Theoretical Analysis of $Al_xGa_{1-x}As/GaAs$ Graded Band Gap Solar Cell

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Abstract

The graded band gap $Al_xGa_{1-x}As/GaAs$ solar cell model has been proposed. This model consists of graded compositions material in the surface layer extending from y=0 to y=D, and uniform band gap from y=D to y=L. The model simulates the absorption, generation, current density, spectral response and the solar efficiency generated from the solar spectrum. These photovoltaic parameters have been calculated by a GRAD computer program. Electric field, mobility and diffusion length of holes gradient are assumed constant in the model to get an analytical solutions. The photovoltaic parameters, obtained from the model, are Jsc =33 mA/cm^2, V_{oc}= .91 V, FF= .87 and η= 31 %. The conversion efficiency is considered high as compared with other similar models.

Keywords: graded band gap, $Al_xGa_{1-x}As/GaAs$ solar cell.

Introduction

The attempt to improve the performance of solar cells, increasing their spectral response and the power conversion efficiency through an increased collection of generated minority carriers in the graded material has been made. Hutchby and Fudrich in 1976 analyzed the graded band gap of $Al_xGa_{1-x}As/GaAs$ solar cell and calculated a theoretical efficiency of 17 % [1]. Hamaker in 1985 has presented a theoretical model of an n–p and p–n $Al_xGa_{1-x}As/GaAs$ cell with graded emitter layers. The highest predicted efficiency was 21.5 % [2]. James P. Connolly in 1997 presented a theoretical study to $Al_xGa_{1-x}As/GaAs$ and he estimated conversion efficiency was 23 % [3]. Joanna in 2005 analyzed the graded band gap (p-$Al_xGa_{1-x}As$/n-GaAs) solar cell structure as a function of the drift field in the surface layer. Conversion efficiency, exceeding 27%, was obtained [4]. Morteza in 2010 presented a study of the electrical characteristics of a single junction $Al_xGa_{1-x}As/GaAs$ solar cell. A conversion efficiency calculated was 21% [5].

In this search theoretical model and computer program GRAD were designed and applied to calculate the absorption, reflection, generation, carrier distribution, photocurrent, spectral response and the conversion efficiency of graded band gap $Al_xGa_{1-x}As/GaAs$ solar cell. Simple model for an ideal graded band gap $Al_xGa_{1-x}As/GaAs$ solar cell was provided.

Model Structure

The model adopted in this analysis is based on a cell structure, whose band-diagram is similar to Hutchby and Fudrich [1]. The model includes a graded compositions material in the surface layer extending from y=0 to y =D and a uniform band gap from y=D to y=L, as shown in Fig.(1).

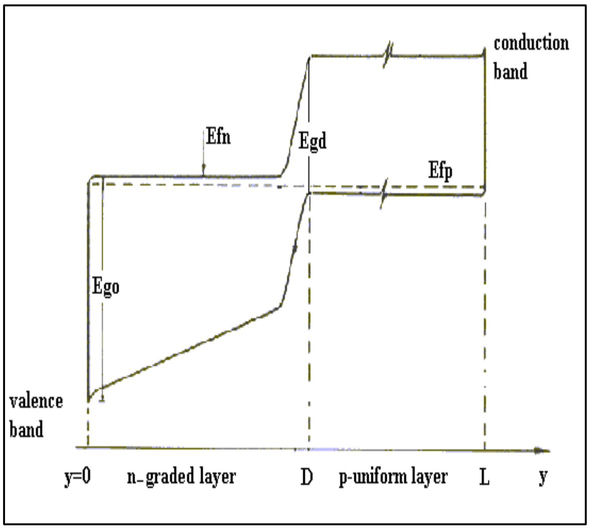

Fig.(1) The band diagram of $Al_xGa_{1-x}As/GaAs$ solar cell [1].

a. Graded $Al_xGa_{1-x}As$ region

The mathematical relations in this analysis used to calculate the current density in the graded region.

