 0.03 \text{ cm}$ ).

The curves in Figure 3 present a weak attenuation of the electromagnetic wave ( $\exp(-g_x/l_p) < 1$ ) in the silicon grain near the junction and a decrease of the attenuation until its cancellation ( $\exp(-g_x/l_p) = 1$ ) in the base depth for a multicrystalline silicon grain ( $1 \text{ mm} \leq g_x \leq 10 \text{ cm}$ ). For a polycrystalline silicon grain ( $1 \text{ } \mu\text{m} \leq g_x \leq 1 \text{ mm}$ ) the curves in Figure 3 show an absence of attenuation of the electromagnetic wave ( $\exp(-g_x/l_p) = 1$ ). From the polycrystalline silicon grain ( $1 \text{ } \mu\text{m}$ ) to the multicrystalline silicon grain ( $10 \text{ cm}$ ), we noted that the great significant value of the attenuation is 1.562%. A fast disappearance of this attenuation appears from 0.001 cm in the base depth to the rear side of the grain. Indeed, when the value of the density of excess minority carriers increases (near the junction of the solar cell), the value of the exponential quantity decreases, resulting in an increase of the attenuation of the electromagnetic wave. In the base depth of the silicon grain, the value of the density of excess minority carriers decreases, resulting in an increase of the value of the exponential quantity and a decrease of the attenuation of the electromagnetic wave. The behavior of the electromagnetic wave into a multicrystalline silicon grain, when the grain size reaches 10 cm and this value corresponds to the size of a polycrystalline silicon solar cell [17,18], can be supposed without attenuation. For a polycrystalline silicon solar cell, the size of 10 cm can be taken like the solar size in the large area case [17], the attenuation is low, and  $\exp(-g_x/l_p) \simeq 1$ . In any case, the attenuation of the electromagnetic field can be neglected from polycrystalline silicon grain to multicrystalline silicon grain and that can also correspond to a polycrystalline solar cell because of the size of the grain.

The curves of evolution of the electromagnetic field are plotted in Figure 4 for different crystalline types of silicon solar cells according to different grain sizes in open-circuit condition.

The evolution of the electromagnetic field into a grain of a solar cell when this solar cell operates in an open circuit shows an attenuation of the electromagnetic field ( $\exp(-g_x/l_p) < 1$ ) at the junction and a decrease of the attenuation until its cancellation ( $\exp(-g_x/l_p) = 1$ ) in the base depth for a multicrystalline silicon grain ( $1 \text{ mm} \leq g_x \leq 10 \text{ cm}$ ), while for a polycrystalline silicon grain ( $1 \text{ } \mu\text{m} \leq g_x \leq 1 \text{ mm}$ ) we observe an absence of attenuation of the electromagnetic field ( $\exp(-g_x/l_p) = 1$ ). When the grain size increases the exponential





**Figure 4.** Evolution of the electromagnetic field versus base depth for different grain sizes in open circuit ( $D_n = 26 \text{ cm}^2 \text{ s}^{-1}$ ;  $\lambda = 0.70 \text{ } \mu\text{m}$ ,  $S_{gb} = 10^3 \text{ cm s}^{-1}$ ,  $S_b = 10^4 \text{ cm s}^{-1}$ ,  $L_n = 0.015 \text{ cm}$ ,  $S_f = 1 \text{ cm s}^{-1}$ ;  $H = 0.03 \text{ cm}$ ).

quantity decreases and its lowest value is about 0.83874 at the junction, resulting in an attenuation of the electromagnetic field of about 16.127%. For a given position in the base depth of the multicrystalline silicon grain, the exponential quantity is weaker than the one obtained when the multicrystalline silicon grain operates in short-circuit condition and the attenuation of the electromagnetic field is about 16.127% near the junction. Indeed, the density of excess minority carriers at the junction of a solar cell in an open circuit is higher than the one in a short circuit; therefore, the exponential quantity in the open circuit is lower than the one in the short circuit, resulting in an increase of the attenuation of the electromagnetic wave in the open circuit.

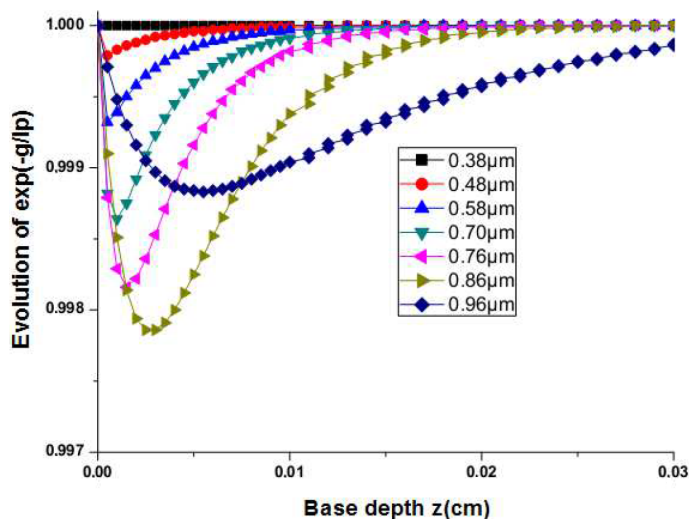
We can conclude that, as in the short-circuit case, the attenuation of the electromagnetic field can be neglected from polycrystalline silicon grain to multicrystalline silicon grain and that can also correspond to a polycrystalline silicon solar cell because of the size of the grain.

