

A model for semiconductor photovoltaic (PV) solar cells: the physics of the energy conversion, from the solar spectrum to dc electric power.

F. B. Matos(MSc)**, J. R. Camacho(PhD)*

* Universidade Federal de Uberlândia, School of Electrical Engineering, Av. João N. de Ávila, 2121; Campus Santa Mônica; 38400.902 - Uberlândia; MG; Brazil – e.mail: jrcamacho@ufu.br

** CEFET – Centro Federal de Educação Tecnológica, Faz. Palmital, Rod. JK 330, Km. 2.5 ; 75970-000 -Urutai; GO; Brazil – e.mail: nando_cefet@hotmail.com

Abstract-- It is well understood that the photovoltaic (PV) energy is a very clean and environmentally friendly renewable energy source. Through the use of the concepts of physics a detailed explanation on the whole mechanics on how electric current can be obtained from the incidence of the solar spectrum in a semiconductor. This work is based in the fact that many bibliographic references make use of the well known $V \times I$ equation for a solar cell or solar panel without explaining adequately the basis of physics processes of current generation in a semiconductor solar cell. This work shows the results of a proposed mathematical model applied to computers showing the basic considerations on how electric power can be pull out of a cell by the incidence of sun light.

Index Terms - photovoltaic effects, photovoltaic cells, semiconductor junctions, charge carrier processes.

I. NOMENCLATURE

A -----Photovoltaic net cell area in cm^2
 A_{Cn} -----N type semiconductor capture area in nm^2
 A_{Cp} -----P type semiconductor capture area in nm^2
Al -----Aluminum
As -----Arsenide
B -----Boron
c -----Speed of light in km/s
C -----Carbon
d -----Diffuse level
 DEE_{cc} ----- Effective density of states in the conduction layer
 DEE_{cv} ----- Effective density of states in the valence layer
 D_n -----Electronic diffusion coefficient
 D_p -----Hole diffusion coefficient
E -----Photon energy (Gap energy)
 E_c -----electron average kinetic energy
 E_f -----Fermi energy
 E_g -----Energy Gap or Separation Energy in eV
 E_λ ----- Photon energy for each wavelength
f -----Fundamental level
fcc -----Face centered cube
 F_{ph} ----- Number of photons close to the depletion layer
Fr -----Fraction of light for certain wavelength
Gap -Energy separating the valence and conduction layers in eV
Ge -----Germanium
GaAs -----Gallium Arsenide
h -----Planck constant
H -----Hydrogen
IL -----Incident light intensity over a distance in J.s/cm^2
 IL_0 -----Incident light intensity over the matter in J.s/cm^2
 I_0 -----Saturation reverse current in Ampere
k -----Extinction coefficient

K -----Boltzmann constant
 k_n ----- wave number
 L_n -----Length traveled by minority carrier *electron* in nm
 L_p -----Length traveled by minority carrier *hole* in nm
 m_{ee} -----Electron effective mass
 m_{el} -----Hole effective mass
 n_i -----Semiconductor intrinsic concentration
 N_a -----Acceptor impurity concentration in atoms per cm^3
 N_d -----Donor impurity concentration in atoms per cm^3
 N_{ph} ----- Number incidence of photons
O -----Oxygen
P -----Weighting coefficient for a fraction of light
p -----Main level
 P_{MAX} -----Maximum power in Watts
 P_m ----- Spin of incidence photon
PN -----Type P and N semiconductor junction
q -----Electron charge
s -----Sharp level
Si -----Silicon
Sn ----- Surface recombination speed in type n semiconductor
Sp ----- Surface recombination speed in type p semiconductor
T -----Temperature in Kelvin
V -----Voltage applied to the load
 V_{bi} -----Potential barrier of a PN junction in volts
 V_{OC} -----Open circuit voltage in volts
 V_{tn} -----Thermal speed for the type N semiconductor
 V_{tp} -----Thermal speed for the type P semiconductor
w -----Penetration depth in nm
 W_n -----Depletion layer length over a type N semiconductor in nm
 W_p -----Depletion layer length over a type P semiconductor in nm
 α -----Matter absorption coefficient
 ϵ -----Permittivity
 ξ -----Electrical field
 λ -----Wave length in nm
 θ -----work function of photo-electric threshold
 σ -----Conductivity
 τ_n -----Electron minority carrier lifetime in s
 τ_p -----Hole minority carrier lifetime in s
 f -----Wave frequency in Hz
 ρ -----Matter resistivity

II. INTRODUCTION

To be possible to establish a computational model for the PV cell it is necessary to know their physical behavior and its relationship with light.

