High Efficiency $Al_xGa_{1-x}As/GaAs$ Quantum Wells Solar Cells

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Abstract

An analytical expression for the maximum obtainable photoconversion efficiency of graded band gap $Al_xGa_{1-x}As/GaAs$ quantum wells solar cell was presented. Computer program WELL was designed to simulate the photocurrent density, spectral response and conversion efficiency to the proposed model. To improve this model, the effect of the number wells was studied. The photovoltaic parameters obtained from this model with 50 quantum wells are J_{sc} =55 mA/cm^2, V_{oc}= .924 V, FF= .875 and η= 52.8 % under AM1.5D solar spectrum conditions. Significant enhancements in short-circuit current and conversion efficiency have been obtained.

الكفاءة العالية للخلايا الشمسية ذات الجيوب الكمية $Al_xGa_{1-x}As/GaAs$

الخلاصة

تم ايجاد تعبير تحليلي لاكبر كفاءة تحويل للخلية الشمسية ذات الحجيرات الكمية والنظام المتدرج في فجوة الطاقة
تم تصميم برنامج حاسوبي لكي يماثل كثافة التيارو الاستجابة الطيفية وكفاءة التحويل للخلية المفترضة. $Al_xGa_{1-x}As/GaAs$
للتطوير هذا النموذج، تم دراسة تاثير عدد الحجيرات. العوامل الكهروضوئية التي تم الحصول عليها لخلية تحوي 50 حجيرة كمية تحت ظروف الطيف AM1.5D الشمسي هي J_{sc} =55 mA/cm^2, V_{oc}= .924 V, FF= .875 and η= 52.8 %
تم الحصول على تعزيز ملحوض في تيار الدائرة القصيرة وكفاءة التحويل.

Keywords: High Efficiency, $Al_xGa_{1-x}As/GaAs$, Quantum Wells

Introduction

Quantum wells (QWs) in solar cells (SCs) are employed to increase the efficiency of common p-i-n solar cells [1-2]. The absorption edge of a solar cell is determined by the width and depth of quantum wells. Higher photocurrent can be generated if wells are deeper, since longer wavelengths are absorpted. The open-circuit voltage depends on the barrier material band gap. Deeper wells increase photocurrent and decrease open-circuit voltage [3].

Quantum well solar cells (QWSCs) originally proposed by Barnham and Duggan in 1990 [4], were touted as a means of enhancing solar cell efficiency over that of conventional cells. The well layers are so thin that quantum mechanics becomes necessary for an accurate description: hence ‘quantum well’ solar cells. There exist several models attempting to predict the behaviour of QWSCs. For recent reviews see Barnham [5] and Anderson [6].Of particular relevance to this article are the models of Anderson [7] and Rimada [8], the latter of whom published in collaboration with Herna´ndez [9,10]. In this paper ideal theoretical simplified analysis of the conversion efficiency of $Al_xGa_{1-x}As/GaAs$ quantum wells solar cell was presented and cell optimization by study the effect of well numbers on the conversion efficiency has been demonstrated.

Theoretical aspects

a. Quantum Well Solar Cells

A quantum well solar cell consists of a p–i–n-junction constructed from high band-gap semiconductor with thin layers of lower band-gap semiconductor grown epitaxially in the intrinsic region where carriers occupy discrete energy levels, forming potential wells as shown in figure 1[11].

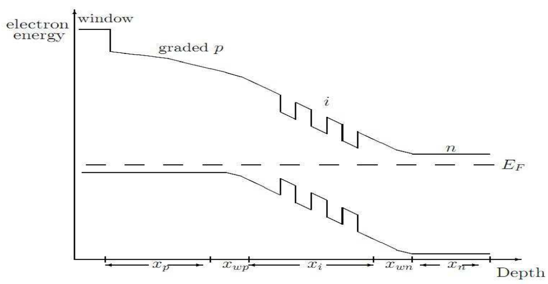


Figure 1: QWSC band diagram.

The structure schematic of the QWSC contains two band gaps E_g and E_a which are the barrier band gap and quantum well band gap respectively. The material behaves like bulk material for electron and hole energies greater than E_g and like a quantum well or superlattice states for energies below E_g as shown in Figure 2 [12].