1. Energy gap

The variation of the energy band gap of the graded region $Al_xGa_{1-x}As$ depends on the range x. For direct material ($0 \le x \le .3$) the energy gap is given by [1]:

$$Eg(x) = 1.44 + 1.04x + 0.47x^2 \text{ ....(1a)}$$

For indirect material ($.4 \le x \le 1$) the energy gap is given by:

$$Eg(x) = 1.92 + 0.17x + 0.07x \text{ ....(1b)}$$

2. Electric field

The built-in electric field is primarily due to band gap gradient. The built-in electric filed is taken to be [8]:

$$E_h = -\frac{dE_g}{dy} \text{ ....(2)}$$

3. Absorption and Generation

The absorption coefficient α of incident light on the graded region is given by [9]:

$$a = a_0 \left(hn - E_g(x)\right)^{1/2} \text{ ....(3)}$$

Where a_o is constant.

And the generation rate G_s in the graded region D is given by [9]:

$$G_s = aN_0(1-R)\exp(-aD) \text{ ....(4)}$$

Where N_o is the number of incident photons on the region.

Some of the incident photons with sufficient energy are reflected, and the reflection coefficient R is given by [10]:

$$R = \frac{(n_r-1)^2 + k_0^2}{(n_r+1)^2 + k_0^2} \text{ ....(5)}$$

Where n_r is the refractive index of the semiconductor is a function of the energy gap [11]:

$$n_r = \left[\frac{77}{E_g(x)}\right]^{\frac{1}{4}} \text{ ....(6)}$$

k_o is the extinction coefficient given by [10]:

$$k_o = \frac{a\,l}{4p} \text{ ....(7)}$$

and λ is the incident wavelength.

4. Current density analysis

Flow of generated carriers is governed by the standard continuity and current density expressions. The continuity equation for steady state with low level injection in one dimension is given by [12]:

$$\sum_i G_s - \frac{\Delta p}{t_h} - \frac{1}{q}\frac{dJ_h}{dy} = 0 \text{ ....(8)}$$

Where Δp is excess minority holes concentration, τ_h is minority holes lifetime, q is the elementary charge, and J_h is the hole minority current density.

Minority carriers current can be caused by drift and diffusion. The former results from the photocurrent which produced from the acceleration of carriers in the electric field. The net current density flow is the sum of the above two components [12]:

$$J_h = qm_hE_h(p_0+\Delta p) - qD_h\frac{d}{dy}(p_0+\Delta p) \text{ .....(9)}$$

Where μ_h is the mobility of holes, D_h is the holes diffusion coefficient, E_h is the built-in electric field, and p_o the equilibrium holes concentration. These parameters are position dependent in the general case.

Dividing equation (9) by q and taking the divergence, then Substituting in the continuity equation (8) results in

$$\sum_i G_s - \left(\begin{array}{l}\frac{d}{dy}(m_hE_h(p_0+\Delta p)) - \\ \frac{d}{dy}(D_h\frac{d}{dy}(p_0+\Delta p))\end{array}\right) - \frac{\Delta p}{t_h} = 0$$

$$\text{.............................. (10)}$$

Several assumptions and approximations are taken in our considerations to solve equation (10) analytically.

5. Assumptions

The basic assumptions of this model are summarized as follows:

- Net current flows is assumed to be zero due to no incidence of light, therefore $\frac{d\Delta p_o}{dy}=0$, in the second and third terms of equation (10).
- The electric field, mobility and diffusion length gradients are negligible (not significant) in spite of the band gap linear dependence on layer thickness.

Equation (10) can be written as:

$$\frac{d^2\Delta p}{dy^2} - e_f \frac{d\Delta p}{dy} + \frac{1}{D_h}\sum_i G_s - \frac{\Delta p}{l_h^2} = 0 \text{ ....(11)}$$

Equation (11) has been solved analytically and the general solution of this transport equation is given by:

$$\Delta p = a_1 \exp(x_1 y) + a_2 \exp(x_2 y) + a_3 \exp(-a y) \text{ ....(12)}$$

Where a_1, a_2, a_3, x_1, x_2 are constant.

