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Effect of Temperature on the GaInP/GaAs Tandem Solar Cell Performances

Mahfoud Abderrezek*‡, Mohamed Fathi*, Saad Mekhilef**, Farid Djahli***

*Unité de Développement des Equipements Solaires, UDES / Centre de Développement des Energies Renouvelables, CDER, 42415, Tipaza, Algérie

**Power Electronics and Renewable Energy Lab- PERAL, Department of Electrical Engineering, Faculty of Engineering, university of Malaya 50603 Kuala Lumpur, Malaysia

***L.I.S Laboratory, Department of Electronic, Faculty of Technology, University of Setif 1, 19000 Setif, Algeria

(Mahfoud_cbi@yahoo.fr, dr_fathimohamed@yahoo.fr, saad@um.edu.my, fdjahli@yahoo.fr)

‡ Corresponding Author; Mahfoud Abderrezek, Unité de Développement des Equipements Solaires, UDES / Centre de Développement des Energies Renouvelables, CDER, 42415, Tipaza, Algérie, Tel: +213-778-503-046, Fax: +213 24410133, mahfoud_cbi@yahoo.fr

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Abstract-GaInP and GaAs being promising materials for large scale photovoltaic applications, the effect of temperature on the electrical parameters of a GaInP/GaAs tandem solar cell has been investigated in this paper. The top GaInP and the bottom GaAs tandem cells were separately simulated using the one dimensional solar simulator SCAPS-1D. The temperature dependency of the solar cell's characteristics was investigated in the temperature range from 25 to 80°C. The simulation results show that voltage losses within the tandem cell are additive (Top cell and Bottom cell), while the short circuit current density depends smoothly on temperature, and the efficiency reduction is about (-0.038), (-0.035) and (-0.054 % / °C) for the bottom, top and tandem cells respectively. The matching current becomes dependent on the top cell, since this last has smaller variation compared with the bottom cell.

Keywords: SCAPS-1D; Solar cell; Temperature; Tandem; GaInP/GaAs.

1. Introduction

The concept of monolithic tandem cell is based on a stack of many solar cells with the same optical target. The cells are connected in series and arranged according to semiconductor energy gap, where each cell absorbs the range of the solar spectrum that corresponds to its gap [1]. Because of the series connection, the efficiency of the tandem solar cell is limited by the solar cell that issues the lower current. An equal current criterion, among the cells building the tandem, must be achieved; all the cells must have the same photocurrent (current matching) [2].

When the tandem cells are used in space applications or in systems under concentration, their temperature increases. This phenomenon affects negatively their electrical parameters and disturbs their operation. The need to meet the origin of this perturbation makes this study of a paramount importance.

The dependence on temperature of solar cells' performance has been extensively investigated by many authors [3, 4 and 5]. In early studies, John and Fan (1986) [3] gave a theoretical formulation for high quality monocrystalline single solar cells GaAs, Si and Ge with different energy gaps. The dependence on temperature of monolithic tandem solar cell parameters is more complex [6]. Recent studies, given by Henning et al (2013) [4] and E. F. Femandez et al (2012) [5] describe the influence of temperature and irradiance on triple junction Ga0.5In0.5P/Ga0.99In0.1As/Ge solar subcells. The temperature coefficient for tandem solar cells performances was studied under different temperature and concentration conditions.

Compared with the single junction, the effect of temperature on the tandem solar cell performances becomes very important for many raisons: the tandem cell was made with different materials and approaches, works on high temperature and its technological parameters (thickness layers and doping level) were chosen on the basis of an equal current criterion between its top and bottom cells [2], the fulfillment of the current equality condition between the cells with the increase in temperature requires a careful design of the solar cells for high temperature applications.