Optical, Electrical, thermal, magnetic and electronic properties of materials are explained through the electronic theory applied to solids as described by Hummel[10]. The quantum theory takes into

consideration the materials sub-atomic behavior and was able to explain light expected behavior. In the same way, this theory is applied in the explanation of many properties of solid materials and its interaction with light and electrons.

A solar cell is basically made of two semiconductors, the first being type N and the second being type P. The structure of the material component of the cell is of enormous importance for the determination of its behavior. Different elements can be used for the assembling of semiconductor that will be the basis of a PV cell, also having a large number of possibilities in the use of doping elements for the formation of semiconductors type N and P. The type N semiconductor is the component of the cell that will be light up by the sun, while the type P semiconductor will be in the back of the solar cell. The union of both kinds of semiconductors makes the PN junction, already well explained by Physics and Electronics. However, to have the photocurrent, it is necessary that the incident photons are able to arrive at the region of the PN junction, in the depletion layer region that means the proximity of the middle of the two regions. So, the structure description of these two crystalline elements is a contrast to help to understand the behavior of these materials when exposed to light.

III. PHYSICS OF PHOTOVOLTAIC CELLS

To build ordinary PV cells, materials used in their assembling are semi-metals and semiconductors. The physics of solar cells are based on the theory of Semi-metals, semiconductors, semiconductors crystalline structure and electrons in the semiconductor crystal[14], Fermi Level and State Density.

A. Fermi Level

This theory says that at 0° Kelvin temperature all the electrons will be occupying the lower energy levels. This energy level is called *Fermi level* or *Fermi energy*.

The level of kinetic energy of a cloud of electrons can be determined by statistical equations called Fermi-Dirac formulation, or Fermi-Dirac functions of temperature, as described by Equation 1.

$$f = \frac{1}{\exp\left(\frac{E - E_f}{KT}\right) + 1} \quad (1)$$

With temperatures above 0° Kelvin, the Fermi level establishes a 50% probability to find an electron in that energy level.

Therefore it is possible, for a certain material, to use the Fermi-Dirac distribution to find the electron (or hole) density in a certain energy level, it is important to highlight that the Fermi level is matter dependent.

Like in the Fermi level, higher temperatures establish the 50% probability to find an electron in a certain energy level, so can be observed that this Fermi level is in general near the centre of the forbidden level. Due to the thermal excitation, vibration in the crystalline lattice, collision and other phenomena, the electron arrives in the

Fermi level, but is attracted by the valence layer, since it has no enough energy to arrive at the conduction layer.

B. State Density

Each semiconductor layer has a set of distributed energy levels, as described by Pankove[11]. In the same way the unitary cell length in the semiconductor crystalline lattice, has its influence in the energy level, being of large significance the characteristics and the crystalline lattice composition.

The energy levels can be superimposed, according to values taken by the quantum numbers for the directions in the three dimensional reference frame. In other words, the same energy level exists for different directions in space. The group with same energy level in different directions is called **Energy State**.

Quantum numbers can assume only non-zero and non-negative integer values, framing only 1 octet of the spatial sphere of the possible directions in which the energy can grow as can be seen in Eq. (2), where n is the quantum number and index x , y and z represents the three-dimensional axes.

$$E = \frac{\left(\frac{h}{2\pi}\right)^2 \pi^2}{2m_{ee}} \cdot (n_x^2 + n_y^2 + n_z^2) \quad (2)$$

The energy states can or can not be populated with electrons, the **electronic density** is obtained with the product of the possible energy layers by the probability of those layers being filled with electrons.

According **Pauli's**¹ principle, each energy state can be filled only by electrons with opposed *spins*, in other words, one with positive and other with negative *spin*.

As a consequence, each energy level (*Sharp* – s , *Principal* – p , *Diffuse* – d and *Fundamental* – f) has a maximum number of electrons that can be accommodated, being two for the s layer, six for the layer p , ten for the layer d and fourteen for the layer f .

Semiconductors considered in this work are the representatives of IV-A column in the periodic table, being the Silicon with atomic number 14 and Germanium with atomic number 32. Both elements have 4 electrons in the last level, in the case of *Si* and *Ge* the filling of energy layers are respectively equal to $3sP^{2P}3pP^{2P}$ and $4sP^{2P}4pP^{2P}$.

In the semiconductors case a superposition of states exists in levels s and p in the valence or in the conduction layer, as described by Hummel[10].

So, this model is used to explain why semiconductors have insulating properties at temperature 0° K and are conductors in high temperatures.

IV. MATHEMATICAL MODELING

The first two equations in the modeling process of PV cells compute the photon energy of the light taking in consideration the frequency or the wavelength. This

¹ The filling of energy states by electrons follows the Pauli Exclusion Principle, proposed by the Austrian Wolfgang Ernest Pauli (1900-1958) in 1925.

relationship is given by equations (3) as described by Tippler[15] and is related to the light behavior in semiconductors.

$$E = h.f = \frac{h.c}{\lambda} \quad (3)$$

Where: E is the photon energy incidence; f is the frequency of incidence wave, and λ is the incidence wavelength.