6. Current density calculation

The current density can be evaluated as [10]

$$J_h = q\left(\Delta p_2 m_h E_h - D_h \frac{d\Delta p_1}{dy}\right)\Bigg|_{y=D} \text{ ....(13)}$$

$\Delta p_2 = 0$ at y = D (Boundary condition)

Then equation (13) can be written as:

$$J_h = \left(-qD_h \frac{d\Delta p_1}{dy}\right)\Bigg|_{y=D} \text{ ....(14)}$$

$$J_h = -qD_h \sum_{j=1}^{N}\begin{bmatrix} x_1 a_1 \exp(x_1 D) + x_2 a_2 \exp(x_2 D) \\ -a a_3 \exp(-a D)\end{bmatrix} \text{ ....(15)}$$

The total current density caused by all photons beams in the graded n-region is:

$$J_n = \sum_i J_h \text{ ....(16)}$$

b. Uniform GaAs region

The current collected from the p-region is determined in the usual manner using the current density and a continuity equation for generated electrons is given by [12]:

$$J_e = qD_e \frac{d\Delta n}{dy} \text{ ....(17)}$$

and

$$\sum_i G_b - \frac{\Delta n}{t_e} + \frac{1}{q}\frac{dJ_e}{dy} = 0 \text{ ....(18)}$$

Where Δn is excess of electrons concentration, D_e is minority electrons diffusion coefficient, τ_e is minority electrons lifetime, and J_e is the minority electron current density.

The generation rate G_b at the uniform layer (L-D) is given by [9]:

$$G_b = N_b b \exp(-b(L-D)) \text{ ....(19)}$$

Where N_b is the number of photons incident in the uniform region, y is the absorption layer and b is the absorption coefficient and given by [9]:

$$b = b_0 (hn - E_{gd})^{1/2} \text{ .... (20)}$$

b_0 is constant and E_{gd} is the uniform energy gap.

Dividing equation (17) by q and by taking the divergence, then Substituting in equation (18)

$$\frac{d^2\Delta n}{dy^2} - \frac{\Delta n}{l_e^2} = -\frac{1}{D_e}\sum_i G_b \text{ .... (21)}$$

This equation, which describes the distribution of the generated carriers in the uniform band gap region, has been solved. The general solution is given as:

$$\Delta n = b_1 \exp(y/l_e) + b_2 \exp(-y/l_e) + b_3 \exp(-b\, y) \text{ .... (22)}$$

Where b_1, b_2, b_3 are constants.

1. **Current density calculations**

The current collected from the uniform band gap region is determined by using the current density equation [12]:

$$J_e = qD_e \frac{d\Delta n}{dy}\Bigg|_{y=L-D} \text{ .... (23)}$$

The photocurrent density caused by photon beam can be evaluated as:

$$J_e = qD_e \begin{bmatrix} -\frac{b_2}{l_e}\exp(-(L-D)/l_e) - \\ b_3 b \exp(-(L-D)b) \end{bmatrix} \text{ .... (24)}$$

The total current density collected in the uniform p-region is:

$$J_P = \sum_i J_e \text{ .... (25)}$$

c. Spectral response

The spectral response (quantum efficiency) is defined as the ratio of the number of collected carriers by the junction to the number of incident photons at a given wavelength [12].

The spectral response for graded band gap is

$$S_n = J_n / qF_s \text{ .... (26)}$$

and for uniform band gap

$$S_p = J_p / qF_b \text{ .... (27)}$$

d. **Efficiency calculation**

The solar efficiency of a solar cell is defined as the ratio of the output electrical power to the incident optical power [13] and given by:

$$h = \frac{P_m}{P_s} \text{ ....(28)}$$

Where P_m is the maximum output electrical power given by

$$P_m = V_{oc} FF J_{sc} \text{ ....(29)}$$

Where V_{oc} is the open circuit voltage, FF is the fill factor and J_{sc} is the short-circuit current and given by

$$J_{sc} = J_n + J_p \text{ ....(30)}$$

And P_s is solar input power and equal to (.0844 w/cm^2) for the direct normal spectrum radiation (AM1.5D) [6].

