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Photocurrent Improvement in *AlGaAs* Quantum Well Solar Cells

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Abstract: *The quantum well solar cell (QWSC) was first introduced by Barnham and co-workers [1]as a novel device in which a series of quantum wells (QWs) forms the i-layer of a p-i-n solar cell. Studies have shown that the insertion of such a series of quantum wells into the depletion region of a solar cell can significantly enhance the cell's short-circuit current and hence the efficiency of the solar cell [2,3]. Experimental results show that the insertion of quantum wells results in an increased photocurrent. An accurate modelling of the absorption spectra of quantum well is of considerable importance in optimizing the performance of QWSC. In the present work we evaluate the generated photocurrent in an AlxGa1-xAs/GaAs p-i-n solar cell using a simple approach. In this model, firstly Schrödinger equation is solved numerically to determine the confined energy states in a single quantum well; the second step consists of calculating the absorption coefficient α (λ) taking into account the allowed valence to conduction bands transitions. Finally the total photocurrent is analysed for various structure parameters specifically; width, height (related to the aluminium concentration x), and number of wells inside the intrinsic layer. The simulated results confirm the enhancement brought about by the presence of quantum wells, this improvement could attain up to 40% of the photocurrent.*

Keywords: *solar cell, quantum well, absorption coefficient.*

I. Introduction

In the past few years multi-quantum well (MQW) solar cells have attracted an increasing interestmostly because of their high solar energy conversion. The inclusion of MQW in the intrinsic region of*p–n* or *p–i–n* solar cell of wider bandgap (barrier) material can be expected to improve the spectralresponse of the cell in the energy region below the absorption edge of host material. The photocurrentis then determined by lower-bandgap (well) material, while the output voltage would be determined bybarrier material. The characteristics of the well, its width and depth, determine the absorption edge and the spectral response of the MQW solar cell. Longer wavelengths can be absorbed if the quantum well is deeper, leading to a higher photocurrent in the cell. Whereas, the output voltage is related to the width of the host material band gap, the recombination in the well and interfaces between barriers and wells. Therefore, in choosing the depth of the wells one has to compromise between the photocurrent and the output voltage. The number of wells is an important factor too, wider wells improve the absorption, but a smaller number of wells fit in the intrinsic region. Whereas, a large number of narrow wells with lower photon absorption can be inserted in the same intrinsic layer. Increasing the number of wells enhances the photocurrent provided the recombination at the interfaces is reduced. In this article, we report a simple theoretical approach which shows the importance of inserting a MQW into the intrinsic region of a *p-i-n* Al*x*Ga*1-x*As solar cell that can significantly enhance the photocurrent. The photocurrent is calculated as a function of width and the number of wells. The wells in this simulation are considered uncoupled with barriers of sufficient width so as to separate wells from each other, as shown in figure 1. Thus the wells can be treated as individual structures.

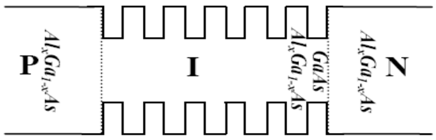

Fig. 1. Schematic diagram of the investigated *p-i-n* Al*x*Ga-*1*-*x*As/GaAs MQW/ Al*x*Ga-*1*-*x*As solar cell. Layers parameters respectively are: ***P***; 0.05 µm, $p = 10^{19}$cm^{-3} , ***I***; 1µm, $n = p = 1.79{\cdot}10^{6}$cm^{-3}, ***N***; 1µm, $n = 10^{19}$cm^{-3}

The confinement of the carriers in the well results in discrete energy levels. In the valance band there are two such sets of levels as a result of the different effective masses of heavy and light holes. In the quantum wells the generation is calculated from Fermi's golden rule governing transition probabilities between electron and hole well states. These are found by solving numerically the effective mass Schrödinger equation for electrons and holes confined in the QW. The photocurrent is calculated from the diffusion equation applied to photogenerated minority carriers in bulk and well material [4]. The current density in the intrinsic region of *p-i-n* Al*x*Ga*1-x*As MQW solar cells is calculated with the consideration of a number of geometrical parameters, namely; the width, the depth (which is related directly to the mole fraction of the Aluminium *x*) and the number of wells in the intrinsic region.