In the two cases, i.e. open circuit and short circuit, when the polycrystalline silicon grain size reaches that of single crystalline silicon, the attenuation of the electromagnetic field can be neglected. The evolution of the electromagnetic wave while the light wavelength varies is analyzed in the following paragraph.

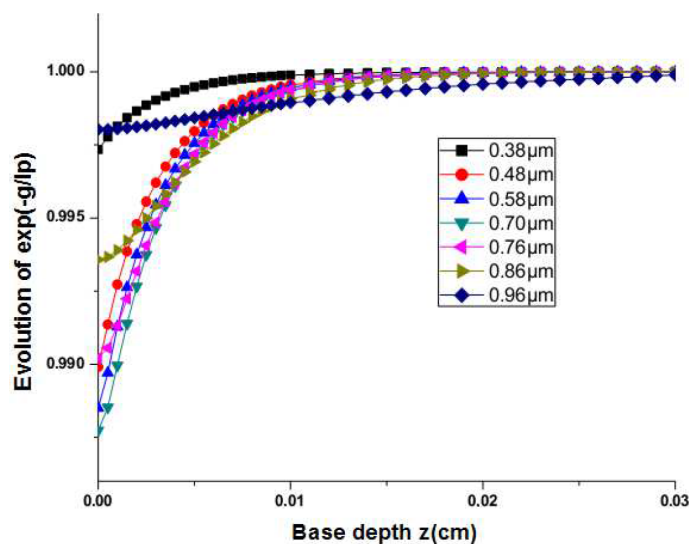
The curves of evolution of the electromagnetic field into a multicrystalline silicon grain for various light wavelengths in the short-circuit condition are plotted in Figure 5. When the light wavelength increases, the exponential decreases as well. The lowest value of the exponential was obtained with wavelength  $\lambda = 0.86 \text{ } \mu\text{m}$ . We observe a decrease of the value of the exponential near the junction and it is more so as the light wavelength increases. There is an attenuation of the electromagnetic field reaching 0.2145% for wavelength  $\lambda = 0.86 \text{ } \mu\text{m}$ . The attenuation of the electromagnetic field when the electromagnetic wave crosses the multicrystalline silicon grain can be neglected. Consequently, we can conclude that the attenuation of the electromagnetic field during the crossing of the polycrystalline silicon grain can also be neglected.

The curves of evolution of the electromagnetic field into a multicrystalline silicon grain for different light wavelengths in open-circuit conditions are shown in Figure 6. The profiles of the curves in Figure 6 give us the evolution of the electromagnetic field into a multicrystalline silicon grain when the solar light wavelength varies and when the grain of the silicon solar cell operates in open-circuit conditions.

For all light wavelengths the attenuation of the electromagnetic wave during the crossing of the mul-



**Figure 5.** Evolution of the electromagnetic field versus base depth for different light wavelengths in short circuit ( $D_n = 26 \text{ cm}^2 \text{ s}^{-1}$ ;  $g_x = g_y = 10 \text{ cm}$ ,  $S_{gb} = 10^3 \text{ cm s}^{-1}$ ,  $S_b = 10^4 \text{ cm s}^{-1}$ ,  $L_n = 0.015 \text{ cm}$ ,  $S_f = 10^8 \text{ cm s}^{-1}$ ;  $H = 0.03 \text{ cm}$ ).



**Figure 6.** Evolution of the electromagnetic field versus base depth for different light wavelengths in open circuit ( $D_n = 26 \text{ cm}^2 \text{ s}^{-1}$ ;  $g_x = g_y = 10 \text{ cm}$ ,  $S_{gb} = 10^3 \text{ cm s}^{-1}$ ,  $S_b = 10^4 \text{ cm s}^{-1}$ ,  $L_n = 0.015 \text{ cm}$ ,  $S_f = 1 \text{ cm s}^{-1}$ ;  $H = 0.03 \text{ cm}$ ).

ticrystalline silicon solar cell can be neglected when the solar cell operates in an open circuit. When the light wavelength passes from wavelength  $\lambda = 0.38 \mu\text{m}$  to wavelength  $\lambda = 0.70 \mu\text{m}$ , the exponential quantity decreases and its minimum value is obtained for wavelength  $\lambda = 0.70 \mu\text{m}$ . From wavelength  $\lambda = 0.70 \mu\text{m}$  to wavelength  $\lambda = 0.96 \mu\text{m}$  we observe a reverse evolution, i.e. an increase of the value of the exponential quantity: it is the inversion phenomenon observed in a previous work [5]. We also notice that the attenuation of the electromagnetic field near the junction of the multicrystalline silicon grain reaches 1.226% for wavelength  $\lambda = 0.70 \mu\text{m}$ . Therefore, the attenuation of the electromagnetic wave can be neglected in the multicrystalline silicon grain and consequently in the polycrystalline silicon grain. Thus, the electromagnetic wave does not vanish while it crosses the polycrystalline and multicrystalline silicon grain.

