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The Effect of Graded Band Gap Structure Inserted in the Multijunction Solar Cell

Hassane Ben slimane*, A. Hemani, A. Helmaoui, B. Dennai
Laboratory of Semiconductors Devices Physics, Physics Department, University of Bechar, Algeria
*E-mil of the corresponding Author: hassane_ben@Yahoo.fr

Abstract
We have theoretically calculated the photovoltaic conversion efficiency of a monolithic dual-graded junction AlGaAs/GaInAs device, which can be experimentally fabricated. By optimizing the band-gap combination of the considered structure, an improvement of conversion efficiency has been observed in comparison to the conventional AlGaAs/GaInAs system. For the suggested graded band-gap combination, our calculation indicates that the attainable efficiency can be enhanced up to 34% (AM1.5d).
Keywords: band gap gradient, multijunction solar cells, AlGaAs, GaInAs

1. Introduction

The solar cell based on single-junction suffered from many type of losses, which could be due to fundamental or technological reasons and showed poor efficiencies. The single-junction cell absorbs photons from only a portion of the solar spectrum and it incompletely utilizes the energy of those photons that it absorbs. [1-2].

Two approaches have been used to increase efficiency above that of the single-junction conventional cell. The first is multijunction solar cell technology, this approches structure consists of multiple layers of different bandgap materials [3-4]. The properties of III-V compound semiconductors are such that these materials are well suited to thel synthesis of monolithic, multijunction cells having theoretical efficiency values approximately 50 percent higher than single-junction GaAs solar cells, in this technology each solar cell absorbs best matched slice of solar spectrum.

The second approache is to use graded band gap asorber layer [5-7]. There are two potential advantages to be gained from a graded band-gap structure. The first of these is an increase in collection efficiency through field-assisted collection. The second potential advantage is the enhancement of the open-circuit voltage resulting from an additional photovoltage produced across the graded region.

The advantages of the graded band gap structure can be inserted in the multijunction solar cell systems are underlined up to now [7-9].

The aim of our work is a comprehensive study of a monolithic dual- graded junction AlGaAs/GaInAs device using a theoretical model, which explains the effect of electric field created by band gap gradient on the performance of the global cell. . To collect the characteristics of photovoltaic component, and determine its behavior versus the electric fields created by BGG (band gap gradient), we must study the following parameters: Short-circuit current; the open circuit voltage; the efficiency photovoltaic.

2. Analysis

The proposed graded multijunction solar cell is also a two-junction device but, unlike the mechanically stacked configuration, is a monolithic structure, as shown in Fig. 1, the cell consists of wide (top) and narrow (bottom) graded band gap junctions joined electrically through a tunnel junction formed as an integral part of the monolithic structure.

The active layers consist of III-V ternary compounds selected so as to achieve the desired bandgap in each junction as well as to ideally minimize lattice mismatch between the various layers. The cascade structure may be fabricated, using liquid phase epitaxy (LPE) or vapor phase epitaxy (VPE) technology. The analytical technique employed is a closed form solution of the transport equations with the general solution obtained for the integral form of the continuity equation. Here the continuity equation considers the entire solar spectrum in the carrier generation term in each of the device regions. The analysis obtains solutions for minority carrier concentrations from the general solutions subject to the appropriate boundary conditions in each distinct region. The configuration treated is shown in figure 1.

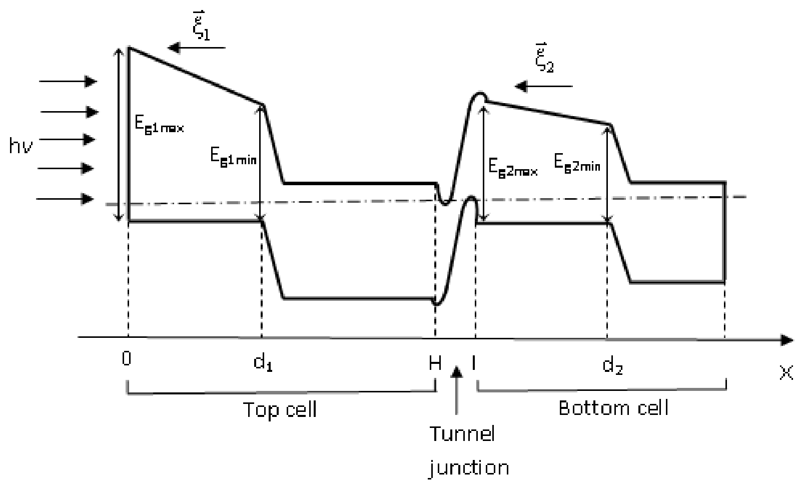

Figure 1.A schematic diagram of the structure of AlGaAs/GaInAs graded tandem cell.