Equation (4) is related to the photoelectric threshold or work function, which means, the minimum energy that is necessary for the electron to be removed from the material, making possible the occurrence of photovoltaic effect as shown by equation (3).

$$\theta = \frac{h.c}{\lambda_{\min}} \quad (4)$$

A similarity can be easily observed between equations (3) and (4), despite the fact that the notation has changed, basically with $E \geq \theta$, the photon has enough energy to remove one electron from the outer atomic level making it auspicious to the photoelectric and photovoltaic effects, on the contrary, the photon will be unable to remove one electron from the atom. Therefore, θ is also known as the photoelectric threshold. Each material has a specific photoelectric threshold that can be changed according to the doping of the main semiconductor element with several types and concentrations of chemical components².

Equation (3) is related to the light intensity with each wavelength between the maximum and minimum values. According Tippler[15] the light incidence on Earth in a sunny day is of approximately 1000 W/m², meaning that the Earth is in effect hit by 4×10^{17} photons.cm²/s.

Each light wave has a contribution for the total light spectrum in the earth surface. This contribution defines the weight of a certain wavelength in the formation of the white light according to standards applied to the formation of light spectrum.

$$Fr = \left(\frac{IL}{\lambda_{\max} - \lambda_{\min}} \right) . P \quad (5)$$

As can be seen in Figure 1 the wavelength for the incident light is between 400 and 700 nm, that is the visible spectrum of sun light.

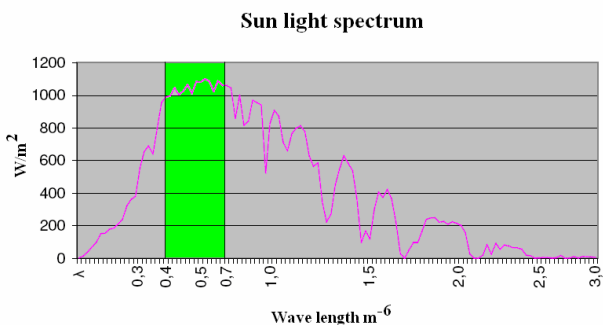


Fig. 1. Sun light spectrum.

² It is important to have the knowledge of the dopant concentration to know if the chemical combination with the main element will be stable in practice.

With the determination of the fraction of light incidence it is possible to find the amount of photons for every wavelength of light incidence in the PV cell. So the next step into modeling is related to the amount of photons in each carrying wave inside the limits of the observation spectrum.

Since every wavelength is absorbed in a very particular way by the material due to its absorption constant and extinction coefficient that will presented further in the text, it is necessary to know how many photons arrive at the target surface per second for each wavelength of light incidence, as it is depicted in equation (6) and presented in his work by Tippler[15].

The amount of photons is directly proportional to the light intensity, and inversely proportional to the photon energy, as can be observed in equation (4) and with support on Einstein's theory.

$$N_{ph} = \frac{Fr}{E_{\lambda} . q} \quad (6)$$

The program built in this work will be able to compute the amount of photons from the total radiation and from all the wavelengths inside the spectrum, therefore for each wavelength; a fraction of light incidence will be computed and also the total of photons contributing from light to electricity conversion for each wavelength.

The next equation is about the absorption coefficient of the material, according to the incidence light wavelength, as indicated in equation (5) and described by Messenger[9] and Pankove[11]. Such equation describes the physical characteristics of the material associated to the type of incidence wave, referred to the solar spectrum absorption.

The absorption coefficient is directly proportional to the extinction constant which is an inherent physical property of the material and dependent of the incidence wavelength, as described by Hummel[10]. In the computational model the values for the extinction coefficient (k) were obtained from the work of Schubert[13].

$$\alpha = \frac{4.\pi.k}{\lambda} \quad (7)$$

The algorithm in Figure 2, shows how to get the extinction coefficient (k), as mentioned previously, the values of k were obtained from the work of Schubert[13] where only a set of incomplete values were displayed. Therefore to cover the whole spectrum it was necessary to obtain other values for the corresponding wavelengths.