e. Program Design

To perform the calculations of this analysis the input data must be presented. These data includes the solar spectrum incident on the solar cell [6], semiconductors parameters for AlAs and GaAs [1] [7], and the device parameters adopted in this model. All these data were used in the program GRAD and the results (The photovoltaic parameters of $Al_xGa_{1-x}As$/GaAs Cell) were obtained. GRAD program consists of individual subprograms. first subprogram represent the input data of the modeled solar cell, consists of solar spectrum, solar cell parameters and design parameters of the solar cell. Second subprogram calculated the distribution of the solar spectrum in each region (n- and n- regions) of solar cell. Third subprogram calculated the current density and the spectral response in the graded n-region. Fourth subprogram calculated the current density and the spectral response in the uniform p-region. Finally subprogram calculated the efficiency of the solar cell.

Result and Discussion

When the beams of light incident on the solar cell some of the photons light is absorbed then an electron-hole pairs are generated. The absorption coefficients (3, 20) and the generation rates (4, 19) as a function of wavelength are shown in Fig.(2) and Fig.(3) respectively.

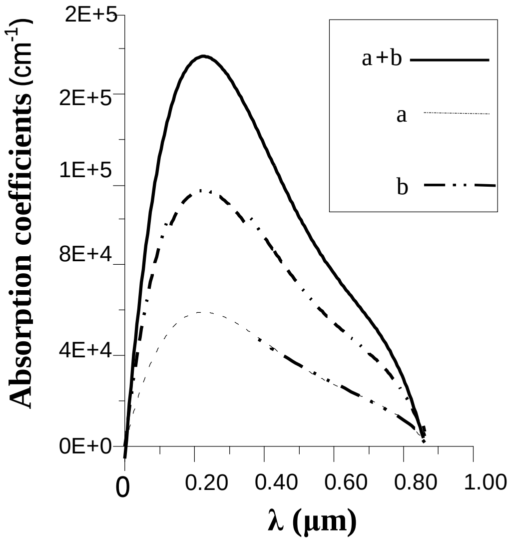

Fig.(2) The absorption coefficients in the graded, uniform regions and total absorption vs. wavelength.

The graded band gap solar cell $Al_xGa_{1-x}As$/GaAs splits each incident beam into individual components according to the number of layers in the solar cell. This splitting makes the absorption and the generation more useful compared with uniform energy gap solar cell by reducing the thermalisation effect [4].

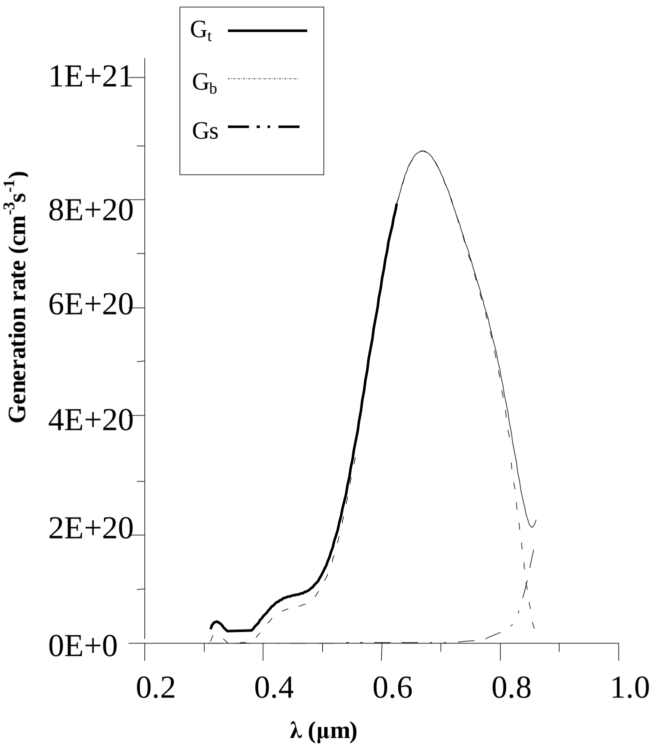

Fig.(3) The generation rates in the graded, uniform and total generation vs. wavelength.