Table 1. Dependence of material parameters on temperature

Parameters	GaInP		GaAs	
E_g (eV)	$1.9614 - 5.4 \times \left(10^{-4} / (T+204)\right) \times T^2$	[10]	$1.5204 - 5.4 \times \left(10^{-4} / (T+204)\right) \times T^2$	[11]
n_i (cm^{-3})	$1.15 \times 10^{15} T^{3/2} \exp - \left(E_g / 2KT\right)$	[10]	$3.62 \times 10^{14} T^{3/2} \exp - (E_G / 2KT)$	[11]
N_c (cm^{-3})	$1.2 \times 10^{14} \times T^{3/2}$	[11]	$4.82 \times 10^{15} T^{3/2} (0.063)^{3/2}$	[11]
N_V(cm^{-3})	$4.82 \times 10^{15} \times T^{3/2} (0.6+0.19x)^{3/2}$	[11]	$4.82 \times 10^{15} T^{3/2} (0.51)^{3/2}$	[11]

In this work, we aim to study the temperature effect on the electrical parameters of the tandem solar cell (open-circuit voltage Voc, short-circuit current density Jsc, fill factor FF and conversion efficiency η). We aim to identify on which cell the electrical parameters of the tandem depend, when the operating temperature increases (the cell producing less current) and the magnitude of the degradation of the electrical parameters.

2. Temperature and Materials Properties

The band gap energy of a semi-conductor plays an important role in the development and design of solar cells; it defines the absorption range of the cell, the amount of absorbed photons and the maximum achievable V_{oc} and J_{sc} [7]. When a solar cell is illuminated, only the photons having energy higher than the bandgap energy (E_g) of the semiconductor are absorbed and create electron hole pairs. For the solar cells, the absorption range of solar spectrum is defined by [8]:

$$\lambda = 1.24 / E_{g(eV)} \quad (\mu m) \qquad (1)$$

Where E_g is the band gap energy and λ is the wavelength.

The variation of the semiconductor gap with the temperature is described by the Varshni model [9]:

$$E_G \text{ (eV)} = E_{g0} - \alpha T^2 / (T + \beta) \qquad (2)$$

Where T is the absolute temperature in Kelvin, α and β are the coefficients of band gap temperature dependence for the considered material (Table 1) and E_{g0} is the band gap energy at T= 0°K.

3. GaInP/GaAs Tandem Devices

Figure 1 shows a schematic diagram of the studied tandem solar cell. It consists of a Ga0.5In0.5P top cell and GaAs bottom cell. The main parameters used in the calculations are found in [12, 13, 14, 15]. The technological parameters for the different layers (thickness and doping level), used in this paper, are the same as those used by Takamoto et al (1994) [16]. Simulations of the Tandem were performed using the solar cells simulator SCAPS1-D (solar cell capacitance simulator in one dimension), developed at ELIS laboratory (Electronics and Information Systems) in GENT University, Belgium [17].

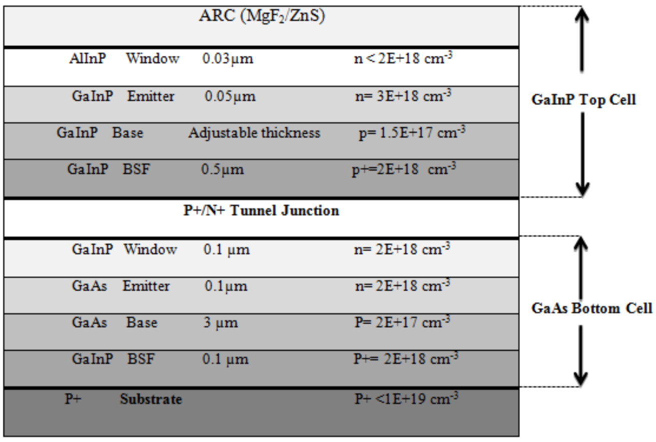


Fig. 1. The structure of the multijunction GaInP/GaAs solar cell used for simulation.

