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RESEARCH ARTICLE

POWER EFFICIENCY ANALYTICAL MODELING OF THE TRI-LAYER SOLAR CELLS BASED ON ENERGY GAP

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ABSTRACT

The semiconductor materials adapted to the tropical zone according to their optoelectronic properties and especially their gap energies and their molar composition were chosen. To cope with the low efficiency encountered in single junction solar cells, these materials were used in the choice of a geometry of a $Ga_{0.67}In_{0.33}P/GaAs/Ga_{0.70}In_{0.30}As$ tri-junction solar cell adapted to our area study. We have made the optimization of this solar cell efficiency by taking into account only the gap energies of the materials constituting the sub-cells and the temperature of the cell as the only design variables while setting the other parameters. An analytical model has been proposed for this purpose to determine the output parameters of the cell namely: the open circuit voltage (V_{oc}), the short circuit current density (Jsc), the fill factor (FF) and conversion efficiency (ɳ).A conversion efficiency found after optimization of the tandem cell was reported and compared to that of literature. The influence of the temperature on these parameters was studied and a coefficient of variation of the voltage as a function of the temperature of - 6.7mV /° K and the decrease of the efficiency (ɳ) of - 0.072% / °K for the tri-junction solar cell were found.

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INTRODUCTION

Currently, the countries of the tropical zone are facing the challenges of economic growth because of a lack of energy supply. Current trends in energy consumption are largely dependent on-non-renewable energy sources that are neither secured nor sustainable (Girija *et al*., 2016). Nowadays, these types of energies have a negative impact on the environment because they pollute, release large amounts of greenhouse gases and generate geopolitical tensions. In addition, the cost per unit of consumption (kWh) is a big challenge considering the purchasing power of the people of developing countries. Research in this area needs to be focused on secure, sustainable and affordable sources of energy. It is in the interest of filling the gap discussed above that many researchers have begun to be interested in new sources of renewable energy and the notable choice is going to be Photovoltaic energy because it is a source of free, inexpensive, clean and renewable energy (Solanki, 2012). Since many years ago, increasing production and use of photovoltaic energy has become a necessity all over the world and this rate of growth has led to a variety of research on the various aspects of the photovoltaic system, the development of new cells, performance analysis, sizing and energy optimization of photovoltaic systems (Celik, 2007; Sadok, 2012). To have the photovoltaic modules with high efficiency and low cost for the consumption unit; so we need a stimulating technology that can harvest most of the solar energy from a cost-effective way and this is feasible through the improvement of existing semiconductor materials or the development of new materials. This development consists in composing semiconductor alloys in order to obtain good materials with optimal optical and electronic properties to increase the solar cell efficiency (Abderrezek, 2015). The first one thing to achieve maximum efficiency of a solar photovoltaic cell is the choice of a semiconductor material suitable for incident solar radiation. The most important part of the solar spectrum arriving on the ground in the tropical zone concerns mainly the visible and near infrared domains. It is therefore very important to use semiconductor materials with forbidden band energies that are suitable for the spectrum of global radiation arriving at the ground in this area.

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The III-V semiconductor materials composed of Gallium (GaAs, GaSb) and Indium (InP, InAs, InSb) have already been identified as the materials of choice in the photovoltaic domain because of their properties, especially their high reliability (growth of excellent quality); their wide range of solar spectrum conversion; their good rate between efficiency and weight; their excellent resistance to solar radiation; their low coefficient of variation of the voltage in term of temperature and especially the openness they give to the design of completely new devices by the adjustment of band structures "*band gap engineering*" (Laval, 1990). The multi-junction III-V solar cells have attracted more attention to researchers in recent years for their very high conversions efficiency, allowing a considerable reduction in the cost of energy produced in the photovoltaic system. They use gap energies multiple to divide the solar spectrum into smaller sections which can be converted into electricity more efficiently, which allows to achieve higher efficiency than Shockly-Queisser theoretical limits for single-junction cells (Nelson *et al.,* 2013). The main purpose of this paper is first to determine the composition and properties of semiconductor alloys that can withstand the climatic and environmental conditions of the tropical zone and capable of absorbing in the widest range of its solar spectrum, then, to use these in the choice of a geometry of the solar-type cell adapted to the study area and finally optimize the geometry to improve its performance.

MATERIALS AND METHODS

Choice of semiconductor materials: The choice, among all the semiconductors, those which are adapted to the environmental and climatic conditions of the tropical zone must be based on several criteria including the optoelectronic properties already mentioned. In addition, under a fixed illumination and in the absence of any loss mechanism, the gap energy (Eg) of the semiconductor becomes an overriding parameter influencing the performance of a solar cell (Green, 1982) and this has strongly influenced our choice. It determines the absorption range of the solar cell and the quantity of photons absorbed (Equation 1):

$$\lambda(\mu m) = \frac{hc}{E_g(eV)} = \frac{1.24}{E_g(eV)} \tag{1}$$

where **λ** is the wavelength, *h* is the planck constant and **c** is the speed of light in a vacuum. Considering all these parameters mentioned above, the alloys constituting GaInP, GaAs and GaInAs semiconductors materials attracted our attention. The identification of the properties of these III-V semiconductor alloys becomes necessary and indispensable for a better exploitation of the characteristics of these materials. There are formulas in the literature which give the gap energy variation of the semiconductor alloys $Ga_xIn_{1-x}P$ and $Ga_xxIn_{1-x}As$ as a function of the molar composition **x** (Vanessa, 2012; Abderrachid, 2006).The other properties of the materials $Ga_xIn_{1-x}P$ and $Ga_xxIn_{1-x}As$ are reported in references (Haas, 2011; Goldberg, 1999; Evoy, 2012; Adachi, 1985; Adachi, 1999; Ryan, 2008). Equation (1) and Ref (Vanessa, 2012; Abderrachid, 2006) give the results in Table 1 for our semiconductor materials. The absorption coefficient is one of the essential optical properties for a semiconductor material used in the design of solar cells. Several models have been proposed for calculating the absorption coefficient. For direct gap semiconductor materials, a simple theoretical treatment based on the following model gives satisfactory results for our case (Martin, 1982):

$$\alpha(h\nu) = A(h\nu - E_g)^{\frac{1}{2}} \tag{2}$$

where A is a constant that has a numeric value of 2×10^4 when α is in (cm^{-1}), $h\nu$ and Eg in (eV).