2. 1. Conversion efficiency of graded top cell

2.1.1 The electron currents in the p region

The continuity equation for excess electron in the p region:

$$D_n \frac{d^2 \Delta n}{dx^2} + \mu \xi_1 \frac{\Delta n}{\tau_n} - \frac{\Delta n}{\tau_n} + g_1(\lambda, x) = 0 \tag{1}$$

Where the generation rate is expressed as,

$$g_1(\lambda,x) = I_0 \alpha_{1eff}(\lambda) exp(-\alpha_{1eff}(\lambda))x \tag{2}$$

With,

$$\xi_1 = \frac{1}{q} \frac{dE_{g1}(x)}{dx} \tag{3}$$

$$L_n = \frac{l_n}{\sqrt{1 + (\frac{\xi_1 l_n}{2V_T})^2} - \frac{\xi_1 l_n}{2V_T}} \tag{4}$$

Δn is the excess electrons concentration, D_n the diffusion constant for electrons, τ_n the electrons lifetime, I_0 is the incident photon flux at surface, $E_{g1}(x)$ is the gradient band gap in the p region of the top cell, ξ_1 is the electric field created by the graded band gap, q is the electron charge, l_n is the diffusion length if $E_g = E_{g1min}$, and L_n is the drift-diffusion length for graded band gap region. The effective absorption α_{1eff} coefficient for graded band gap semiconductors (for the top cell) is given by [10] (Table 1)

Table.1

Absorption coefficient for graded band gap absorber region

With $\alpha_{1min} = A(h\nu - E_{g1min})$

Absorption coefficient (α_{1eff})	**Photon energy ($h\nu$)**
0	$0 < h\nu < E_{g1min}$
$\frac{2}{3}\alpha_{g1min}\left(\frac{h\nu - E_{g1min}}{E_{g1max} - E_{g1min}}\right)$	$E_{g1min} < h\nu < \frac{3}{2}(E_{g1max} - E_{g1min}) + E_{g1min}$
α_{g1min}	$\frac{3}{2}(E_{g1max} - E_{g1min}) + E_{g1min} < h\nu$

Where A is a constant which depends upon the effective masses of both electrons and holes in the semiconductor, ν is the frequency of the incident radiation and I_0 Incident photon flux at surface. The short circuit current densities into the p-n junction are then determined by the minority gradient at the junction.

$$J_{scn} = eD_n \left.\frac{d\Delta n}{dx}\right|_{x=d_1} \quad (5)$$

2.1.2. The hole currents in the n region

Without the electrons field in the top n region cell, the continuity equation is expressed by

$$D_n \frac{d^2\Delta p}{dx^2} - \frac{\Delta p}{\tau_p} + g_2(\lambda, x) = 0 \quad (6)$$

$$g_2(\lambda, x) = I_1 \alpha_{1\,min}(\lambda) \exp(-\alpha_{1\,min}(\lambda) x) \quad (7)$$

The flux of photons at $x = d_1 + w_1$ is:

$$I_1 = I_0 \exp[(-\alpha_{1eff}(\lambda)(d_1 + w_1)] \quad (8)$$

Where Δp is the excess holes concentration, D_p the diffusion constant for holes, τ_p the holes lifetime, w_1 is the space charge region width for the top cell.