4. Results and Discussions

4.1. Tandem solar cell characteristics at 300°K

The performance of a GaInP/GaAs monolithic tandem cell at the ambient temperature 300°K and for standard spectrum AM1.5G (1000W/m²) was simulated and the cell was optimized. The top and the bottom cells of the GaInP/GaAs monolithic solar cell are dealt with separately.

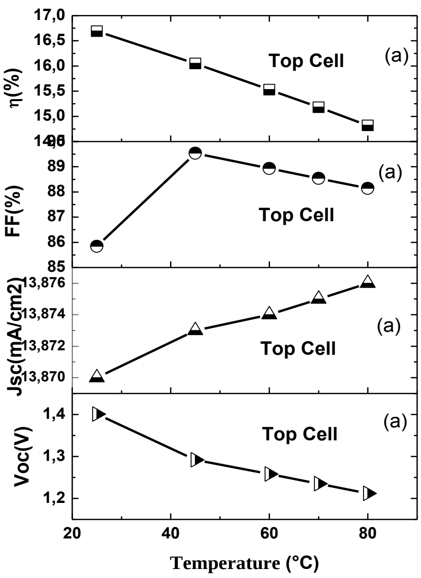
The short-circuit current density matching between the top and the bottom cells, is obtained for an optimized value of 0.7µm of the top GaInP base layer. The obtained results are given in Table 2; they are in agreement with those obtained by Takamoto et al [16].

Table 2. Output characteristics of the optimized cells

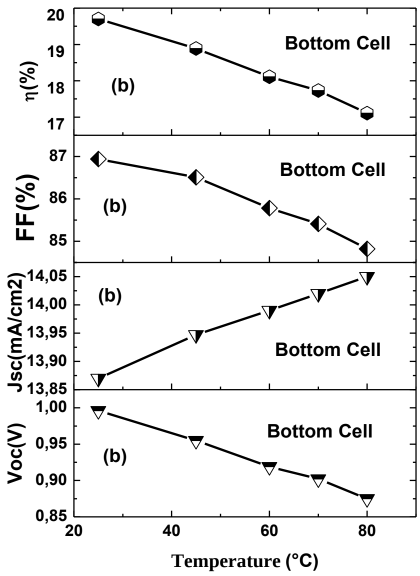
Cell Parameters at 300°K	Top cell GaInP	Bottom cell GaAs	Tandem cell GaInP/GaAs
V_{co} (Volt)	1.401	0.996	2.397
J_{sc} (mA/cm^2)	13.87	13.87	13.87
FF(%)	85.84	86.94	89.74
η(%)	16.69	19.7	29.83

4.2. Effect of temperature on the optimized tandem solar cell

After calibration of the GaInP/GaAs solar cell, the effect of temperature on the GaInP/GaAs tandem solar cell is investigated with two components: Top cell (GaInP) and Bottom cell (GaAs). The operating temperature of the cells was varied from 25°C to 80°C. The simulation results are shown in Figures 2, 3 and 4. From these simulation results, we can see a slight increase of the short-current density in both Top and Bottom cells (Fig. 2). The variation is more important in the Bottom cell (Fig. 3) because the Top cell is considered as a filter for the Bottom cell.



(a)



(b)

Fig. 2. Temperature dependence of the characteristics V_{oc}, J_{sc}, FF and η for solar cell: (a) Top cell, (b) Bottom cell

This is due to the diminution of the energy gap Eg of the semiconductor (the absorption range of the bottom GaAs cell widens with the diminution of the gap of the GaInP material constituting the top cell). This is also due to the increase of the material conductivity because of the variation of the electron-hole pairs mobility [18], as shown in expressions (3) and (4).

$$\sigma = q\left(\mu_n(T) + \mu_p(T)\right) n_i(T) \tag{3}$$

$$J = \sigma\epsilon \tag{4}$$

Where σ is the material conductivity, n_i is intrinsic concentration, μ_n and μ_p are electrons and holes mobility, q is the elementary charge, ϵ is electrical field intensity and J is the current density [19, 20]. These two phenomena accompanying the temperature increase allow the exploitation of more photons in the tandem cell. The increase in the short circuit current with temperature is about 0.01mA/cm^2 /°C.

