Internal reflection influence on the multiple quantum well solar cell efficiency♣

M. PAULESCU*, E. TULCAN-PAULESCU, A. NECULAE, P. GRAVILA
Department of Physics, West University of Timisoara V Parvan 4, 300223 Timisoara

The Multiple Quantum Well Solar Cell (MQWSC) consists of a quantum well system placed in the undoped region of a p-i-n solar cell. Despite an abundance of reports on MQWSC modeling, most of them are not addressing photon reflection at barrier-well interfaces. This paper evaluates the reflection influence on MQWSC conversion efficiency. For this, a realistic model for internal reflection in MQW system is derived and inserted into an ideal electro-optical MQWSC model. Our results based on numerical simulations substantiate that MQWSC efficiency decays significantly when reflection is considered. Thus, our model dealing with non-ideal structures is intended to be a tool to investigate cell optical parameters and to optimize the conversion efficiency.

1. Introduction

Quantum Well Solar Cell (QWSC), whose concept was pioneered by Barnham et al in 1990 [1], is a traditional p-i-n diode where the intrinsic layer is replaced with a Multiple Quantum Well (MQW) system [2]. It is intended to broaden the absorption band beyond the one of the host cell semiconductor. In simple terms, the MQW cell is a structure of *sandwiched* layers between two n and p doped bulk semiconductors as seen in Fig. 1. Because there are multiple interfaces it is expected that reflection losses to be significant. For the past two decades, many studies have been run to predict the properties of QWSC [3], in particular the energy conversion efficiency. But almost all of these studies are silent concerning the photon reflection at interfaces. As we demonstrate below it cannot be neglected if we keep in mind that a MQW system in a MQWSC encloses a number of interfaces in the order of tens.

We attach a mathematical description of reflectance to a conventional QWSC model sealed as reference and study the MQW system geometry and material parameters influence to the cell conversion efficiency.

2. MQWS model

Reflectance: The MQW refraction index is modeled following the approach of Alman et al. [4] assuming the MQW cell as a pseudo-homogeneous single layer with effective index $n_{ef.}$

$$n_{ef}^2 = \sum_j n_j^2 l_j \Big/ \sum_j l_j = \frac{1}{L} \sum_j n_j^2 l_j \qquad (1)$$

l_j and n_j are the thickness and refractive index of j layer, respectively, as figure 1 shows. Subsequently, the entire cell reflectance has been calculated using a Fresnel like-type formula [5]:

$$R = \frac{\rho_1^2 + \rho_2^2 + 2\rho_1\rho_2 \cos 2\theta}{1 + \rho_1^2 \rho_2^2 + 2\rho_1\rho_2 \cos 2\theta} \qquad (2)$$

with $\rho_1 = (1 - n_{ARC})/(1 + n_{ARC})$,

$\rho = (n_{ARC} - n_{ef})/(n_{ARC} + n_{ef})$, $\theta = 2\pi n_{ARC} d_1 / \lambda$; n_{ARC} and d are the refractive index and depth of antireflection coating (ARC), respectively. The thickness of ARC is computed by minimizing Eq. (2).

Absorption coefficient. The absorption coefficient α_x of ternary alloy ($Al_xGa_{1-x}As$ in example below) has been derived from the one of binary compound α_0, with a non-linear axis shift [6]: $\alpha_0(\hbar\omega) = \alpha(\hbar\omega_x)$:

$$\hbar\omega_x = \hbar\omega - E_g(x) + E_g(0) + a\Big[\hbar\omega - E_g(0) \Big]^b x \qquad (3)$$

For $Al_xGa_{1-x}As$, we use the empirical parameters $a = 0.62$ and $b = 0.5$. The MQW system absorption coefficient is generated by density of states in the bulk and 2D confined system comparison approach, detailed in our paper [7]. Energy levels in MQW structure has been calculated using the transfer matrix technique [8].
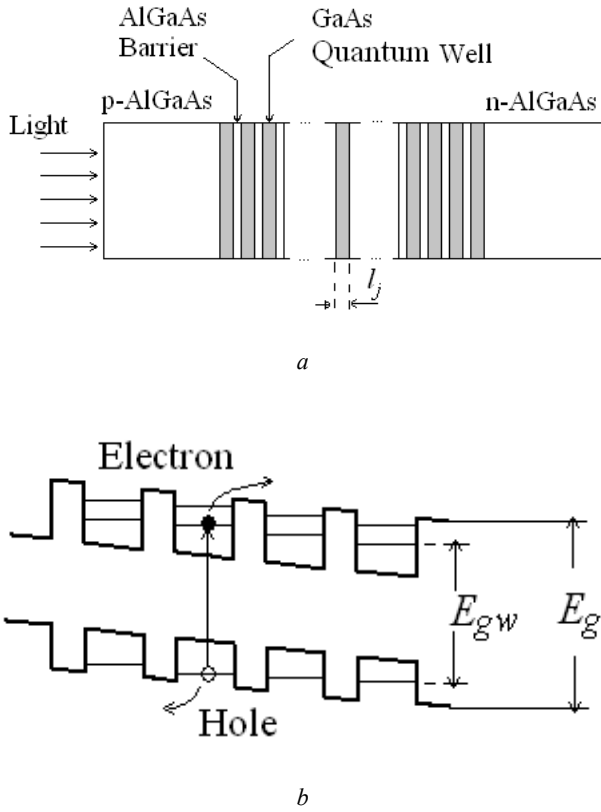
a