The current density generated in the solar cell for graded region J_n, uniform region J_p and the total photocurrent J_t are shown in figure 4. The most contribution to the total current J_t comes from the graded region although the difference between the distributions of the minority carriers in n-and p-regions are not so large. This is because the transport in the n-graded region is dominated by the drift electric field.

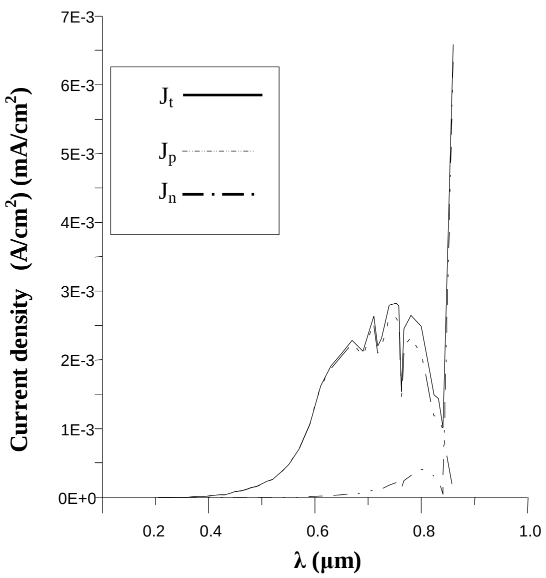

Fig.(4) The current density in the graded, uniform, and total current vs. wavelength.

The spectral response of the solar cell is a good indication about the performance of the solar cell devices. Figure 5 shows the total spectral response S_t, the contribution from the $Al_xGa_{1-x}As$ region S_n, and the base GaAs region S_p as a function of wavelength. It is clear from this figure that the blue response (response in the short wavelengths) increased in the graded band gap (window effect) compared with the uniform band gap.

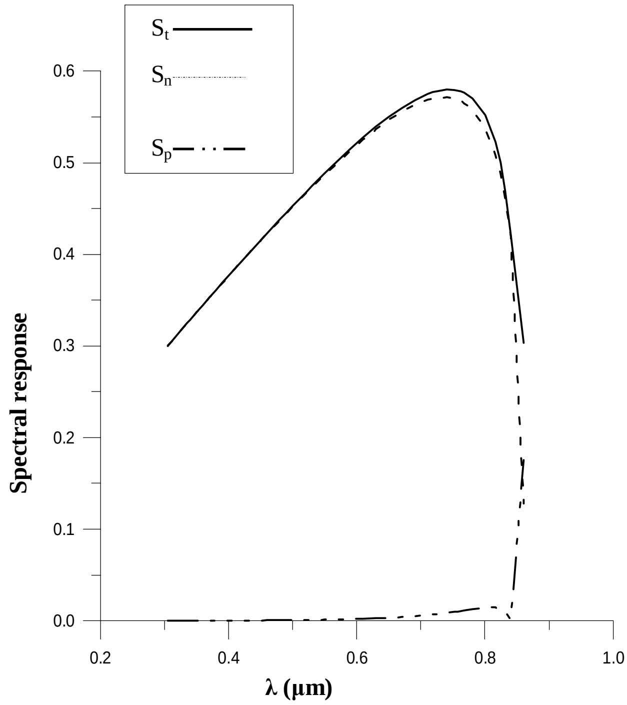

Fig.(5) The spectral response in the graded, uniform and total response vs. wavelength.

The calculations of the performance parameters of the graded band gap $Al_xGa_{1-x}As/GaAs$ with device parameters are presented in Table (1).

Table (1)
The photovoltaic parameters of $Al_xGa_{1-x}As/GaAs$ Cell.