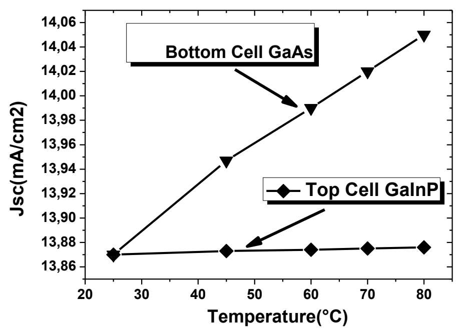


Fig. 3. Temperature dependence of the short-current density of the GaInP top cell and GaAs bottom cell

Due to the augmentation of the darkness current density Jo (reverse saturation current density) of the cell, the open circuit voltage decreases linearly with the increase of temperature. This is true for the top cell, bottom cell and the monolithic tandem cell [21]. The open circuit voltage is given by:

$$V_{oc} = (AKT/q)\ln\left({J_{sc}}/{J_0} + 1\right) \quad (V) \qquad (5)$$

Where A is the ideality factor of the diode. For the p-n junction, the darkness current is given by [10]:

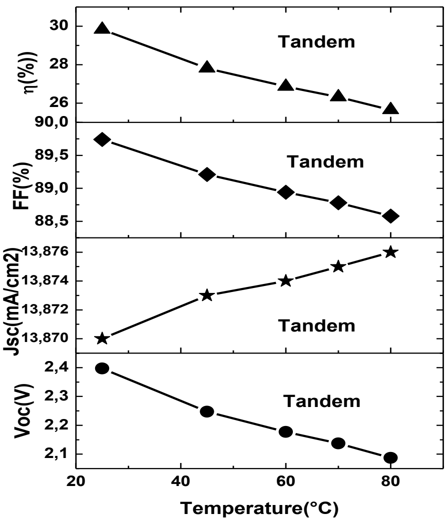


Fig. 4. Temperature dependence of the characteristics V_{oc}, J_{sc}, FF and η of the GaInP/GaAs tandem solar cell

$$Jo = K'T^{3/n}\exp\left({-Eg}/{mkT}\right) \qquad (6)$$

Where K' is an empirical parameter, k is Boltzmann's constant, m and n are empirical parameters depending on the quality of the material and the junction.

The increase of Jo is mainly due to the increase of the intrinsic carrier concentration ni [4]. For the two materials (GaInP and GaAs) used in this study, the variation in the intrinsic carrier concentration with the temperature is represented by the expression listed in Table 1, $ni = cT^{1.5}\exp - \left({E_g}/{2KT}\right)$, where C $=1.15 \times 10^{15}$ for GaInP Semiconductor and 3.62×10^{14} for GaAs.

The coefficient of the voltage variation to temperature $\Delta V_{oc}/\Delta T$ (tandem), for a tandem cell, is about - 4 mV/°C. This quantity is additive, it represents the sum of variation of the tow cells: top cell GaInP (-2.3 mV/°C) and bottom cell GaAs (-1.7 mV/°C).

The fill factor FF depends on the open circuit voltage (it decreases when the temperature increases), but it does not depend on the increase in J_{sc} with temperature. The temperature dependence of FF with temperature can be determined from the following expression [22]:

$$FF = {(v_{oc} - \ln(v_{oc} + 0.72))}/{(v_{oc} + 1)} \qquad (7)$$

Where, $v_{oc} = V_{oc}/V_{th}$ is defined as normalized V_{oc}, and $V_{th} = kT/q$ is the thermal voltage.

$$dFF/dT = \left(\left({dV_{oc}}/{dT} - {V_{oc}}/{T}\right)/(V_{oc} + V_{th})\right)\left(\left({V_{oc}}/{V_{th}} - 0.28\right)/\left({V_{oc}}/{V_{th}} + 0.72\right) - FF\right) \qquad (8)$$

The diminution in V_{oc} leads frequently to a reduction of the cell conversion efficiency. This reduction is in order of -0.038 - 0.035 and - 0.054 % / °C for the bottom, top and tandem cells respectively.