In order to do that two two-dimensional matrices are used, they are nominated c_wave_k and $c_wave_k_calc$. The first matrix stores the values corresponding to the sampling obtained from Schubert[13]. The second matrix store the complete values calculated by Algorithm 1. The first dimension in both matrices stores the incidence wavelength and the second dimension the value for the extinction coefficient (k) corresponding to that wavelength.

```

Algorihtm 1
begin
j=0;
for num_p of  $\lambda_{min}$  ro  $\lambda_{max}$  step1 do
begin
i=0;
while (c_wave_k [ i,0] <= num_p) do
begin
I=I+1;
end_while;
L_XI = c_wave_k [ ( i -1), 0 ];
L_XS = c_wave_k [ i, 0 ];
L_YI = c_wave_k [ ( i -1), 1 ];
L_YS = c_wave_k [ i, 1 ];
Aux_X = (L_XI + L_XS)/2;
Aux_Y = (L_YI + L_YS)/2;
while ( |Aux_x - num_p| > 1x10-14 ) do
begin
if (Aux_X >= num_p) then
begin
L_XS = Aux_X;
L_YS = Aux_Y;
end_if;
if (Aux_X <= num_p) then
begin
L_XI = Aux_X;
L_YI = Aux_Y;
end_if;
Aux_X = (L_XI + L_XS)/2;
Aux_Y = (L_YI + L_YS)/2;
end_while;
c_wave_k_calc [ j, 0] = Aux_X;
c_wave_k_calc [ j, 1] = Aux_Y;
j=j+1;
end_to;
end_Algorithm;

```

Fig. 2. Algorithm for the computation of the extinction coefficient for all the required wavelengths.

The next computation in the program is about the light intensity after traveling certain depth into the material component of the PV cell. This result is expressed by equation (8), as described by Pankove[11] and Messenger[9]. This equation allows us to infer on the amount of photons at certain depth in the material, and belongs to the group referred to the absorption of the solar spectrum

$$IL = IL_0 \cdot e^{-\alpha x} \quad (8)$$

x is the length traveled in the material.

So with the computation of equation (8) it is possible to notice that the light intensity has an exponential decay as it penetrates in the material function of the absorption coefficient.

Equation (9) deals with the wave number associated to the carrying wave. This number is going to define the number of waves for the same wavelength, which is known as *wave package*. The equation below is presented in the work by Tippler[15].

$$k_n = \frac{2\pi}{\lambda} \quad (9)$$

The incidence photon torque is obtained according to Equation (10) as also described by Tippler[15].

Once calculated the wave number, it is possible to obtain the photon spin. This is very important information, since from Physics it is well known that, two types of semiconductors exist, with direct and indirect *gap*. The semiconductors with indirect *gap* need a change in the electron spin in order for the PV effect to happen.

The interaction with a photon only doesn't mean that for a change in the electron spin, it is necessary the interaction with one phonon.

$$P_m = \left(\frac{h}{2\pi} \right) \cdot k_n \quad (10)$$

Equation (2) defines the electron energy for each level of quantum energy, based on quantum numbers n_x , n_y and n_z as described by Pankove[11].

The above mentioned levels of energy define the energy states that can be filled or not by electrons. The electronic levels indicated by main quantum numbers can only assume nonzero positive values up to a maximum of seven, due to the fact that there are seven electronic levels as indicated by Pauli(1900-1958).

Equation (11) estimates the length covered by type N minority carriers, as mentioned in Pankove[11]. This distance is of huge importance to the computational modeling, if the photon hits an atom in a type P semiconductor, a majority carrier (hole) and a minority carrier (electron) will be produced, generating a hole-electron pair. In this case if the minority carrier is able to cover a distance L without recombination and arrives at the depletion layer, it will be tossed in the type N semiconductor, therefore it will increase de electron concentration in the type N semiconductor and holes in the type P semiconductor, in this sense the conditions will be more favorable for the photocurrent generation.

$$L_p = \sqrt{D \cdot \tau_p} \quad (11)$$

Either the diffusion constant or lifetime of minority carriers is a function of the material.

So, Equation (11) shows de distance covered by type P minority carriers also present in the work done by Pankove[11].

This distance is also very important for computational modeling, if the photon hits an atom in a type N semiconductor, generating an electron-hole pair, a majority carrier (electron) and a minority carrier (hole). Therefore if the minority carrier is able to cover a distance L without recombination and get into the depletion layer, this carrier will be tossed in the P type semiconductor, increasing the concentration of electrons and holes in the type N semiconductor, making favorable conditions for the photocurrent.

$$L_n = \sqrt{D \cdot \tau_n} \quad (12)$$

Equation (13) accounts for the concentration of type N semiconductors, that according Swart[14] is used to define the semiconductor majority and minority carrier's concentration, the semiconductor intrinsic concentration depends on the component materials.

$$n \approx N_d \quad \text{and} \quad n \approx \frac{n_i^2}{N_d} \quad (13)$$

Where n is the concentration of majority carriers (electrons) in the type N semiconductor, N_d is the donor impurity concentration added in the semiconductor, p semiconductor minority carriers concentration (holes), and n_i semiconductor intrinsic concentration.