The absorption coefficient **α** increases when the energy of the photons **hν** above the gap energy of the material increases according to equation (2). The band gap energies of GaInP, GaAs and GaInAs semiconductor materials have small temperature dependence according to (equation 3) (De soto *et al.,* 2005). This equation was used for all types of materials considered in this study.

$$E_g(T_c) = E_{g,T_{ref}}[1 - 0.0002677(T_c - T_{ref})] \tag{3}$$

with T_c the cell temperature and T_{ref} the reference temperature which is 300K for our case. T_c depends on ambient temperature, irradiance and wind speed in the region. The average annual ambient temperature in the African countries (West, Central and East) of the tropical zone is around 25 ° C and the wind speed w = $5ms^{-1}$.

Equation (4) gives us the expression of the temperature of the cell (Ayaz, 2014):

$$T_c = 1.14(T_a - T_{STC}) + 0.0175(G - 300) - K_r\omega + 30 \tag{4}$$

where T_a is the ambient temperature, T_{STC} is the temperature in the standard conditions of the test, *G* is the irradiance, k_r: coefficient varying from 1.4 -1.6 according to the technology of the photovoltaic system and ω is the wind speed.

The choice of the geometry of the solar cell: The limitation of the efficiency encountered in monojunction solar cells comes mainly from heat loss sources related to incident photons having an energy hν greater than the gap of the semiconductor constituting the cell and those related to transmission due to incident photons having a lower energy hν to the gap (Eg) of the semiconductor. In order to minimize these types of losses, and to have a wide range of absorption of the solar spectrum, the proposed solution is to use multi-junction solar cells. The latter consists of a stack of several solar sub-cells, in a decreasing order of their gap, where each sub-cell exploits the portion of the solar spectrum adapted to its gap. Theoretically, in the design of multi-function solar cells, an unlimited number of sub-cells can be used.

But in reality, the process of designing and manufacturing this component exponentially complicates with the number of cells to be added (Ryan, 2008; Stephen, 2010). However practical achievements now reach up to three or four sub-cells. Taking into account the specificity of the solar spectrum arriving at the ground in tropical zone, we chose in this work, the monolithic solar cell with three junctions (3J) whose structure is $Ga_{0.67}In_{0.33}P/GaAs/Ga_{0.70}In_{0.30}As$ or in terms of gap energies $1.93eV/1.42eV/1.00eV$. The gap energies of the GaInP and GaInAs materials were chosen so as to have an ideal compromise between the short circuit current (Isc) generated in each junction and the open circuit voltage (Voc) delivered by the cell.

The solar sub-cells are arranged in series and are interconnected electrically and optically by tunnel junctions. The performance of the tandem solar cell depends on the properties of the three sub-cells composing the structure (Top, middle and Bottom). The Top cell (GaInP) contributes with a large percentage in the total efficiency of the cell, it must have a large gap and a sufficient thickness to absorb the photons of high energy and must be transparent to low energy photons. The Bottom cells convert the low energy photons into current and must have a small gap with respect to the top cell. All the sub-cells are crossed by the same current, they must therefore check the current matching. The total voltage delivered by the cell will be the sum of all the voltages delivered by the sub-cells.

Optimization of the structure: The procedure of optimization of the geometry of the cell retained in this work will consider only the gaps energies of the top and bottom sub-cells respectively (GaInP and GaInAs) and the temperature of all the sub-cells as available design variables while setting other parameters. The optimum value of gap energy (Eg) depends on several factors. From the point of view of photon absorption, it is preferable to have a reduced gap energy, making it possible to absorb a wider spectrum of solar radiation. This results in a higher short circuit current density (J sc) delivered by the solar cell. However, it is the high value of the gap energy that determines the maximum voltage delivered by the cell. In order to maximize the conversion efficiency of the solar cell, it is therefore necessary to obtain an ideal compromise between the current and the voltage.

Analytical model: The analytical model is proposed to evaluate the maximum theoretical efficiency of solar cells and to provide data for the design of multi-junction solar cells. The current density generated as a function of the band gap is calculated directly from the spectral data. The open circuit voltage (Voc) is determined by the calculated short-circuit current density (Jsc) and the inverse saturation current density (Jo) which depends on the gap energy (Eg) and the temperature (Matthias, 1987).

The short-circuit current density is given by (Abderrezek, 2015):

$$J_{sc} = \int_{\lambda_i}^{\lambda_f} q\Phi(\lambda)EQE(\lambda)d\lambda \tag{5}$$

where q is the elementary charge, *Φ(λ)* is the flux of the incident photons, EQE(λ) is the external quantum efficiency.

$$EQE(\lambda) = \frac{Jsc(\lambda)}{q\Phi(\lambda)} = \frac{hcJsc(\lambda)}{qPin(\lambda)} \tag{6}$$

$$EQE(\lambda) = 1240\frac{Jsc[A/cm^2]}{\lambda[nm]Pin[W/cm]} \tag{7}$$

The flux $\Phi(\lambda)$ can be calculated from the irradiant (I) and the wavelength (λ):

$$\Phi(\lambda) = \frac{I\lambda}{hc} \tag{8}$$

Where *h* is the planck constant and *c* is the speed of light in the vacuum. The short-circuit current density (Jsc) at the EQE = 1 that is to say, when each incident photon creates an electron-hole pair is given by:

$$J_{sc} = \int_{\lambda_i}^{\lambda_f} q\Phi(\lambda)d\lambda \tag{9}$$

The inverse saturation current density (Jo) is given by (Hu, 1983):

$$Jo(T) = q\left(\frac{D_e}{LnN_A} + \frac{D_h}{LpN_D}\right)n_i^2(T) \tag{10}$$

where n_i is the intrinsic concentration, D_e and D_h are the diffusion coefficients of the electrons and holes respectively, Ln and Lp are the diffusion lengths of the minority carriers in the n and p-type materials, N_A and N_D are the impurity concentrations acceptors and donors. For typical levels of donor and acceptor impurity concentration for which $N_A = 10^{17} cm^{-3}$ and $N_D = 10^{18} cm^{-3}$ the parenthesized term in equation (10) can be neglected, so we have (Gerald Siefer and Andreas, 2012):

$$Jo(T) = qni^2(T) \tag{11}$$

with

$$\begin{cases} n_i^2 = N_V N_C \exp\left(\dfrac{-E_g}{kT}\right) \\ N_V N_C = 4\left(\dfrac{2\pi kT}{h^2}\right)^3 m_e^{*3/2} m_h^{*3/2} \end{cases} \tag{12}$$

so, we have

$$ni^2 = N_V N_C \exp(\frac{-Eg}{kT}) = 4\left(\frac{2\pi kT}{h^2}\right)^3 me^{*\frac{3}{2}} m_h^{*\frac{3}{2}} \exp(\frac{-Eg}{kT}) \tag{13}$$