The short circuit current J_{scp} is expressed as,

$$J_{scp} = -eD_p \left.\frac{d\Delta p}{dx}\right|_{x=d_1} \quad (9)$$

The generation current in space charge region J_{dr} is given by [6]. The total photocurrent at a given wavelength is:

$$J_{ph} = J_{scn} + J_{scp} + J_{dr} \quad (10)$$

The total current of top cell under illumination is simply a summation of the dark current (J_d) and the photocurrent (J_{ph}), given as-

$$J(V) = J_{ph} - J_d \quad (11)$$

$$J_d = J_S(e^{\frac{eV}{kT}} - 1) \quad (12)$$

Where J_S is the saturation current given by [11]

We consider the same analysis for the bottom cell.

2.2. Conversion efficiency of multijunction tandem graded cell

For any set of n series-connected subcells (or, indeed, any sort of two-terminal element or device) whose individual current–voltage $(J - V)$ curves are described by $V_i(J)$ for the ith device, the $J - V$ curve for the series-connected set is simply

$$V(J) = \sum_i^n V_i(J) \quad (13)$$

The current density of a tandem cell J is given by the least of the current densities produced by the junctions of the tandem cell.

J = Mini(Ji), i = 1,…., n, n is the number of junctions incorporated in the tandem cell. The maximum generated power is calculated as

$$P_{mT} = J.\sum_i^n V_{mi}(J) \quad (14)$$

$$\eta_T = \frac{P_{mT}}{G} \quad (15)$$

G is the value of the total power global irradiance of the incident photon flux (AM1.5)

3. Results and Discussion

For a two-junction cell, optimizing the parameters of the top cell (width, electric field ξ_1,..) will reapportion the light between the two cells, increasing the bottom cell current(J_B) at the expense of the top cell current (J_T). If, before optimizing, $J_B < J_T$, then the top cell can be to make $J_B \approx J_T$. Because the series multijunction cell current J is limited to the lesser of J_B and J_T, J and hence the cell efficiency will be maximized when the top cell is optimized to achieve this current matching.

3.1. Cell performance with variable value of electric field ξ_2

Electric Field is varied from 2625 V/cm to 5250 V/cm through the variation of d_2, with. The performances of our cells are shown in terms of Voc, Jsc and efficiency in Fig.2. All the performance parameters show an increasing trend as the electric field ξ_2 is increased from 2625 V/cm to 5250 V/cm. For electric field ξ_2= 2625 V/cm, the obtained efficiency is 29.47%. The highest efficiency obtained is 34.84% which corresponds to electric field equal to 5250V/cm. The increase in the conversion efficiency is mainly due to the increase in the electric field created by BGG. As the électric field ξ_2 is increased more electron photogenerated in emitter of the bottom cell can be collected in the junction [9]. This eventually will contribute to more electron-hole pair generation therefore increasing the open circuit voltage, *Voc* and short circuit current, Jsc. An increase in Jsc and Voc will collectively increase the conversion efficiency of the solar cell

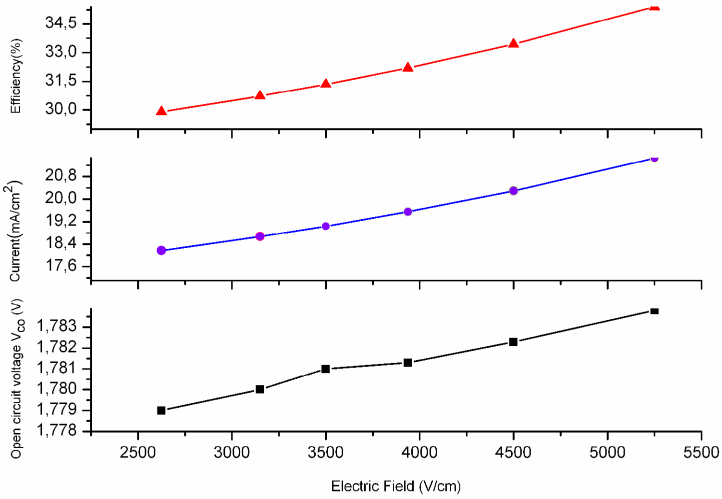

Figure 2- Cell performances with variable electric field ξ_2

3.2 Spectral response of optimized cell

The contributions to the total spectral response of the optimized graded tandem cell structure are shown in Fig. 3. It is seen that the total spectral response at 300 K is high over the wavelength 0.2 to 1.6 µm. The electron contributions to the total response of both cells are higher than their respective hole contributions because the solar radiation is first incident on the p regions in each of the cells and the electric field created by band gap gradient helps to drive minority carriers (electrons) toward the junction.