Similarly, to Equation (13) the carrier concentration (p) in the type P semiconductor, according Swart[14], is estimated approximately by substituting N_d by N_a in equation (13) above.

Equation (14) calculates the value of the potential barrier or pn junction internal potential as described by Martino[15]. This is the value formed in the pn junction and opposes to the electron and hole transference from one semiconductor to the other.

$$V_{bi} = \left(\frac{k.T}{q} \right) \cdot \ln \left(\frac{N_a \cdot N_d}{n_i^2} \right) \quad (14)$$

Equation (15) computes the type N depletion layer length based on the impurity concentration and internal potential as described by Messenger[9]. Larger the layer, bigger is the probability of a hole, generated by the formation of hole-electron pair from a collision of a photon with an atom, to arrive in the depletion layer and get tossed into the P type semiconductor.

$$W_n = \left[\frac{2 \cdot \epsilon \cdot N_a}{q \cdot N_a \cdot (N_a + N_d)} \right]^{1/2} \cdot (V_{bi} - V)^{1/2} \quad (15)$$

As in equation (15), Equation (16) calculates the type P depletion layer length based also on the impurity concentration and internal potential. Larger the layer, bigger is the probability of an electron, generated by the formation of hole-electron pair from a collision of a photon with an atom, to arrive in the depletion layer and get tossed into the N type semiconductor.

$$W_p = \left[\frac{2 \cdot \epsilon \cdot N_d}{q \cdot N_d \cdot (N_a + N_d)} \right]^{1/2} \cdot (V_{bi} - V)^{1/2} \quad (16)$$

Equation (17) computes the intrinsic current value I_0 as described by Messenger[9]. The value for the intrinsic current also called saturation reverse current must be smaller as possible, it opposes to the photocurrent, decreasing the cell efficiency.

This current depends on a number of factors as the intrinsic semiconductor concentration, cell transverse area, type of material, minority carrier's lifetime and length of depletion layer for type N and P semiconductors.

$$I_0 = q \cdot A \cdot n_i^2 \cdot \left(\frac{1}{N_a} \cdot \sqrt{\frac{D_n}{\tau_n}} \cdot \coth \left(\frac{W_p}{L_n} \right) + \frac{1}{N_d} \cdot \sqrt{\frac{D_p}{\tau_p}} \cdot \coth \left(\frac{W_n}{L_p} \right) \right) \quad (17)$$

Equation (18) estimates the electronic average kinetic energy that will be used in the computation of thermal speed, as presented in the work of Swart[14].

$$E_c = \left(\frac{3}{2} \right) \cdot K.T \quad (18)$$

Equation (19) estimates the value for the thermal speed in the type N semiconductor. This is the generation speed

for hole-electron pairs due to the thermal excitation factor. In a semiconductor in thermal equilibrium, the generation speed for hole-electron pairs is the same for the recombination of electrons and holes; therefore a constant equilibrium exists in the concentration of carriers.

$$V_{tn} = \sqrt{\left(\frac{2 \cdot E_c}{m_{ec}} \right)} \quad (19)$$

Therefore, as in equation (19), an identical equation estimates the thermal speed for the type P semiconductor (V_{tp}), in this case m_{ec} is replaced by m_{el} .

Equation (20) gives the area where can occur the capture of a hole by a trap, it means, hole-electron pairs are generated by thermal perturbation and though impact of atoms and photons. So, a minority carrier in the type N semiconductor can be attracted by an electron formed in another electron-hole pair, or that can be in excess in the material. This generally happens after the minority carrier have traveled a distance greater than L_n in the semiconductor and after a time τ_n have passed.

$$A_{cn} = A - (\pi \cdot L_n) \quad (20)$$

As described in Equation (20), the area in which can occur the capture of an electron by a trap, it means, electron-hole pairs are created though thermal agitation and through the collisions of atoms and photons. So, a minority carrier in the type P semiconductor can be attracted by a hole formed in another electron-hole pair or in excess in the material. This generally happens after the minority carrier has traveled a distance greater than L_p in the semiconductor and after a time τ_p have passed.

$$A_{cp} = A - (\pi \cdot L_p) \quad (21)$$

In the type N semiconductor, the minority carrier's recombination happens in a differentiated form in its surface. The speed in which it occurs is called surface recombination speed expressed by Equation (22).

The result of this equation will be used in the photocurrent component.

$$S_n = A_{cn} \cdot V_{tn} \cdot DEE_{cc} \quad (22)$$

In the same fashion as in the type P semiconductor, the minority carrier's recombination happens in its surface in a differentiated form. The speed in which it occurs is called surface recombination speed given by equation (23).