II. Absorption Coefficient

Prior to the calculation of the absorption coefficients of $Al_xGa_{1-x}As$ MQW Schrödinger equation for one dimensional single square quantum well is numerically solved. The quantum-mechanical motion of a carrier inside the well is described by a wave function $\psi_{e,h}(z)$ solution of the Schrödinger equation for the unperturbed potential for electrons (*e*) and holes (*h*) as follows:

$$\left[-\frac{\hbar^2}{2m^*_{e,h}}\frac{d^2}{d\,z^2}+V_{e,h}(z)\right]\psi_{e,h}(z)=E_{e,h}\,\psi_{e,h}(z) \quad 01$$

Where $\hbar$ is Planck constant, $m_{e,h}^*$ is the carrier effective mass, $E_{e\,h}$, the carrier energy and $V_{e\,h}$ (z) , is the potential energy of the finite well determined by the energy discontinuity between well and barrier material [5]. In the GaAs /AlGaAs system, this discontinuity can be expressed as 1.247 *x* at *T* = 300 K for $x < 0.45$, where *x* represents the mole fraction of the Aluminium in the alloy. This discontinuity is then split between conduction and valence bands with a split ratio of 0.6/0.4 [6,7]**.** The finite difference technique is used for the solution of the Schrödinger equation mainly due to its simplicity and efficiency for this kind of problems. The well absorption coefficient is then calculated by summing over the electron-heavy hole and electron-light hole transitions:

$$\alpha_w(E)=\alpha_c(E)+\sum_n \alpha_{e_n-hh_n}(E)+\sum_n \alpha_{e_n-lh_n}(E) \quad (2)$$

Where $\alpha_c(E)$ is the absorption coefficient of the continuum, which could be approximated to the barrier absorption coefficient and determined using the well known relation for direct transitions as follows:

$$\alpha_c(E)=A(h\nu-E_g)^{1/2} \quad (3)$$

Where A = 3.5.10^4 cm^{-1} (for $Al_xGa_{1-x}As$ for x<0.4), $h\nu$ is the photon energy and *Eg* is the semiconductor energy band gap, at room temperature (300K) the band gap energy is *Eg* (*x*) = 1.424 eV + *x* 1.247 eV [8]

$\alpha_{en-h\,hn}$ (*E*) and $\alpha_{en-l\,hn}$ (*E*) α are the well absorption coefficients of the confined *n*th heavy and light holes transitions respectively. To calculate these parameters we adopt the ideal quantum well model suggested by Rimada and revised later by Lade et al [7]:

$$\alpha_{e_n-hh_n}(E)=\frac{\pi q^2 E_p}{4\pi\varepsilon_0 n_r c m_0 E \ell \hbar}\frac{m_{e,w_{xy}} m_{hh,w_{xy}}}{m_{e,w_{xy}}+m_{hh,w_{xy}}}Y(E-E_n) \quad (4.a)$$

$$\alpha_{e_n-lh_n}(E)=\frac{\pi q^2 (E_p/3)}{4\pi\varepsilon_0 n_r c m_0 E \ell \hbar}\frac{m_{e,w_{xy}} m_{lh,w_{xy}}}{m_{e,w_{xy}}+m_{lh,w_{xy}}}Y(E-E_n) \quad (4.b)$$

where *Y* is the step function and *l* is the quantum thickness of the heterostructure, where E_p = 23 eV; m_{ew} , and $m_{hh\,w}$, are the well electron and heavy hole effective masses, ε_0 is the dielectric constant, n_r is the well refractive index, E_n are the transition energies, *q* the electronic charge, *c* the speed of light in a vacuum, ђ is the Planck constant over 2π and m_0 is the free electron mass. For the electron-light hole transitions E_p is replaced by E_p /3 and the heavy hole masse by the light hole masse $m_{lh\,w}$, Eq. (4b).