Where N_C and N_V are actual densities of electrons and holes, h is the Planck constant, m_e* et m_h* are effective masses of electrons and holes, Eg is the gap energy of the semiconductor used. If we replace equation (13) in (11), we have:

$$Jo(T) = 4q\left(\frac{2\pi kT}{h^2}\right)^3 me^{*\frac{3}{2}} m_h^{*\frac{3}{2}} \exp(\frac{-Eg}{kT}) \tag{14}$$

Let $C = 4q\left(\frac{2\pi k}{h^2}\right)^3 me^{*\frac{3}{2}} m_h^{*\frac{3}{2}}$

Equation (14) becomes:

$$Jo(T) = CT^3 \exp\left(\frac{-E_g}{kT}\right) \tag{15}$$

In this way, the dimensions, the doping and some parameters of the materials used in the design of the solar cell are combined in this constant ***C***. The product $\boldsymbol{CT^3}$ is approximately equal to 1.5 × $10^8 mA/cm^2$ (Fan, 1986). The only important parameters for model calculations are the temperature and gap energies of the sub-cells. In this work, the gap energy (Eg) varies according to the temperature and the composition ***x*** of the alloys which constitute our materials.

Equation (15) becomes:

$$\begin{cases} J_o(T) = CT^3 \exp\left(\dfrac{-E_g(T)}{kT}\right) \\ J_o(T,x) = CT^3 \exp\left(\dfrac{-E_g(x)}{kT}\right) \end{cases} \tag{16}$$

To determine the open circuit voltage (Voc), we can start from the single-diode model that describes the characteristics (J-V) of the solar cell:

$$J(V) = Jo\left(\exp\left(\frac{qV}{AkT}\right) - 1\right) - J_{ph} \tag{17}$$

From equation (17), the temperature and the gap energy dependence of the open-circuit voltage (Voc) is deduced by placing J(Voc) = 0, and we get (Friedman, 1996):

$$V_{oc}(T) = \frac{AkT}{q}\ln\left(\frac{J_{ph}}{Jo(T)} + 1\right) \tag{18}$$

for each junction or sub-cell, we can consider in the ideal case that Jph = Jsc

$$\begin{cases} V_{OC}(T) = \dfrac{AkT}{q}\ln\left(\dfrac{J_{sc}}{J_O(T)}\right) \\ V_{OC}(T,x) = \dfrac{AkT}{q}\ln\left(\dfrac{J_{sc}}{J_O(T,x)}\right) \end{cases} \tag{19}$$

There is also a logarithmic dependence of the open circuit voltage (Voc) in concentration:

$$\begin{cases} V_{oc}(T,C) = \dfrac{AkT}{q}\ln\left(\dfrac{C \times Jsc}{J_O(T)}\right) \\ V_{oc}(T,C,x) = \dfrac{AkT}{q}\ln\left(\dfrac{C \times Jsc}{J_O(T,x)}\right) \end{cases} \tag{20}$$

where C represents the concentration of incident power, ***C = 1*** under standard conditions AM1.5G (1000W/m^2).

The equation (19) shows that it is necessary to minimize the saturation current density (Jo) which represents the recombination phenomenon to increase the open-circuit voltage (Voc).

For the fill factor calculation (FF) and the conversion efficiency (η), we use the following analytic formula (Writing, 2012):

$$FF = \frac{V_{OC} - AV_t \ln\left(\dfrac{V_{OC}}{AV_t + 0.72}\right)}{V_{OC} + AV_t} \tag{21}$$

where $V_t = \dfrac{kT}{q}$ is the thermal voltage, k : Boltzmann constant, q : the elementary charge and n is the ideality factor that can be taken as 2 at $T = 300° K$ and the conversion efficiency will be calculated using the expression:

$$\eta = \frac{FF \times Voc \times Jsc}{Pin} \tag{22}$$

Where $\boldsymbol{P_{in}}$ is the incident power of the AM1:5G spectrum (1000W/m^2)

RESULTS

The output parameters of the Tandem $Ga_{0.67}In_{0.37}P/GaAs/Ga_{0.70}In_{0.30}As$ solar cell to be determined during our work are as follows: The open circuit voltage (V$_{oc}$) as a function of the gap energies of the semiconductor materials constituting the top (GaInP), the middle (GaAs) and the bottom (GaInAs) sub-cells and as a function of the temperature of the solar cell; the optimal short-circuit current density (Jsc) between the three sub-cells; the fill factor (FF) and the conversion efficiency (η) of the Tandem cell. These parameters will be calculated according to the following steps: The short circuit current density (Jsc) of the tandem cell is defined by the lowest current density flowing in the three sub-cells; the open circuit voltage (Voc) of the tandem cell is the sum of the open circuit voltages delivered by the three sub-cells. The open circuit voltage (Voc) degrades linearly with increasing temperature. This degradation comes from the increase of the saturation current density (Jo) of the sub-cells. This is true for the top, middle and bottom subcell and for the GaInP/GaAs/GaInAs tri-junction solar cell (Figure 6).