The result of this equation will be used in the photocurrent component.

$$S_p = A_{cp} \cdot V_{tp} \cdot DEE_{cv} \quad (23)$$

Finally equation (27) shows the photocurrent expression that occurs in the type N semiconductor according to Messenger[9].

This expression gives the electrical current generated by the exposition to the sun in the semiconductor type N, and it depends on the amount of photons in the depletion layer region and on the spectrum of incident light.

Different materials have a better gain in different range of the solar spectrum. The photocurrent in the type N material also depends on the surface recombination speed, as well as the length of the depletion layer in the type P semiconductor and the distance that the minority

carrier can travel in the type N semiconductor without having a recombination.

$$I_{ln} = \frac{q.A.F_{ph}.\alpha.L_n}{\alpha^2.L_n^2 - 1} \left[\frac{S_n \cdot \cosh\left(\frac{W_p}{L_n}\right) + \frac{D_n}{L_n} \cdot \sinh\left(\frac{W_p}{L_n}\right) + (\alpha.D_n - S_n) \cdot e^{-\alpha.W_p}}{S_n \cdot \sinh\left(\frac{W_p}{L_n}\right) + \frac{D_n}{L_n} \cdot \cosh\left(\frac{W_p}{L_n}\right)} \right] - \alpha.L_n \quad (24)$$

In order to implement equation (24), it is necessary to break it in parts to make easy the implementation. So the following presented algorithms are used to solve the following parts of equation (25) represented by equations (24.a), (24.b), (24.c) and (24.d) where:

$$I_{ln} = \frac{A_n}{B_n} \cdot \Gamma_n \quad (24.a)$$

and:

$$A_n = q.A.F_{ph} \cdot L_n \quad (24.b)$$

$$B_n = \alpha^2 \cdot L_n^2 - 1 \quad (24.c)$$

$$\Gamma_n = \left[\frac{S_n \cdot \cosh\left(\frac{W_p}{L_n}\right) + \frac{D_n}{L_n} \cdot \sinh\left(\frac{W_p}{L_n}\right) + (\alpha.L_n - 1) \cdot e^{-\alpha.W_p}}{S_n \cdot \sinh\left(\frac{W_p}{L_n}\right) + \frac{D_n}{L_n} \cdot \cosh\left(\frac{W_p}{L_n}\right)} \right] - \alpha.L_n \quad (24.d)$$

The algorithm of Figure 3 represents the solution of equation (24.a).

Algorithm 7

begin

Ftn1=0;

Ftn2=0;

Ftn3=0;

for i from λ_{min} to λ_{max} step 1 do

begin

Ftn1=Ftn1 + Beta_n [i];

Ftn2=Ftn2 + Gama_n [i];

Ftn3=Ftn3 + Lambda_n [i];

end_for;

fotocurrent_n=(Ftn1/Ftn2).Ftn3;

end_Algorithm;

Fig. 3. Algorithm that demonstrates the final result for the photocurrent in a type N semiconductor.

Therefore, in a similar way Equation (25) gives the expression for the photocurrent that occurs in a type P semiconductor that was developed from Equation (24).

This expression gives the information on the electrical current generated by photons that arrives at the type P semiconductor, and it is dependent on the amount of photons in the depletion layer region and the light spectrum incidence.

Different materials have its highest performance in different solar spectrum regions.

Photocurrent in the type P material also depends on the surface recombination speed, and also of the length of the depletion layer in a type N semiconductor and the distance that the minority carrier can travel in the type P semiconductor without recombination, as described by Messenger[15] in his work.

$$I_{lp} = \frac{q.A.F_{ph}.\alpha.L_p}{\alpha^2.L_p^2 - 1} \left[\frac{S_p \cdot \cosh\left(\frac{W_n}{L_p}\right) + \frac{D_p}{L_p} \cdot \sinh\left(\frac{W_n}{L_p}\right) + (\alpha.L_p - 1) \cdot e^{-\alpha.W_p}}{S_p \cdot \sinh\left(\frac{W_n}{L_p}\right) + \frac{D_p}{L_p} \cdot \cosh\left(\frac{W_n}{L_p}\right)} \right] - \alpha.L_p \quad (25)$$

In order to implement the expression of Equation (26), it is necessary to break it up in parts to make it easy to understand.