Figure 2 represents the calculated absorption coefficient (α(*E*)) versus the photon energy (*E*) for different well widths (50, 100 and 200 Å) for a fixed Aluminium molar fraction *x* = 0.4 (*Eg* = 1.922 eV) in the barrier. The absorption coefficient of the continuum is plotted for comparison. It can be seen clearly that the absorption inside the quantum well is significant, which can be explained simply by the lower confined energy levels inside the well and a shift of the absorption energy threshold towards lower energies. Two distinct regions can be observed; the first one is due to the transition from the bound states in the well and corresponds to low energies. This fraction of the curve has a stair-like shape which fits well with discrete transition levels in both the valence and conduction bands. The number of stairs depends on the number of allowed transitions. The second part of the curve matches with the absorption by the continuum.

In figure 3, the absorption coefficient is plotted versus photon energy for different aluminium fraction *x* in the barrier material (0.2, 0.3 and 0.4) while maintaining the well width at 100 Å. The absorption coefficient of GaAs (*x* =0) is plotted for comparison. The curves comprise of two distinct regions the first one (stair-like form) illustrates the contribution of the bound states in the well while the second represents the absorption of the continuum energy range. As the fraction *x* is increased the depth of the well is increased then absorption threshold shifts to greater energies and the number of stairs is also increased.

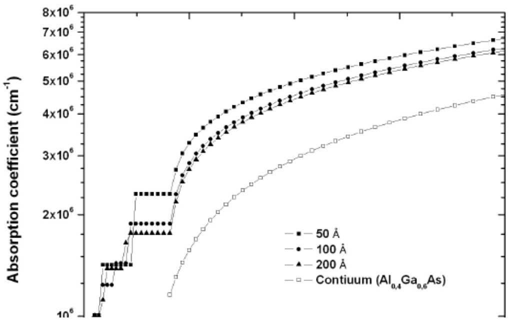

Fig. 2. Absorption coefficient of a Al*0.4*Ga*0.6*As/GaAs/Al*0.4*Ga*0.6*As single quantum well for different thicknesses

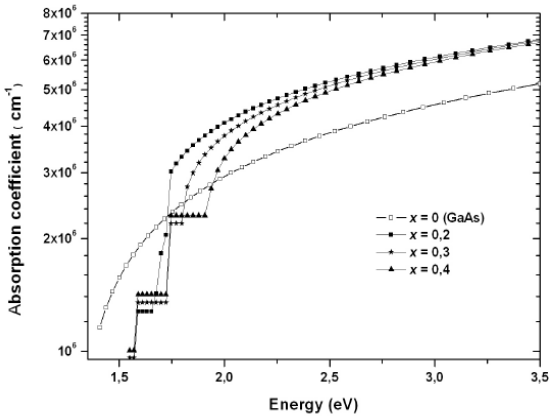

Fig. 3. Absorption coefficient of a Al*x*Ga*1-x*As/GaAs/ Al*x*Ga*1-x*As 100 Å single quantum well for different aluminium molar fractions *x*.

III. SPECTRAL RESPONSE

The total photocurrent generated by the quantum well solar cell is the sum of the photo generated current at the *n* and *p* layers together with current at the intrinsic layer.

$$J_{Ph}(\lambda) = J_{Ph,N}(\lambda) + J_{Ph,P}(\lambda) + J_{Ph,IQW}(\lambda) \quad (5)$$

Where $J_{Ph,N,P,IQW}(\lambda)$ are the photocurrent densities at the *n*, *p* and *i* regions respectively. The photocurrents of *n* and *p* layers are determined using commonly known expressions [9]. The spectral response is defined as:

Where *F* (λ) is the number of incident photon /cm2/s per bandwidth, and *R* (λ) the fraction of these photons reflected from the surface. The analysis is carried out under one AM1.5

$$SR(\lambda) = \frac{J_{Ph}(\lambda)}{qF(\lambda)[1 - R(\lambda)]} \quad (6)$$

global normal sun conditions. Empirical expression approximating photon flux density *F*(λ) is adopted from Ref. [10]. Figure 4 shows the spectral response of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cell with 20 wells for different well widths respectively 50, 100 and 200 Å. From this figure we can see that for greater wavelengths (λ>0.6 µm) the spectral response improvement is significant, particularly for wider wells.