As the attenuation of the electromagnetic field can be neglected in the polycrystalline silicon grain, the exponential quantity is taken equal to one, that is  $\exp(-x/l_p) = 1$ . Thus, in real notation, the expression of the electric field in the polycrystalline silicon grain can be written as:

$$\vec{E}(x, t) = E_0 \vec{e}_z \cos(\omega \sqrt{\varepsilon \mu} x - \omega t) \quad (12)$$

Likewise, the expression of the magnetic field in the polycrystalline silicon grain, in real notation, is:

$$\vec{B}(x, t) = -\frac{E_0 \sqrt{\mu_r \varepsilon_r}}{c} \vec{e}_y \cos(\omega \sqrt{\mu \varepsilon} x - \omega t) \quad (13)$$

#### 4. Conclusion

A modeling of the evolution of electromagnetic waves in the base region of a polycrystalline silicon solar cell under monochromatic illumination was studied. Based on the solutions of the dispersion equation in the polycrystalline silicon grain, obtained from the combination of the four equations of Maxwell, we obtained the expressions of the electric field and the magnetic field in the grain. These expressions, which are different from those in free space, are dependent on the conductivity of silicon, which in turn is a function of the density of the excess minority carriers. The density of the excess minority carriers, and hence the conductivity of the silicon solar cell, was solved for using the continuity equation. The study of the evolution of the electromagnetic wave into the grain of the polycrystalline and multicrystalline silicon solar cell showed a nonuniform attenuation of the electromagnetic field in the base depth but this attenuation is insignificant and can therefore be neglected. This result will allow us, in a future study, to solve the magneto-transport and continuity equations of excess minority carriers to find the expression of the density of excess minority carriers and the related electronic and electrical parameters of a polycrystalline silicon solar cell when exposed to radio waves.

#### References

- [1] Billy, N.; Desbois, J.; Duval, M. A.; Elias, M.; Monceau, P.; Plaszczyński, A.; Toulmonde, M. *CAPES de Sciences physiques, Tome 1-Physique*, 3rd ed.; Belin: Paris, France, 2004 (in French).
- [2] Drapalik, M.; Schmid, J.; Kancsar, E.; Schlosser, V., Klinger, G. In *International Conference on Renewable Energies and Power Quality (ICREPQ'10)*, Granada, Spain, 23–25 March 2010.
- [3] Erel, S. *Teknoloji* **2008**, *11*, 233-237.
- [4] Zerbo, I.; Zoungrana, M.; Seré, A. D.; Ouedraogo, F.; Sam, R.; Zouma, B.; Zougmore, F. *Revue des Energies Renouvelables* **2011**, *14*, 517-532 (in French).
- [5] Zerbo, I.; Zoungrana, M.; Ouedraogo, A.; Korgo, B.; Zouma, B.; Bathiebo, D. J. *Global J. Pure Appl. Sci.* **2014**, *20*, 139-148.
- [6] Zerbo, I.; Zoungrana, M.; Seré, A. D.; Zougmore, F. *IOP Conf. Ser. Mater. Sci. Eng.* **2012**, *29*, 012019.
- [7] Ba, B.; Kane, M. *Sol. Energ. Mat. Sol. C* **1995**, *37*, 259-271.
- [8] Ba, B.; Kane, M.; Sarr, J. *Sol. Energ. Mat. Sol. C* **2003**, *80*, 143-154.
- [9] Dugas, J. *Sol. Energ. Mat. Sol. C* **1994**, *32*, 71-88.
- [10] André, M. *Electronique et photo-électronique des matériaux et composants 2 photo-électronique et composants*; Lavoisier: Paris, France, 2009 (in French).
- [11] Dominique, F. *Endommagements et rupture de matériaux*; EDP Sciences: Paris, France, 2004 (in French).

- [12] Diallo, H. L.; Maiga, A. S.; Wereme, A.; Sissoko, G. *Eur. Phys. J. Appl. Phys.* **2008**, *42*, 203-211.
- [13] Dieng, A.; Zerbo, I.; Wade, M.; Maiga, A. S.; Sissoko, G. *Semicond. Sci. Technol.* **2011**, *26*, 095023.
- [14] Mbodji, S.; Ly, I.; Diallo, H. L.; Dione, M.M.; Diasse, O.; Sissoko, G. *Res. J. Appl. Sci. Eng. Technol.* **2012**, *4*, 1-7.
- [15] Mathieu, H.; Fanet, H. *Physique des semiconducteurs et des composants électroniques*; Dunod: Paris, France, 2009 (in French).
- [16] Green, M. A. *Sol. Energ. Mat. Sol. C* **2008**, *92*, 1305-1310.
- [17] Bassore, P. *Prog. Photovolt., Res. Appl.* **1994**, *2*, 177-179.
- [18] Equer, B. *Energie Solaire Photovoltaïque: Physique et technologie de la conversion photovoltaïque*; UNESCO: Paris, France, 1991 (in French).