So the following presented algorithms will be used to solve the following parts of Equation (25) represented by Equations (25.a), (25.b), (25.c) and (25.d) where:

$$I_{lp} = \frac{A_p}{B_p} \cdot \Gamma_p \quad (25.a)$$

where:

$$A_p = q.A.F_{ph} \cdot \alpha.L_p \quad (25.b)$$

$$B_p = \alpha^2 \cdot L_p^2 - 1 \quad (25.c)$$

$$\Gamma_p = \left[\frac{S_p \cdot \cosh\left(\frac{W_n}{L_p}\right) + \frac{D_p}{L_p} \cdot \sinh\left(\frac{W_n}{L_p}\right) + (\alpha.L_p - S_p) \cdot e^{-\alpha.W_n}}{S_p \cdot \sinh\left(\frac{W_n}{L_p}\right) + \frac{D_p}{L_p} \cdot \cosh\left(\frac{W_n}{L_p}\right)} \right] - \alpha.L_p \quad (25.d)$$

The algorithm of Figure 4 represents the solution of Equation (28.a).

Algorithm 11

begin

Ftp1=0;

Ftp2=0;

Ftp3=0;

for i from λ_{min} to λ_{max} step 1 do

begin

Ftp1=Ftp1 + Beta_p [i];

Ftp2=Ftp2 + Gama_p [i];

Ftp3=Ftp3 + Lambda_p [i];

end_for;

photocurrent_n=(Ftn1/Ftn2).Ftn3;

end_Algorithm;

Fig. 4. Algorithm for the determination of the final result for the photocurrent in a type P semiconductor.

Once found the photocurrent on semiconductors type N and P, it is possible to find the total cell photocurrent by the summation of the two photocurrents, as described in Equation (26).

$$I_t = I_{ln} + I_{lp} \quad (26)$$

Where I_t is the total photocurrent, I_{lp} is the photocurrent generated in type P semiconductor, and I_{ln} is the photocurrent generated in the type N semiconductor.

With the obtained photocurrent, it is possible to find the open circuit voltage for the solar cell, that is one of the key parameters for the determination of its physical and behavioral characteristics.

This value is given in Equation (27)

$$V_{oc} = \left(\frac{k.T}{q} \right) \cdot \ln \left(\frac{I_t}{I_0} \right) \quad (27)$$

With the value of V_{oc} known, it is possible to find the solar cell short-circuit current, that is dependent of the photocurrent, of the reverse saturation current and the applied voltage.

This can be observed in Equation (28)

$$I_{sc} = I_t - I_0 \cdot \left(e^{\frac{q.V_{oc}}{k.T}} - 1 \right) \quad (28)$$

equations (27) and (28) were described in the work by Messenger[9].

To find the characteristic curve for the solar cell through voltage and current it is used the algorithm present in Figure 15, where the voltage is changed from zero to V_{oc} (open circuit voltage) where it is built the graph of Figure 5.

```

Algorithm 12
begin
  k=0;
  for v from 0 to Voc step  $1 \times 10^{-5}$  do
    begin
       $I[k] = (I_l - I_0 \cdot (e^{(-q \cdot v)/(K \cdot T)} - 1))$ ;
      Graph(v, I[k]);
      k=k+1;
    end_for;
  end_Algorithm;

```

Fig. 5. Algorithm of the graph of voltage against current characteristic for the PV cell.

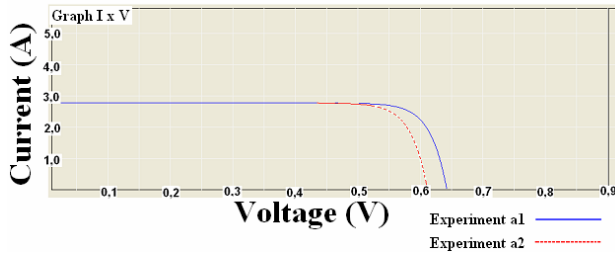


Fig. 6. Characteristic graph for the current against voltage of a PV cell for experiments a1 and a2.

In a similar fashion in order to find the maximum power point (MPP) and to draw the graph of power against voltage it is used the Algorithm present in Figure 18. Therefore the maximum power point coordinates can be found. The graph of voltage against power is presented in Figure 18.

```

Algorithm 13
begin
  k=0;
  Max=0;
  for v from 0 to Voc step  $1 \times 10^{-5}$  do
    begin
       $P = I[k] \cdot v$ ;
      if ( $P > Max$ ) then
        begin
          Max= P;
        end_if;
      Graph(P, v);
    end_for;
  end_Algorithm;

```

Fig. 7. Algorithm for the determination of the maximum power point and the drawing of the graph power against voltage.

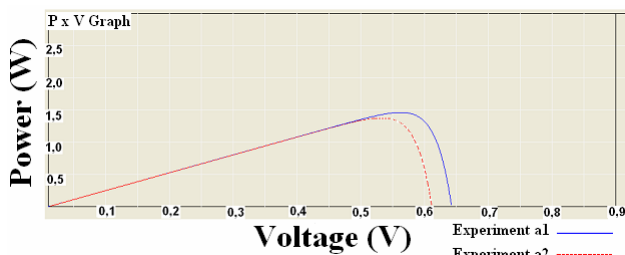


Fig. 8. Graph characteristic of power against voltage in a PV cell for experiments a1 and a2.