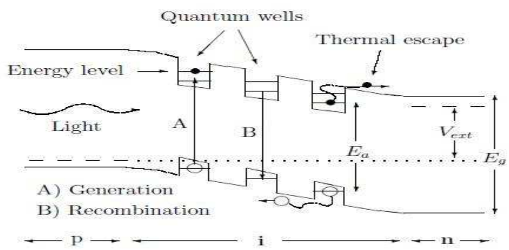


Figure 2: schematic of the QWSC structure, absorption, recombination and escape mechanisms.

For incident photons with energy greater than E_g, the QWSC operates like a conventional single band gap p - i - n cell. Photons with energies between E_g and E_a however are absorbed in the quantum well states. Once excited into well states, they can recombine radiatively or nonradiatively or escape from the well. The escape mechanisms are thermionic emission into a bulk state, tunnelling, or a combination of the two. The QWSC operates in a physically different way to single band gap cells because of the minority carrier escape from the quantum wells. Since it is in principle capable of generating the same photocurrent as a single band gap cell with a higher voltage, the design has a higher fundamental efficiency limit than a single band gap cell. p - i - n serves as a useful starting point for the design of an efficient quantum well solar cell due to better collection efficiencies and overall transport properties. [12]

b. $Al_xGa_{1-x}As/GaAs$ graded p-region

The photocurrent density in the determination of the conversion efficiency is present in this analysis. For an ideal solar cell model, the photocurrent can be modulated by the diode equations. The photocurrent can be calculated from drift and diffusion equations. The transport equation in the graded region is given by [12]:

$$\frac{d^2\Delta n}{dx^2} - \frac{\mu_e}{D_e} E_e \frac{d\Delta n}{dx} + \frac{1}{D_e} \sum_i G_p - \frac{\Delta n}{l_e^2} = 0$$

(1)

Where Δn is excess of electrons concentration, D_e is electrons diffusion coefficient, G_p is the generation rate in the graded p-region, l_e is electrons diffusion length and E_e is the built-in electric field.

To solve equation (1) analytically, all parameters (D_e, l_e, μ_e, E_e) are assumed to be constants. Then the general solution is given by:

$$\Delta n = A\exp(z_1 x) + B\exp(z_2 x) + C\exp(-\alpha_p x)$$

(2)

Where A, B, C, z_1 and z_2 are constants and α_p is the absorption coefficient in the graded p-region. The photocurrent density in graded p-region is given by [12]:

$$J_p = \left(-qD_e \frac{d\Delta n}{dx}\right)\Bigg|_{x=x_p}$$

(3)

$$J_p = -qD_e \sum_i \sum_1^j \left[z_1 A\exp(z_1 x_p) + z_2 B\exp(z_2 x_p) - \alpha_n C\exp(-\alpha_p x_p)\right]$$

(4)

Where i is the photon beam incident on the solar cell and j is the graded layer number.

c. depletion region

The photocurrent density from the depletion layer is based on the depletion approximation. The electric field in this region is generally high; the photo-generated carriers are accelerated out of the depletion region before they can recombine. The photocurrent density contribution from the quantum wells is calculated assuming an escape efficiency of 100%. The photocurrent density J_{dep} from the space charge region is then simply given by [13]:

$$J_{dep} = qF(\lambda)[1-R(\lambda)]\exp(-\sum_i x_p\alpha_p)(1-e^{(-\alpha_p x_{wp} - \sum_k N_k\alpha_k L_k - \alpha_n x_{wn})}) \quad (5)$$

F(λ) is incident photon flux, R(λ) is the reflection coefficient, x_{wp} is p-layer depletion width, x_{wn} is n-layer depletion width, N_k is the number of quantum wells, α_k is absorption coefficient in the depletion region and L_k is the well plus barrier width.

d. GaAs uniform n-region

The photocurrent density in the uniform p-region can be calculated from the diffusion equation. The transport equation in the uniform region is given by [12]:

$$\frac{d^2\Delta p}{dx^2} - \frac{\Delta p}{l_h^2} = -\frac{1}{D_h}\sum_i G_n \quad (6)$$

Where Δp is excess holes concentration, l_h is holes diffusion length, D_h is holes diffusion coefficient and G_n is the generation rate in the uniform n-region. Then equation (6) can be solved analytically. The general solution is given by:

$$\Delta p = D\exp(x/l_h) + E\exp(-x/l_h) + F\exp(-\alpha_n x) \quad (7)$$

Where D, E and F are constants and α_n is the absorption coefficient in the uniform n-region. The current density collected from the uniform band gap n-region is given by [12]:

$$J_n = qD_h \left.\frac{d\Delta p}{dx}\right|_{x = x_p + x_{wp} + x_i + x_{wn}} \quad (8)$$