The coefficient of variation of this voltage as a function of temperature () is -2.4mV/° K for the top sub-cell, -2.2mV/ °K for the middle sub-cell and -2.1mV/ °K for the bottom subcell. The coefficient of variation of the voltage as a function of the temperature for the tri-junction Solar cell is the sum of the coefficients of variation of the voltages of the three sub-cells composing the solar cell and is equal to -6.7mV/° K. This result is confirmed by the results of the Ref (Sze, 1998). The fill factor (FF) is a function of the open circuit voltage according to equation (21), it decreases with increasing temperature. The decrease of the open circuit voltage (Voc) contributes, in most cases, to the decrease of the efficiency (η) of the cell (equation 22). This decrease is of the order of de -0.027%/° K,-0.024%/° K,-0.031%/°Kand-0.072%/° K for the top, middle, bottom sub-cell cells and the Tandem cell. Figure (9) shows the increase of the open circuit voltage (Voc) as a function of the increase in the proportion of gallium in the alloys $Ga_xIn_{1-x}P$ and $Ga_xIn_{1-x}As$ constituting the top and bottom sub-cells of a $GaInP/GaAs/GaInAs$ tri-junction solar cell. For our case where x = 0.67 for the $Ga_{0.67}In_{0.37}P$ alloy, V_{oc} = 1.94V and x = 70 for the $Ga_{0.70}In_{0.30}As$ alloy, the open circuit voltage Voc = 0.74V.

Table 1. The band gap energies of selected semiconductor alloys and their absorption range in the solar spectrum

	$Ga_{0.67}In_{0.33}P$	$GaAs$	$Ga_{0.70}In_{0.30}As$	Comment
Bandgap(eV)	1.93	1.42	1.00	
λ_i cut-on(nm)	380	650	870	λ_i are approximate
λ_f cut-o (nm)	641	873	1237	
Composition en In (%)	33		30	

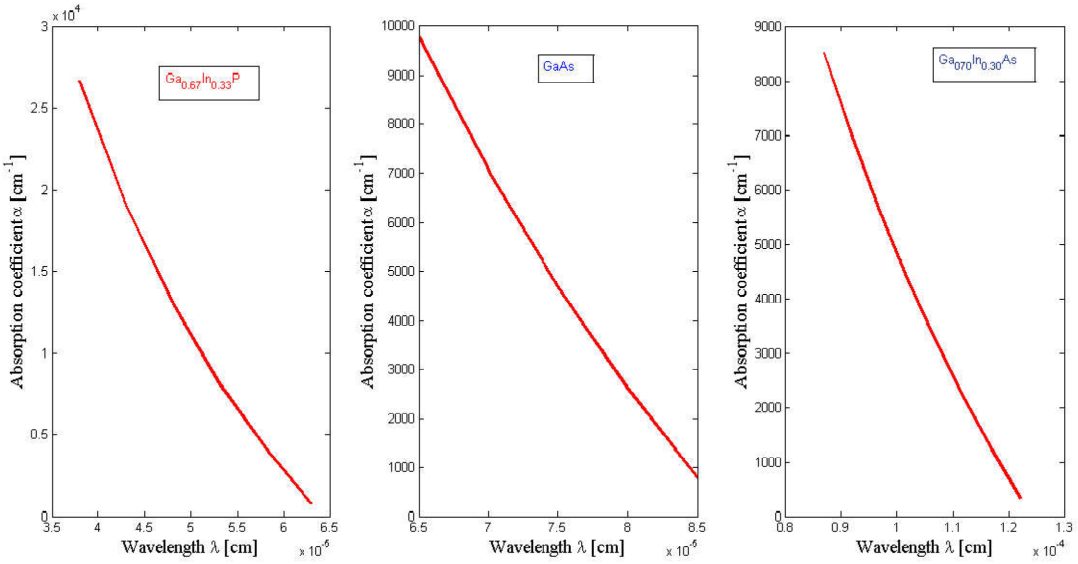

Figure 1. Variation of absorption coefficients for GaInP, GaAs and GaInAs semiconductor materials as a function of wavelength

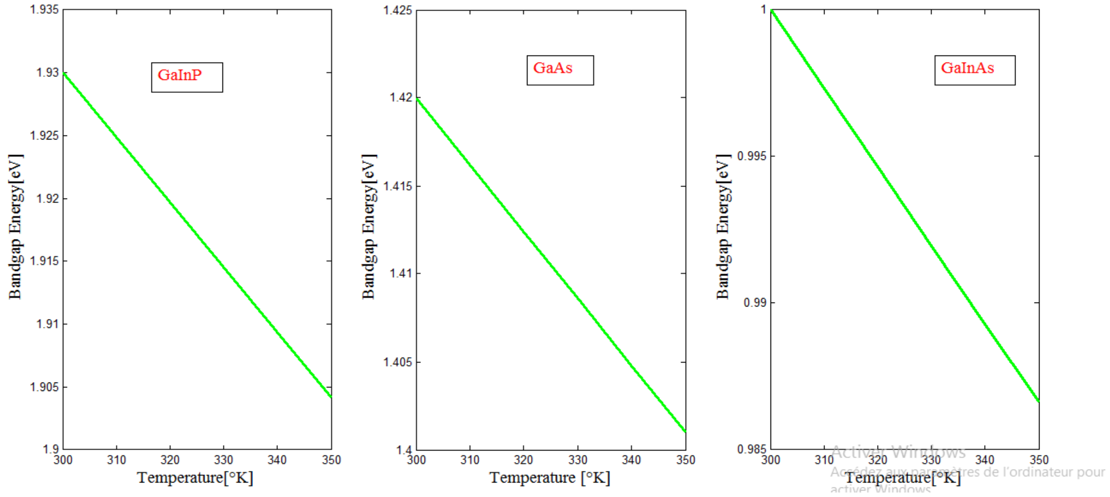

Figure 2. Variation of the gap energy of GaInP, GaAs and GaInAs semiconductors materials as a function of the temperature

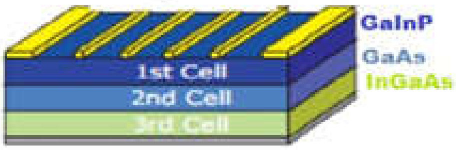

Figure 3. Approach chosen to realize multi-junction solar cells for our case

We also find that the top sub-cell contributes largely in the efficiency of the multijunction solar cell. The decrease the efficiency (η) with increasing temperature (Fig 7 and 8) is mainly controlled by the decrease of the open circuit voltage (Voc) and of the fill factor (FF) with the increase the temperature. In equation (22), Jsc increases linearly with Pin and therefore does not affect the efficiency (η), whereas the open circuit voltage (Voc) increases logarithmically with the incident power (Pin) (figures 10 and 11) and affects η.