V. RESULTS

In the first group it is analyzed what are the better doping elements for the base semiconductors on PV cells, it is considered constant concentration and the measured external parameters. In this group it is examined the doping elements only for Silicon and Germanium, as shown in Table 1.

Table I. Doping variation according to the base element for the most common semiconductor in the solar cell.

Silicon (Si)		
	Donor	Acceptor
a1	Phosphorus (P)	Boron (B)
a2	Arsenium (As)	Aluminum (Al)

Four experiments are made, split two by two according to the type of the PV cell base semiconductor. Experiments a1 and a2 are related to Silicon.

As shown in Table I, comparative experiments are made with the Silicon doping elements. Parameters used in the experiment can be seen in Table II.

Table II. Experimental parameters.

System parameters						
λ initial	λ final	Lighting	Temperature	Thickness (N)	Depth (P)	Cell Area
400 nm	700 nm	1000 W/m ²	25°C	0,2 nm	300 nm	100 cm ²

Table II with system parameters will be used as a data for experiments a1 and a2, showing how to search for better Silicon doping elements. Table III shows the concentration used for each Silicon doping element.

Values for average doping are described in the work of Swart[14], the range for the light spectrum chosen is the range of the white light from the sun and is a photon carrier with energy between 1.77 to 3.10 eV. The light is split among the wavelengths of the spectrum range allowing a sampling of 300 different wavelengths.

For each wavelength, 4.6×10^{-4} J.s/cm² of a total 0.14 J.s/cm² is attributed to each wavelength, as described by Tippler[15] the light intensity is split among the feasible spectrum. Based on the interval of the analyzed spectrum, the program computes some constants that are necessary to the study. One of them is the extinction constant k that is used to calculate the absorption coefficient α . Relationship between k and α is given by an analytical expression.

Table.III. Doping concentration amount.

Doping parameters for the Silicon.					
Experiment: a1			Experiment: a2		
Dopant	Concentration	Type	Dopant	Concentration	Type
Phosphorus (P)	5×10^{14} atm/cm ³	N	Arsenium (As)	5×10^{14} atm/cm ³	N
Boron (B)	1×10^{13} atm/cm ³	P	Aluminum (Al)	1×10^{13} atm/cm ³	P

In such a way it is possible for the program to calculate the amount of photons after the light have

traveled certain distance in the material. For the experiment *a1* the following values shown in Table IV are given for the internal potential behavior, depletion layer and intrinsic current

Table IV. Initial results for the *a1* and *a2* experiments.

Experiment <i>a1</i>			
Internal Potential (V)	RDD side N (nm)	RDD side P (nm)	Intrinsic current (A)
$3,37 \times 10^{-3}$	$1,93 \times 10^{-3}$	$9,69 \times 10^{-2}$	$5,67 \times 10^{-11}$
Experiment <i>a2</i>			
$3,26 \times 10^{-3}$	$1,96 \times 10^{-3}$	$9,84 \times 10^{-2}$	$1,89 \times 10^{-10}$

As results we have:

Table V. Results.

Exp	Power(W)	Photocurrent (A)	Current at max. power	Open Circuit Voltage	Max. Power Voltage
a1	1,403	2,701	2,580	0,623	0,544
a2	1,323	2,701	2,570	0,529	0,515

As can be seen the exchange of both doping elements resulted in an increase of the intrinsic current. It is well known that the intrinsic current acts against the photocurrent and the performance of the solar cell as a whole, so it is expected to have a better performance of the solar cell built with the elements of experiment *a1* than with the elements of experiment *a2*.

Figure 6 presents a comparison of voltage graphs against current for experiments *a1* and *a2*.

Figure 8 presents a comparison for voltage curves against power for the same two experiments.

VI. CONCLUSIONS

The study of renewable energy sources is becoming one of the most up to date themes for the world economy, and a number of factors are related to its adoption.

So, the comprehension and command of the photovoltaic energy technology are essential for the strategic planning of the technology in the world concerning this topic. This is a complex subject in developing countries, some of them have fantastic geographical conditions for the implementation of photovoltaic energy generation, however, due to high cost, it remains far from the economical reality for such countries.

It is apparent that photovoltaic cells computational modeling software becomes an important tool for the research of new materials, new configuration, and behavior prevision under a diversity of application scenarios. As well as it happens in a large number of applications in the world industry to make cheaper the prototype making.

With the use of the computational model to find the behavior of the PV cells from material physical properties, it is possible to predict the gradual reduction cost in research and development of a model that gives the reaction of a PV cell from its electrical load.

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