This results in greater photon absorption in the *p* regions, and consequently, there is a higher concentration of excess electrons produced.

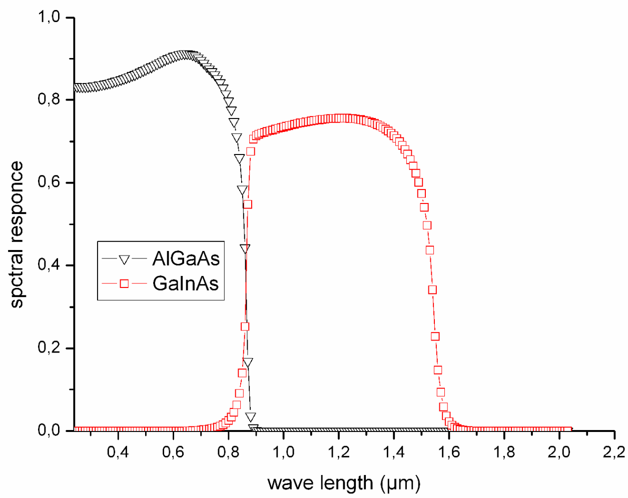

Figure 3. Spectral response of graded tandem cell and individual AlGaAs and GaInAs cells under AM1.5 illumination.

3.3. Characteristic J-V of optimized cell

J-V characteristics of the tandem cell and individual AlGaAs and GaInAs cells under AM1.5 illumination at

300K are shown in fig. 4. The short circuit current densities of the tandem cell, the AlGaAs and the GaInAs are 22.43 and 21.20mA/cm^2, respectively, because, while the open circuit voltage of these cells are 0.91 and 0.87V, respectively. As result, the short circuit current densities of the AlGaAs cell and the GaInAs cell are not the same in the tandem structure, and a short circuit current density of the tandem cell equals the one of the GaInAs cell.
The graded tandem cell features a high open-circuit voltage (V_{oc}) of 1.78 V and the current of 21.20mA/cm^2, this tow graded junction solar cell in a two terminal configuration has an overall power conversion efficiency of 34.84%.

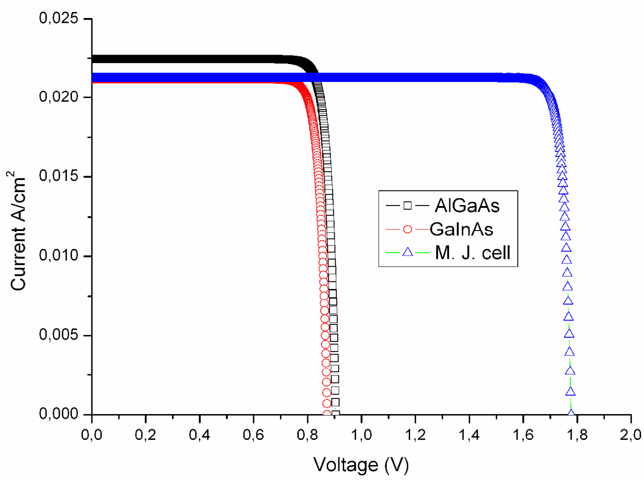

Figure4. *J-V* characteristics of graded multijunction cell and individual *AlGaAs and GaInAs cells under AM1.5 illumination***.**

4. Conclusion

The design configurations and the performance of the AlGaAs- GaInAs graded tandem solar cells have been demonstrated. Open circuit voltage of 1.78 V, short circuit current density of 21.20 mA/cm ^{2} and the conversion efficiency of 34.84% are predicted at AM1.5 illumination.
The improvement efficiency is mainly due to the existence of electric fieldsin the emitter of each cell; their origin is related to the gradients of the band-gap.
These electric fields have the effect of accelerating the minority carriers created by photons to the junction. Graded band-gap layers have the advantage of giving the important electric field (more than the electric field created by gradient doping), this field can be used as (FSF, Front Surface Field) of the one part, on the other hand, the multijunction cell with gradient band gap layers, minimizes a significant thermalization losses and non-photon absorption.

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