This is attributed to the absorption of photons with longer wavelengths. In this region of the spectre the SR has a stair-like shape this is because of the wells absorption coefficient, as discusse d above. Whereas for wavelengths between 0.2µm and 0.6 µm there is a slight improvement as the wells width is increased. The limitation of the wells number is due to restriction of the intrinsic layer thickness, which is limited to 1 µm in this work.

The effect of the number of wells (10 to 30 wells) on the spectral response of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cell is shown in figure 5; the wells are 100 Å wide. The improvement of the SR is remarkable, particularly for longer wavelengths (λ>0.6 µm). This could be explained by the absorption of an increased numbers of photons with longer wavelengths. The increase of the wells number has the tendency of widening the part of semiconductor (GaAs) having smaller energy band gap (1.424 eV), thus more 'longer wavelengths' photons are absorbed. This situation is very similar to the case of double junction tandem solar cell with $Eg1 = Eg_{,\ AlGaAs}$ and $Eg2 = Eg_{,\ GaAs}$.

We can deduce from the dependency of the internal spectral response on the width and the number of wells in the intrinsic layer of an $Al_xGa_{1-x}As$/GaAs MQW/ $Al_xGa_{1-x}As$ solar cell that the best cell should have as many as possible wider wells. Unfortunately, there are many technological and physical factors that act against this, therefore a compromise is needed. The main limit is the size of the intrinsic layer which could not be much thicker, to maintain the uniform electric field and ensure an even absorption. On the other hand, increasing the number of wells will augment the number of interfaces leading to a growing recombination.

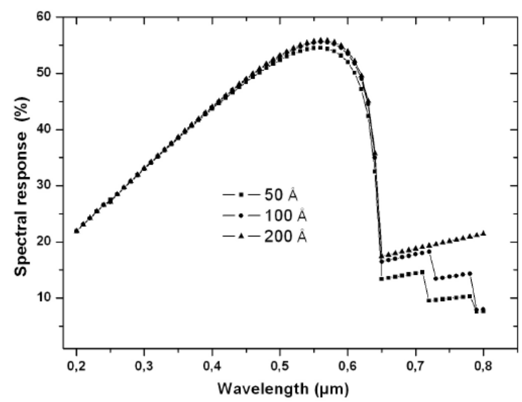

Fig. 4. Internal spectral response (SR(λ)) of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cell with 20 wells for different thicknesses.

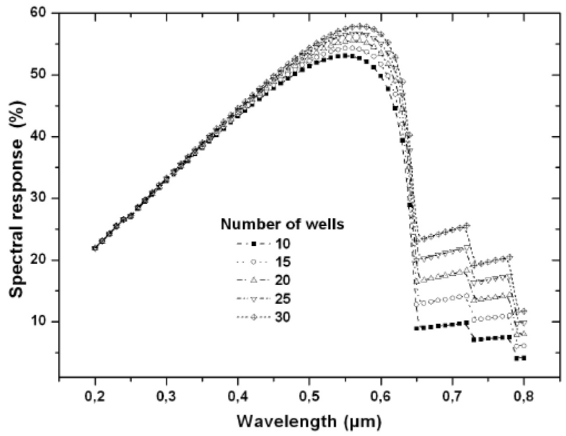

Fig. 5. Internal spectral response (SR (λ)) of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ A $l_{0.4}Ga_{0.6}As$ solar cell with 100 Å wide wells for different well numbers.

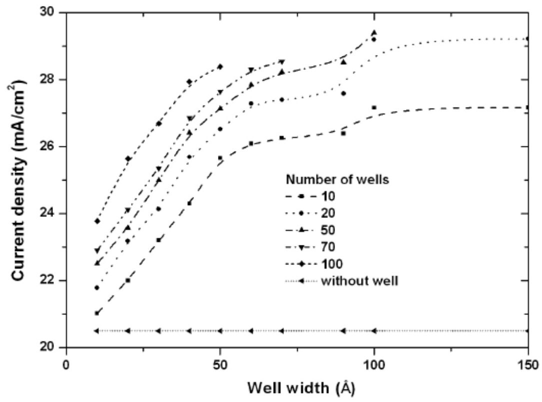

Fig. 6. Total photocurrent of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cell plotted as function of the wells thickness for different number of wells.