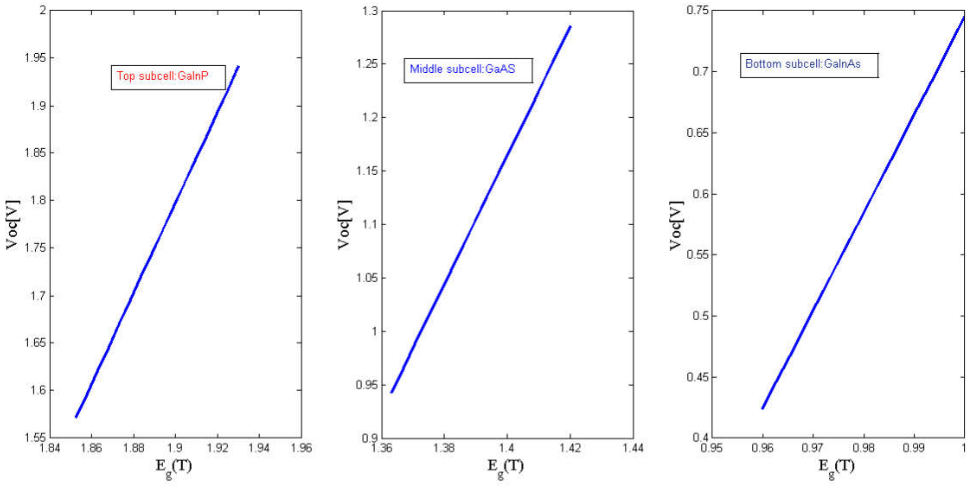

Figure 4. Variation of the open circuit voltage (Voc) as a function of the gap energies (Eg) of the sub-cells composing the GaInP/GaAs/GaInAs tri-junction cell ; Eg also varies depending on the temperature of the cell

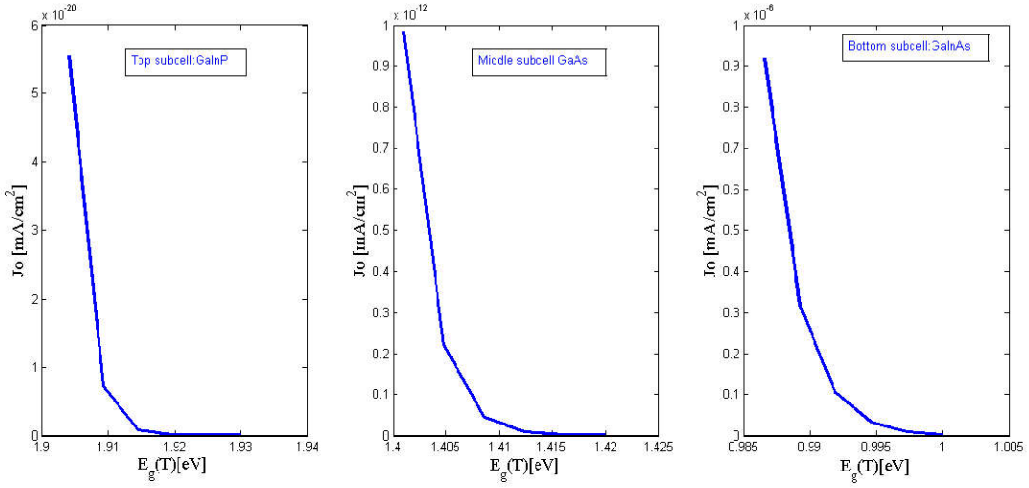

Figure 5. Variation of the saturation current density (Jo) as a function of the gap energies (Eg) of the sub-cells composing the GaInP/GaAs/GaInAs tri-junction cell

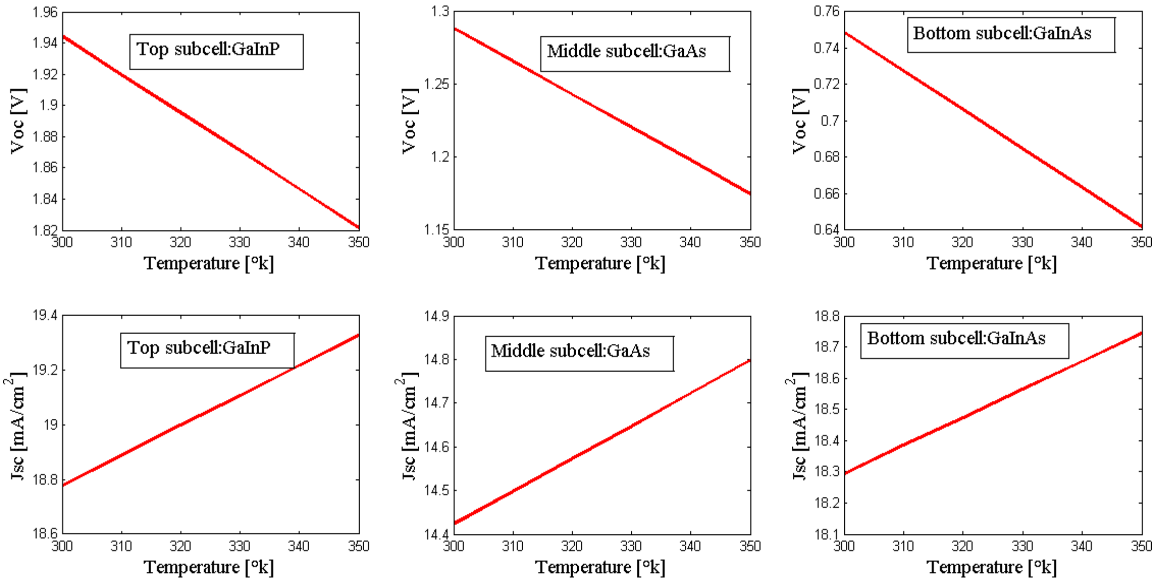

Figure 6. Variation of the open circuit voltage (Voc) and the short circuit current density (Jsc) of the sub-cells composing the GaInP/GaAs/GaInAs tri-junction solar cell as a function of the temperature

