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Dependence of Photovoltaic Characteristics on various parameters of InGaN/GaN MQW Solar Cells

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Abstract- This paper deals with a comparison of the performance of InGaN/GaN based multiple quantum well (MQW) solar cell for increased number of wells and varying thicknesses. Studies have revealed that increasing the number of quantum wells and thickness have shown significant improvement in terms of the open circuit voltage and the efficiency. Also the effect of the p-GaN based emitter layer thickness and the doping concentration on the electrical parameters of the multiple quantum well solar cell have been undertaken.

Index Terms-AMPS-1D; Absorption Coefficient; InGaN/GaN; ITO; MOCVD; Radiative Recombination.

1. INTRODUCTION AND LITERATURE REVIEW

Group III nitride based semiconductor materials have been used for the fabication of electronic and optoelectronic devices like LEDs, photodetectors, laser diodes and photovoltaic cells [1-4]. InGaN alloys have high saturation velocity, high mobility, large absorption coefficient and good radiaion tolerance [5-6]. One of the most attractive property of InGaN is its tunable bandgap, which can be varied between 0.7 to 3.4eV covering a wide range of wavelengths from near infrared to ultraviolet by changing the indium composition [7-8]. Improving the spectral response of InGaN based solar cells requires a high proportion of indium in the active layer, above 20%. At the same time an increase in the indium content is responsible for the degradation in the quality of the InGaN layer due to phase separation [9]. The layers of InGaN can be deposited using efficient and inexpensive techniques such as Metal Organic Chemical Vapor Deposition (MOCVD), Molecular Beam Epitaxy (MBE), Metal Organic Vapor Phase Epitaxy (MOVPE).

Quantum Well structures can enable photons of lower energy than the bandgap of the semiconductor material to participate in the photogeneration process. The carriers generated in the MQWs can thermally escape into the conduction band and the valence band to contribute to the total photogenerated current. Thus the efficiency of the solar cell can be improved by the incorporation of InGaN MQWs in the absorber layer [10].

Researchers have conducted extensive studies in the past to explore the potential of InGaN/GaN MQW solar cells. With a relatively low indium content of 0.15 the short circuit current density, fill factor and open circuit voltage obtained were 0.7mA/cm^2, 0.40 and 2.22V respectively for an InGaN/GaN MQW solar cell [11]. For an indium content of 0.15 the obtained values of the short circuit current density (J_{SC}), open circuit voltage (V_{OC}), Fill Factor (FF) and Efficiency (η) were 1.05, 2.30, 63% and 1.52% respectively. However when the indium content was increased to 25% the performance of the cell deteriorated. The increased indium content led to greater strains creating misfit dislocations which acted as non-radiative recombination centres [12]. An improvement in performance in terms of the maximum efficiency~1.30% was reported for an InGaN/GaN MQW based solar solar cell by the introduction of a copper doped indium oxide layer at the interface between indium tin oxide (ITO) p-electrode and p-GaN [13]. Also fabrication of InGaN/GaN MQW solar cells incorporating InN fractions of 30% and 40% were reported. The results showed that the devices exhibited a fill factor of 60% and delivered a very high external quantum efficiency of 40% at 420nm and 10% at 450nm [14].

2. NUMERICAL MODELING AND SIMULATION

AMPS-1D (Analysis of Microelectronic and Photonic Structure) is a very general program for analyzing and designing transport in microelectronic and photonic structures. The principal equations solved by AMPS-1D (using finite differences and Newton-Raphson technique) are: the Poisson’s equation, the continuity equation for free electrons and holes together with the electron and hole current density equations. To determine the transport characteristics AMPS solves the first three of these coupled non-linear differential equations which have with each of them two associated boundary conditions. In AMPS-1D, these three coupled equations are solved simultaneously to obtain a set of three unknown state variables at each point in the device: the local vacuum level, the electron and hole quasi-Fermi levels. From these three state variables, the free carrier concentrations, fields, currents, etc. can then be computed.