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

$$J_n = qD_h \sum_i \left[\frac{E}{l_h} \exp(-(x_p + x_{wp} + x_i + x_{wn})/l_h) - F\alpha_h \exp(-(x_p + x_{wp} + x_i + x_{wn})\alpha_h) \right] \quad (9)$$

e. Spectral response

Spectral response is defined as the probability of an incident photon of wavelength λ generating an electron-hole pair which contributes to the short-circuit current. The total spectral response of the solar cell is given by [12]:

$$SR(\lambda) = J_{sc} / qF(\lambda) \quad (10)$$

Where J_{sc} is the short-circuit current density and given by [12]:

$$J_{sc} = J_p + J_{dep} + J_n \quad (11)$$

f. Efficiency

The overall efficiency of the cell η is given by the ratio of the maximum power P_{max} and incident power P_{inc}. It is usually expressed as follows [12]:

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{inc}} \quad (12)$$

Where V_{oc} is the open-circuit voltage and FF is the fill factor.

g. Model program

The BASIC program WELL is designed to simulate the spectral response, and conversion efficiency in the graded band gap $Al_xGa_{1-x}As/GaAs$ quantum well solar cell. The input data of program WELL are classified as solar spectrum [14], semiconductor parameters [15] and model parameters used in design the solar cell. program WELL distribute the flux of incident light in the graded, depletion and uniform regions then calculate the current density in each region and finally calculate the spectral response and the conversion efficiency of the graded band gap $Al_xGa_{1-x}As/GaAs$ quantum wells solar cell.

Result and discussion

The photocurrent density collected from the graded band gap $Al_xGa_{1-x}As/GaAs$ for a 50 QWs solar cell is shown in figure 3. Figure 3 shows the total photocurrent density is increase in the range between λ=.6 μm to λ=.8 μm due to The contribution of the photocurrent density in the depletion region that was large due to the present of the quantum wells that absorbed more solar spectrum and the high collection efficiency in the graded n-region due to high built-in electric field.

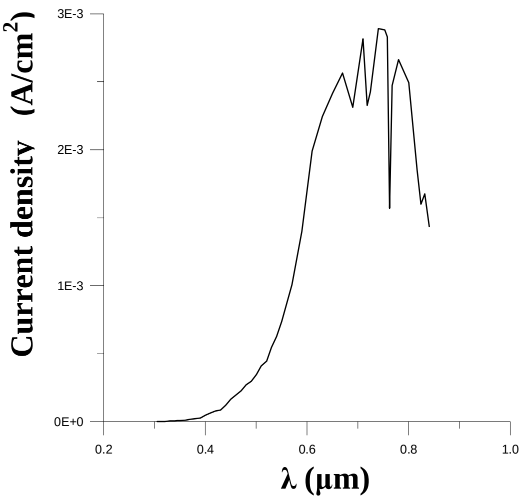


Figure 3: total current density for a 50 QWs as function of wavelength.

The spectral response of the graded band gap $Al_xGa_{1-x}As/GaAs$ for a 50 QWs solar cell is shown in figure 4.