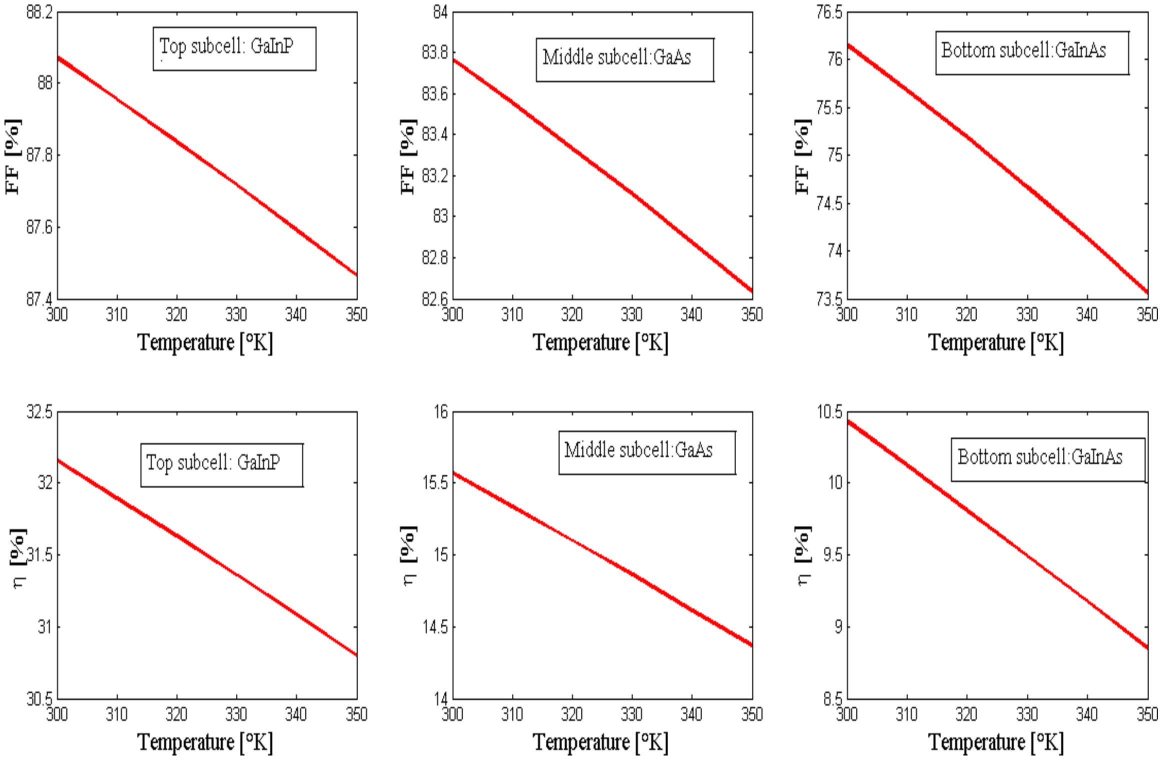

Figure 7. Variation of the fill factor (FF) and conversion efficiency (*η*) of the sub-cells composing the GaInP/GaAs/GaInAs tri-junction solar cell as a function of temperature

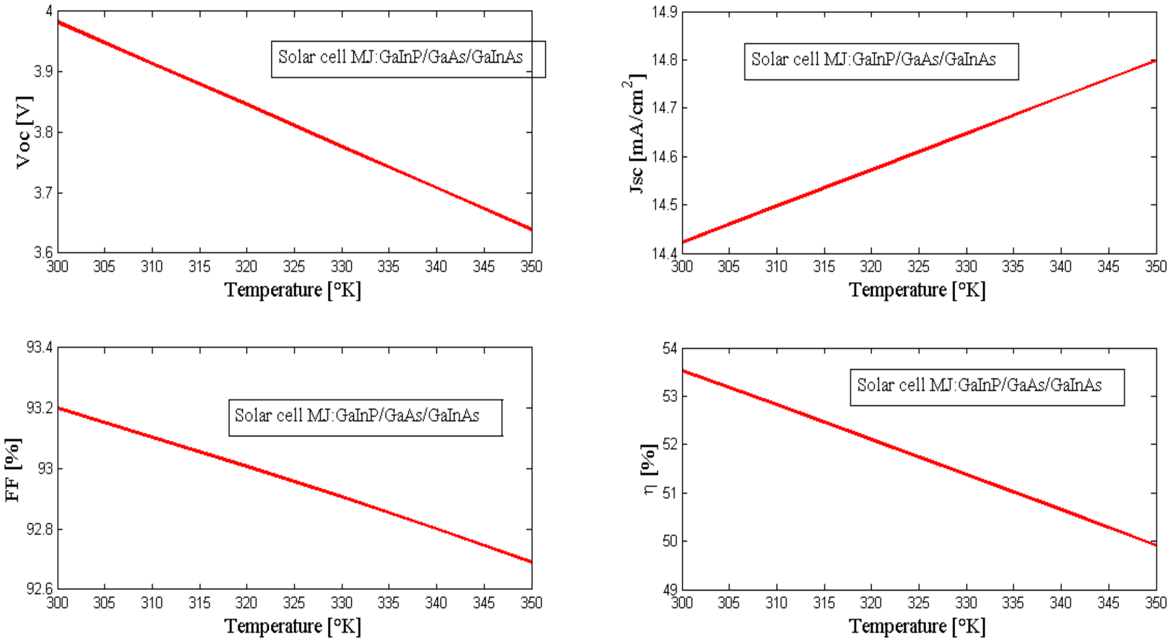

Figure 8. Effect of temperature on the output parameters of GaInP/GaAs/GaInAs tri-junction solar cell

Table 2: Comparison of conversion efficiencies (*η*) between our $Ga_{0.67}In_{0.33}P/GaAs/Ga_{70}In_{0.30}As$ tri-junction solar cell simulation results optimized with those of the Ref (Bremner, 2008) at AM1.5G spectrum

Eg_1 (eV)	Eg_2 (eV)	Eg_3 (eV)	Efficiency (*η*) (%)	
1.93	1.42	1.00	53.52	optimized solar cell
1.90	1.34	0.94	51.58	Ref (29)
2.05	1.40	0.93	51.94	Ref(29)

Table 3: Parameters of the sub-cells composing the $Ga_{0.67}In_{0.33}P/GaAs/Ga_{70}In_{0.30}As$ tri-junction solar cell