IV. PHOTOCURRENT DENSITY

Figure 6 shows the total photocurrent of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cell versus the wells thickness for different number of wells. From this graph we can see that the photocurrent generally increases when the numbers of wells is increased, while it has the tendency to saturate if the well thickness is increased. Therefore, the only limit to improve the performance is the maximum number of wells that the intrinsic layer could host. From the conducted investigation we arrived to an optimal configuration of the $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cell, that is; 20 wells of 100 Å in 1µm thick intrinsic layer. The photocurrent of this optimised structure is 29.2 mA/cm^2 compared to 20.5 mA/cm^2 of a single $Al_{0.4}Ga_{0.6}As$ *p-i-n* cell, which represents a gain of more than 40%. To make this type of cells more competitive other aspects has to be analysed i.e., it is needed to reduce its dark current in order to minimise the reduction of the open circuit voltage therefore improving the energy conversion efficiency.

V. CONCLUSION

There is no doubt that the insertion of quantum wells in a *PIN* structure solar cell will improve its short circuit current. In the conducted study we showed that the width in addition to the number of wells has a remarkable effect on the photocurrent of $Al_{0.4}Ga_{0.6}As$/GaAs MQW/ $Al_{0.4}Ga_{0.6}As$ solar cells. Using a simple approach with the previously revised model of Rimada applied to an idealised quantum well, we were able to demonstrate that the photocurrent of a quantum well solar cell will augment with increasing either the width or the number of wells in the intrinsic region. This improvement could be achieved provided that thickness of the intrinsic layer is not over taken. In addition, the thickness of the *i*-layer should not be too thick to avoid the perturbation of the electric field, which is essential for photogenerated carriers' collection. Alternatively, the insertion of a large number of quantum wells (lower band gap) in the *i*-layer is expected to reduce the open circuit voltage, thus it is important to deal with these opposing effects. A complementary work is under way to examine the effect of quantum wells parameters (depth, width and number) on the dark current, open circuit voltage and the energy conversion efficiency.

References

[1] K.W.J. Barnham and G. Duggan, A new approach to high-efficiency multi-band-gap solar cells, J. Appl. Phys. 67 (1990) 3490.
[2] J.C. Rimada, L. Hernandez, J.P. Connolly, K.W.J. Barnham, Conversion efficiency enhancement of AlGaAs quantum well solar cells, Microelectronics Journal 38 (2007) 513.
[3] X.B. Xiang, W.H. Du, X.L. Chang, H.R. Yuan, The study on high efficient AlxGa1-xAs/GaAs solar cell, Solar Energy Materials & Solar Cells 68 (2001) 97.
[4] A. Belghachi and A. Helmaoui, Analysis of photocurrent in the i-layer of GaAs-based n–i–p solar cell, Solar Energy Materials & Solar Cells 90 (2006) 1721.
[5] G. Bastard and J. A. Brum, Electronic states in semiconductor heterostructures, IEEE Journal of Quantum Electronics, QE-22, No. 9 (1986) 1625.
[6] G. Lengyel, K. w. Jelley, and R. H. Engelmann, A Semi- mpirical Model for Electroabsorption in GaAs/AlGaAs Multiple Quantum Well Modulator Structures, IEEE Journal of Quantum Electronics, 26, No 2, (1990) 296.
[7] S.J. Lade, A. Zahedi, A revised ideal model for AlGaAs/GaAs quantum well solar cells, Microelectronics Journal 35 (2004) 401.

[8] F. K. Rault, A. Zahedi, Computational analysis of the refractive index of multiple quantum wells for QWSC applications, Microelectronics Journal **34** (2003) 149.
[9] S.M. Sze, Physics of Semiconductor Devices, second ed., Wiley, New York, 1981.
[10] J.J. Liou (Ed.), Advanced Semiconductor Device Physics and Modeling, Artech House, Norwood, MA,1994