Note that the open circuit voltage decrease is considered important compared with the short circuit current diminution. It decreases linearly with the temperature increase; this is proved by the model of Green [22], given by Eq. (9) and (10).

$$dV_{oc}/dt = -\left(\left(< {E_{g0}}/{q} >\right) - V_{oc} + \left({KT}/{q}\right) < \gamma f\, {d\zeta}/{\zeta df} >\right)/T \qquad (9)$$

$$\zeta = np\exp\left({-E_g}/{KT}\right)/n_{ie}^2 \qquad (10)$$

Where f is a general function used in the reference [23] by Green, and n_{ie} is the effective intrinsic carrier concentration.

Table 3, presents the variation of the tandem cell characteristics with respect to a variation in temperature in the range 25 to 80°C. By increasing temperature from 25°C to 80°C, the conversion efficiency (ŋ) and open circuit voltage (V_{oc}) of GaInP/GaAs tandem solar cell decrease by -14.01 % and -12.93 % respectively. It should be noted that the short-current density (J_{sc}) and the fill factor (FF) were less sensitive to temperature than open circuit voltage (V_{OC}) and conversion efficiency (η); their variations are in the order of + 0.043 % and -1.29 % for J_{sc} and FF respectively.

Table 3. Performances of the GaInP/GaAs solar cell at 25 and 80 °C.

Parameters	25°C	80°C	Variation
V_{oc} (Volt)	2.397	2.087	-12.93 %
J_{sc} (mA/cm^2)	13.87	13.876	+ 0.043 %
FF (%)	89.74	88.58	-1.29 %
η (%)	29.83	25.65	-14.01 %

From Table 4, and with comparison with other results published in papers [24] and [25], it can be seen the tandem VOC temperature coefficient (ΔVoc/ΔT) is simply the sum of the top and bottom cell temperature coefficients. The dependence of the tandem temperature coefficient on the top and bottom cells and on temperature is more complex than its dependence on Voc [24]. The variation in Jsc for top cell is slightly less than its variation for bottom cell, when temperature increases. These results are in accordance with the published data [24].

Table 4. Open circuit voltage temperature coefficient of the Top, Bottom and Tandem solar cells

$\Delta V_{oc}/\Delta T$(mV/°C)	Top Cell	Bottom Cell	Tandem
Simulation result	- 2.3	- 1.7	- 4
Ref [25]	-2.2	-1.99	-4.2
Ref [26]	-	-	-3.9

5. Conclusion

In this work, we have studied the behavior of GaInP/GaAs tandem solar cell under the variation of the temperature. The electrical properties of the cells are studied for a varying temperature in the range between 25 and 80°C. We have shown that:

The increase in temperature causes the reduction of the open circuit voltage, the fill factor and the conversion efficiency of the cell.

For the tandem cell, the variation of the short circuit current with temperature is remarkable in the bottom cell. We can see that the performances of the tandem cell depend on the characteristics of the top cell when the temperature of the cell is increased.

The variation coefficient ($\Delta V_{oc}/\Delta T$), in the tandem cell, is on the order of -4 mV/°C. This quantity is additive; it represents the sum of the variation of the top cell GaInP (- 2.3 mV/°C) and the bottom cell GaAs (- 1.7 mV/°C).

The obtained results are useful for a full understanding of temperature dependence of tandem solar cells and contribute to the design and manufacturing of the tandem. In comparison with other studies, which analyze the whole tandem cells structure, this study analyses the two (bottom and top) cells separately using a one dimensional solar simulator. This allows the identification of the cell responsible for the perturbation of the current equality condition.

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