Sub-cell	E_g (eV)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	*η* (%)
GaInP	1.93	1.94	18.77	88.07	32.15
GaAs	1.42	1.28	14.42	83.76	15.57
GaInAs	1.00	0.74	18.2	76.15	10.43

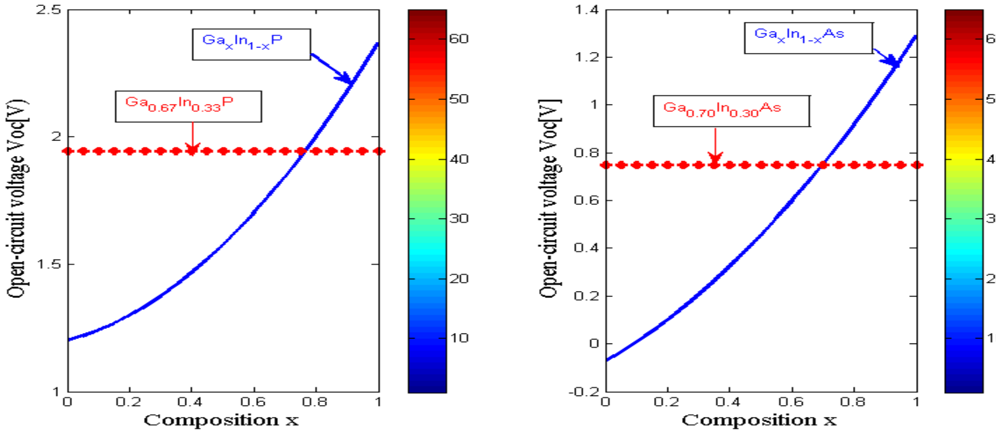

Figure 9. Variation of the open circuit voltage (Voc) as a function of the percentage of Gallium (Indium) constituting the sub-cell of a top and a bottom of the tri-junction GaInP/GaAs/GaInAs cell

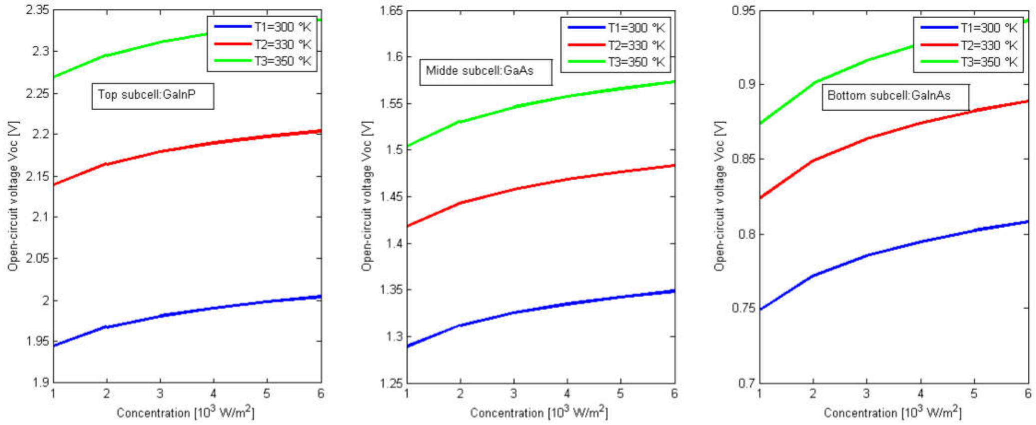

Figure 10 Variation of the open circuit voltage Voc as a function of the irradiance for different values of the temperature.

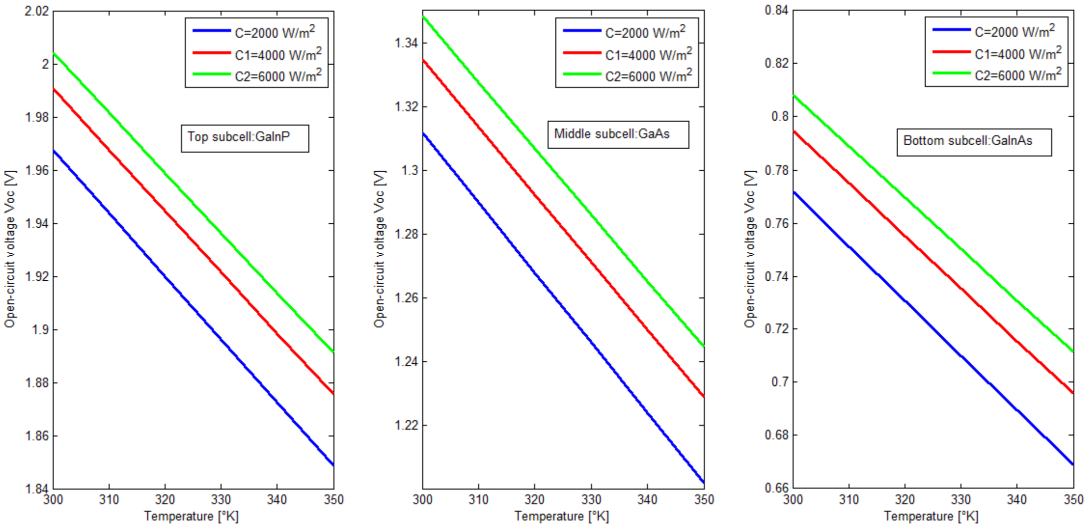

Figure 11. Variation of the open circuit voltage (Voc) as a function of the temperature for different values of the irradiance

Table 4. Calculated temperature dependence on output parameters of GaInP/GaAs/GaInAs Tri- junction solar cell, one sun AM1.5G.