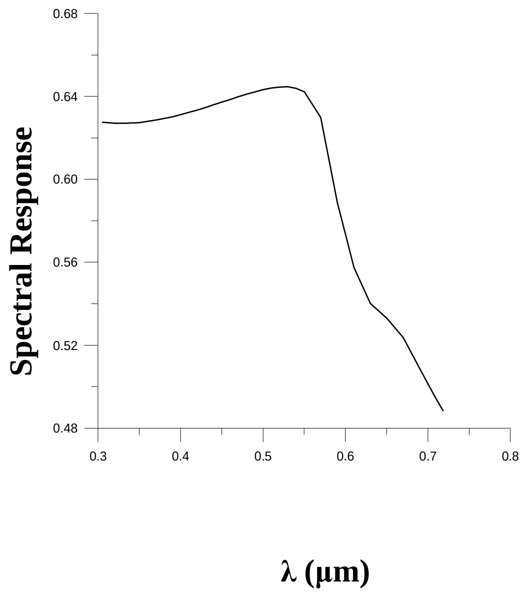
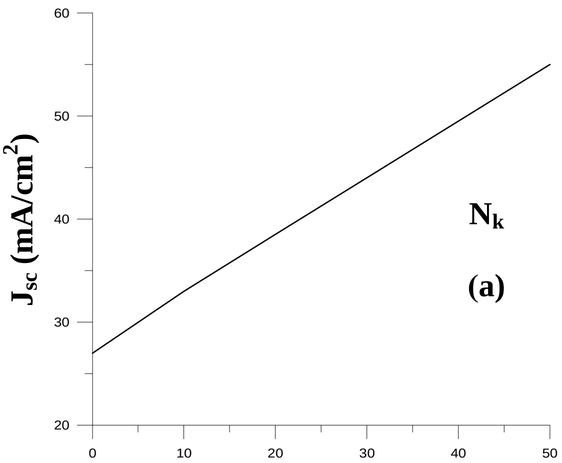
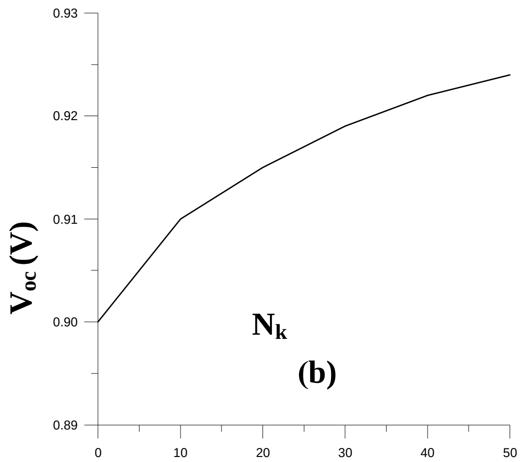


Figure 4: total spectral response for a 50 QWs as function of wavelength.

Figure 4 shows the total spectral response was optimized, mainly dependent on the absorptivity of the quantum wells and the light levels in the depletion region.

The effect of increasing the number of quantum wells on the photovoltaic parameters is shown in figure 5. Figure 5 illustrates the numbers of quantum varied from 0 to 50. The large increases in short-circuit current generated in the calculations as the number of wells was increased, however leading to the large efficiency increases. The open-circuit voltage is slightly increased due to logarithm relation with short-circuit current. The best efficiency was obtained for a 50 quantum wells was 52.8 %.





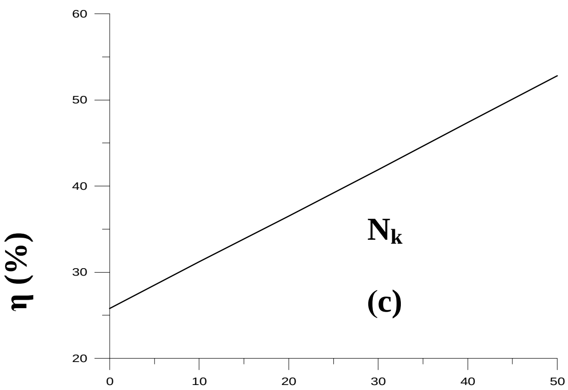


Figure 5: short-circuit current (a), open-circuit voltage (b) and efficiency (c) as function of number wells.

The photovoltaic parameters of the graded band gap $Al_xGa_{1-x}As/GaAs$ with a 50 QWs solar cell is shown in table 1. The calculated efficiency in this model is considered as high efficiency over the GaAs single junction cell, but it correspond with Ramada's model, that has an optimum efficiency of 41.9% [9] with 25 quantum wells.

Table 1: The photovoltaic parameters of $Al_xGa_{1-x}As$/GaAs with a 50 QWs solar cell.

Cell	J_{sc} mA/cm^2	V_{oc} V	FF	η %
$Al_xGa_{1-x}As$/ GaAs	55	.924	.875	52.8

Conclusion

Efficiency enhancements for quantum wells solar cells over single GaAs solar cells were observed. The most important advantage of quantum wells solar cells is the short-circuit current density J_{sc} value that appears good result. The open-circuit voltage V_{oc} slightly increased with increasing the numbers of quantum wells. The maximum obtainable efficiency is 52.8 %. Quantum well solar cell could provide a new approach to the high efficiency solar cell.

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