b

Fig. 1 a. Schematic of the QWSC sandwich; b. Energy band diagram of QWSC under forward bias

Carrier photo-generation. The generation rate is given by the product of the absorption coefficient $\alpha(\hbar\omega)$, and the photons flux:

$$g_k(z,\hbar\omega) = \alpha_k(\hbar\omega)\left[1 - R(\hbar\omega)\right]I_k(z,\hbar\omega) \qquad (4)$$

The spectral density of incident photon flux on each interface is sequentially computed according to the Bouguer-Lambert rule. The spectral distribution of the incident solar flux on the top cell surface is assumed AM1.5G [9].

Transport equation. A lot of theoretical and experimental studies (for instance [10]) demonstrate that nearly all photo-generated carriers in MQW escape from the wells: electrons in the conduction band and holes in the valence band, where they obey macroscopic Shockley transport rules [11]. We agree a master equation for cell current-voltage trace which takes into account the shrinking of the photocurrent J_L through radiative recombination J_{RR} [12], non-radiative Shockley-Read-Hall recombination J_{SRH} [13] and Shockley dark diode J_D currents:

$$J(\hbar\omega,V) = J_L(\hbar\omega) - J_{RR}(E,V) - J_{SRH}(V) - J_D(V) \quad (5)$$

where:

$$J_L(\hbar\omega) = q\sum_{k=0}^{N_m+1}\int_{l_k} g_k(z,\hbar\omega)dz \ ,$$

$$J_{RR} = q\frac{2n_{ef}{}^2 L}{h^3 c^2}\int \frac{E^2\alpha(E)}{e^{\frac{E-qV}{kT}}-1}dE \ ,$$

$$J_{SRH} = q\frac{\pi L_{SCR}n}{\tau\Delta V}\sinh\left(\frac{qV}{2k_B T}\right)$$

with q the electron charge, c the light speed, L_{SCR} the width of the space charge region.

The above equations summarize a multi-stage QWSC modeling: a quantum level at which the MQW structure and properties is deduced; the results are input for expressing MQW interaction with optical radiation; the carrier transport is a macroscopic level from which QWSC I-V properties are derived.

3. Results

We assume a MQW system GaAs/Al$_{0.3}$Ga$_{0.7}$As with $N_w = 30$ number of wells, each of 10 nm width, delimited by barriers also of 10 nm width. The potential barriers are 0.231 eV high for electrons and 0.144 eV for holes. Heavy and light holes are separately treated. A plot of MQW levels and density of states as results from transfer matrix computations is given in Fig. 2.
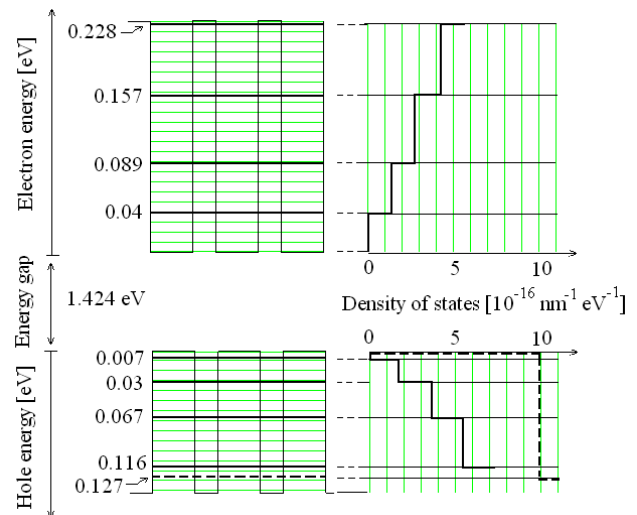