T(° K)	$V_{oc}(V)$	$J_{sc}(mA/cm^2)$	FF (%)	η(%)
300	3.98	14.42	93.20	53.52
310	3.9134	14.49	93.10	52.82
320	3.8447	14.57	93.00	52.10
330	3.7761	14.64	92.90	51.38
340	3.7061	14.72	92.80	50.68
350	36388	14.79	92.69	4990

Tableau 5. Calculated temperature dependence of GaInP Top subcell parameters, one sun AM1.5G

T (° K)	E_g (eV)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η(%)
300	1.93	1.9445	18.77	88.07	32.15
310	1.9248	1.92	18.88	87.95	31.89
320	1.9197	1.8954	18.99	87.83	31.62
330	1.9145	1.8709	19.10	87.71	31.35
340	1.9093	1.8463	19.21	87.50	31.07
350	1.9042	1.8218	19.32	87.46	30.78

Tableau 6. Calculated temperature dependence of GaAs Middle subcell parameters, one sun AM1.5G

T (° K)	E_g (eV)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η(%)
300	1.42	1.2888	14.4225	83.76	15.57
310	1.4162	1.2661	14.4975	83.55	15.33
320	1.4124	1.2432	14.5725	83.33	15.09
330	1.4108	1.2204	14.6475	83.10	14.85
340	1.4086	1.1976	14.7225	82.87	14.61
350	1.4010	1.1749	14.7975	82.63	14.36

Tableau 7. Calculated temperature dependence of GaInAs Bottom subcell parameters, one sun AM1

T (° K)	E_g (eV)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η(%)
300	1.00	0.7488	18.24	76.15	10.43
310	0.9973	0.7275	18.38	75.67	10.12
320	0.9946	0.7061	18.47	75.18	9.80
330	0.9920	0.6848	18.56	74.66	9.49
340	0.9893	0.6634	18.65	74.12	9.17
350	0.9866	0.6421	18.74	73.55	8.85

The result found after optimization of our tri-junction $Ga_{0.67}In_{0.33}P/GaAs/Ga_{70}In_{0.30}As$ solar cell for efficiency is compared to that found in the simulations of Ref (Bremner, 2008) in Table 2. $Ga_{0.67}In_{0.33}P/GaAs/Ga_{70}In_{0.30}As$ tri-junction solar cell simulation results optimized with those of the Ref (Bremner, 2008) at AM1.5G spectrum.

DISCUSSION

Equation (19) shows that it is necessary to minimize the saturation current density (Jo) which represents the recombination phenomenon to increase the open circuit voltage (Voc). Figures (4) and (5) show the variation of Voc and Jo as a function of the gap energies of GaInP;GaAs and GaInAs. We notice that there is an inverse variation between the saturation current density (Jo) and the open circuit voltage (Voc) as a function of the gap energy (Eg). This is because the gap energy of the semiconductor materials constituting the tri-junction solar cell decreases as the temperature of the cell increases as shown in equation (3) and in figure (2). In addition, the short-circuit current density (Jsc) decreases as the Eg increases, this is justified by the fact that if the band gap energy of the semiconductor increases, the latter will absorb a very small spectrum and therefore very few photons and this results in a lower current density. Figure 6 shows a slight increase in the short circuit current density (Jsc) of the three sub-cells as a function of temperature. This is due to the increase in the absorption of light by these three sub-cells following a slight decrease in their gap energies Eg(T) as a function of the increase in temperature. Figure (9) shows the increase of the open circuit voltage (Voc) as a function of the increase in the proportion of gallium in the alloys $Ga_xIn_{1-x}P$ and $Ga_xIn_{1-x}As$ constituting the top and bottom sub-cells of a *GaInP/GaAs/GaInAs* tri-junction cell . This increase of Voc is due to the increase of the gap energies (Eg) of the semiconductor alloys $Ga_xIn_{1-x}P$ and $Ga_xIn_{1-x}As$ following the increase in the proportion of Gallium. The open circuit voltage (Voc) and the efficiency (η) decrease linearly with increasing the temperature, while the short circuit current density (Jsc) increases slightly with increasing temperature. This is largely due to the increase the absorption of light caused by the decrease in gap energy (Eg(T)) of the semiconductor materials constitute the tri-junction GaInP/GaAs/GaInAs cell following the increase the temperature.

Conclusion

In this work, we chose among the different materials likely to be used in the Photovoltaic field, those adapted to the environmental and climatic conditions of the tropical zone considering their optoelectronic properties. The essential element that guided our choice is the gap energy of the semiconductor taking into account the spectrum of solar radiation arriving on the ground in the tropical zone. The GaInP, GaAs and GaInAs semiconductors alloys were chosen and their properties studied; their gap energies are 1.93eV for $Ga_{0.67}In_{0.33}P$, 1.42 eV for GaAs and 1.00eV for $Ga_{70}In_{0.30}As$. In order to cope with the low efficiency encountered in single-junction solar cells mainly due to thermal losses related to incident photons having an energy $h\nu$ greater than the gap of the semiconductor constituting the cell and those related to transmission due to incident photons having a $h\nu$ energy less than the gap (Eg) of the semiconductor, we choose a tri-junction solar cell $Ga_{0.67}In_{0.33}P/GaAs/Ga_{70}In_{0.30}As$ or in terms of gap energy 1.93 eV/1.42 eV/1.00 eV where each sub-cell exploits the part of the solar spectrum adapted to its gap.

Optimization of the solar cell used in this work was based mainly on the band gap energies of the materials constituting the sub-cells and the temperature of the cell as the only design variables while setting the other parameters. An analytical model has been proposed for this purpose to determine the output parameters of the cell namely: the open circuit voltage (Voc), the short circuit current density (Jsc), the form factor (FF) and conversion efficiency (η). The influence of temperature on these parameters has been studied and reported in Table (4). We found that the coefficient of variation of the voltage as a function of temperature is -2.4mV/° K for the top sub-cell, -2.2mV/° K for the middle sub-cell and -2.1mV/° K for the bottom sub-cell. The coefficient of variation of the voltage as a function of the temperature for the tri-junction cell is the sum of the coefficients of variation of the voltages of the three sub-cells composing the cell and is equal to -6.7mV/° K. Moreover, the decrease the open circuit voltage (Voc) contributes, in most cases, to the decrease of the efficiency (η) of the cell. This decrease is of the order of -0.027% /° K, -0.024%/° K, -0.031%/° K and -0.072%/° K for the top, middle, bottom sub-cells solar and the Tandem cell. As a perspective, we propose an improvement of the absoption of our cell by adding anti-reflective layers and a texturing of the front face to reduce the reflection, in addition to improving the efficiency of the tri-junction cell at high temperature by playing on technological parameters that can reduce the voltage coefficient as a function of temperature.

Conflict of interest statement : The author declares that there is no conflict of interest with the co-authors or anyone else regarding this article submitted.

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