Device Parameters	*Current Density*	*Performance Parameters*
Surface energy gap E_{go}= 2.6 eV	J_n= 23.3 mA/cm^2	J_{sc}= 33 mA/cm^2
Junction energy gap E_{gd}= 1.42 eV	J_p= 7.95 mA/cm^2	V_{oc}= .91 V
Junction depth D= 1 μm	J_{sc}= 33 mA/cm^2	FF= .87
Surface recombination velocity s= 1×10^7 cm/s		η= 31 %

The performance results of the modeled device in this search are compared to the results published in the literatures as shown in Table (2).

Table (2)
The performance parameters of graded band gap cells compared with theoretical models.

Cell	J_{sc} mA/cm^2	V_{oc} V	*FF*	*η %*
$Al_xGa_{1-x}As$/ GaAs	33	.91	.87	31
$Al_xGa_{1-x}As$/ GaAs [1]	34.59	0.99	0.82	17.6
$Al_xGa_{1-x}As$/ GaAs [5]	33.73	0.85	1.00	21.1
$Al_xGa_{1-x}As$/ GaAs/ GaAs [7]	37	0.95	0.80	20
$Al_xGa_{1-x}As$/ GaAs [14]	18	0.89	0.80	14
$Al_xGa_{1-x}As$/ GaAs [15]	33.96	1.02	0.83	21.5

Table (2) shows that the photovoltaic parameters, obtained from the model, are J_{sc} =33 mA/cm^2, V_{oc}= .91 V, FF= .87 and η= 31 %. The short-circuit current J_{sc} =33 $mA/cm^2$is not the highest value as compare with J_{sc} =37 mA/cm^2[7], but the conversion efficiency still the highest value due to the high fill factor FF= .87 and the lowest input solar power for the direct normal spectrum radiation (AM1.5D) as compared with another models used air mass zero (AM0) with greater input solar power.

The computer simulation results also compare with experimental results applied different conditions published in the literatures as shown in Table (3).

Table (3)
The performance parameters of graded band gap cells compared with empirical models.

Cell	J_{sc} mA/cm^2	V_{oc} V	*FF*	*η %*
$Al_xGa_{1-x}As$/ GaAs	33	.91	.87	31
$Al_xGa_{1-x}As$/ GaAs [16]	6	0.73	0. 7	23
$Al_xGa_{1-x}As$/ GaAs [17]	12.2	2.08	0. 77	18.1

Table (3) shows that the photovoltaic parameters, obtained from the model, are J_{sc} =33 mA/cm^2, V_{oc}= .91 V, FF= .87 and η= 31 % are highest and great as compared with experimental results obtained from another models due to thr differences between an ideal theoretical model and experimental models.

The photovoltaic parameters of graded band gap $Al_xGa_{1-x}As$/GaAs solar cell are correspond with other model that was compared. The conversion efficiency obtained in this model is greater than the other models because the different comes from the ideal analysis of this work but the other analysis are theoretical analysis with different assumptions and approximations or semi-empirical models.

Conclusion

The solar efficiency in the graded band gap $Al_xGa_{1-x}As$/GaAs solar cell is increased due to the effect of the electric field that was presented in the graded band gap region. The electric field cause high collection of carriers in the graded region and thus increase current collected from the device. The blue response in the graded region increase the conversion efficiency by increasing the absorption and generation in the long wavelength, therefore; the current collected increase too.

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الخلاصة

تم اقتراح نموذج للخلية الشمسية المتعددة الفجوات $Al_xGa_{1-x}As/GaAs$. هذا النموذج يتكون من مادة متدرجة التركيب على السطح من y=0 إلى y=D.هذا النموذج يماثل الامتصاص والتوليد، كثافة التيار، الاستجابة للطيف والكفاءة الشمسية المتولدة من الطيف الشمسي.تم حساب عوامل الكهروضوئية بواسطة تصميم برنامج حاسوب GRAD. اعتبار المجال الكهربائي، الحركية وطول الانتشار ثوابت في هذا النموذج للوصول إلى حل تحليلي.العوامل الكهروضوئية التي تم الحصول عليها من هذا الموديل J_{sc}=33mA/cm^2, V_{oc}= .91 V, FF= .87 and η=.31 % الكفاءة التحويلية تعتبر أعلى بالمقارنة مع نماذج مشابهة.