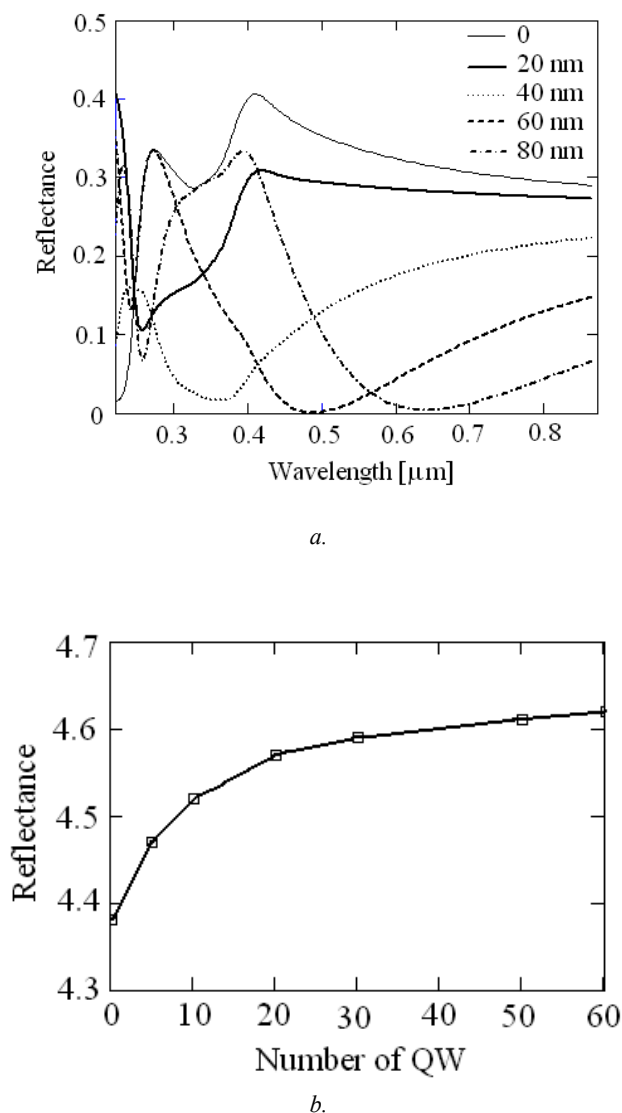*Fig. 2. Calculated sample energy levels and density of states (dot).*

a.

Fig. 4. QWSC V-A characteristic. M(0.8V, 21 mA/cm^2) corresponds to maximum power delivered by the cell.

4. Conclusions

We set up a model for QWSC reflectance and demonstrate the relative importance of reflection loses in the energy conversion process. We show that losses can be reduced using an adequate antireflection layer, even if MQW system contain multiple interfaces. However, the calculations point out that the cell efficiency, in the ideal assumption of radiative limit, is placed outside of the high efficiency class.

The presented model, dealing with non-ideal structures, can be employed as a helpful tool to develop a cell based on a MQW system of a design that is closer to the full spectrum concept.

b.

Fig. 3. a. ARC thickness effect on sample spectral reflectance; b. QW number influence on cell reflectance

The cell reflectance in respect to wavelength is plotted in Fig. 3. The curve parameters are ARC layer depth in figure 3a and number of wells N_w in figure 3b. It can be seen that without ARC the reflectance is over 30% in all wavelength interest band; ARC decrease reflectance to 4.5%. As Fig. 3b shows, the number of QW has a low influence on the cell reflectance.

The QWSC performance resulted from running the model in radiative limit is sinthetized in the following parameters: short circuit current J_{SC} = 0.24 mA/cm^2, open circuit voltage V_{0C} = 0.869 V, fill factor Ff = 0.809, conversion efficiency η = 18.3. The voltage-current characteristic plotted in Fig. 4 shows that the cell behaves as a conventional p-n solar cell.
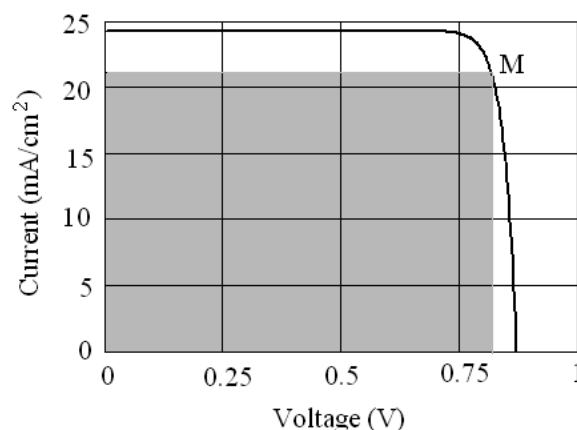
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*Corresponding author: marius@physics.uvt.ro