The absorption coefficient, bandgap energy and the electron affinity of $In_xGa_{1-x}N$ semiconductor can be expressed as [15-16]:

$$\alpha(E(\lambda)) = \alpha_0 \sqrt{\frac{E(\lambda) - E_g(x)}{E_g(x)}} \quad (1)$$

$$E_g(x) = 0.7x + 3.4(1-x) - 1.43x(1-x) \quad (2)$$

$$\chi = 4.1 + 0.7(3.4 - E_g(x)) \quad (3)$$

respectively, where α_0 is the absorption coefficient of GaN, $E(\lambda)$ is the energy of photon corresponding to the associated wavelength and $E_g(x)$ is the bandgap of $In_xGa_{1-x}N$ semiconductor.

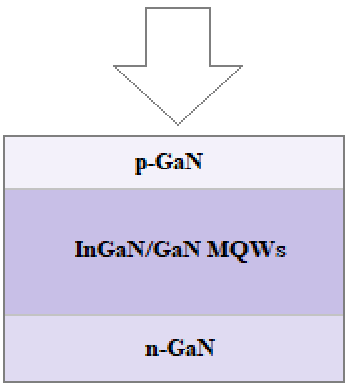

Fig. 1. Schematic diagram of the InGaN/GaN MQW solar cell

Fig. 1 shows the schematic of the MQW solar cell under investigation. It has a p-type GaN layer at the top which acts as an emitter and an n-type GaN layer layer at the bottom which is the base. Sandwiched between the top and the bottom is the active layer which is embedded with alternating layers of intrinsic GaN and InGaN quantum wells. In order to avoid the possibility of phase separation the indium content in the InGaN quantum wells is limited to only 5%. The initial values of the n-type GaN base and the p-type GaN thickness were kept constant at 2µm and 200nm respectively while the doping concentrations were set to $2x10^{18}$ and $5x10^{17}/cm^3$ respectively [11,12]. Simulations were performed under AM1.5G one sun illumination having an intensity of $100mW/cm^2$ at an operating temperature of 300K. The electron and hole recombination velocities were set to 10^7cm/s. The reflection at the front contact and the back contact were set to 0 and 1 respectively. The parameters used for the simulation are presented in Table 1 in detail. Both the front and the back contact were assumed to be flat-band for simplicity.

Table 1. Some initial parameter values adopted for the InGaN/GaN MQW solar cell in the simulations

Parameters/Layers	**p-type GaN**	**n-type GaN**	**i-type GaN**	**InGaN MQWs**
Thickness (µm)	0.2	2	0.005	0.005
Dielectric Constant	8.9	8.9	8.9	9.22
Bandgap Energy (eV)	3.42	3.42	3.42	3.215
Electron Affinity (eV)	4.1	4.1	4.1	4.25
Conduction Band Density of States ($/cm^3$)	$1.2x10^{18}$	$1.2x10^{18}$	$1.2x10^{18}$	$1.2x10^{18}$
Valence Band Density of States ($/cm^3$)	$3.1x10^{19}$	$3.1x10^{19}$	$3.1x10^{19}$	$3.2x10^{19}$
Mobility of electrons (m^2/Vs)	400	400	400	400
Mobility of holes (m^2/Vs)	10	10	10	10
Donor Concentration ($/cm^3$)	_	$2x10^{18}$	_	_
Acceptor Concentration ($/cm^3$)	$5x10^{17}$	_	_	_

3. RESULTS AND DISCUSSION

3.1. *Dependence of performance on the number of Quantum Wells*

The quantum well solar cell is generally a p-i-n structure where quantum well layers are implanted inside the intrinsic absorber layer (Fig 2). The light absorbed in the quantum wells result in the generation of electron-hole pairs in the quantum confined well. Before these electrons and holes contribute to the photocurrent they must escape from the well through a combination of thermal and tunneling processes. In most quantum confined solar cells at room temperature both the carriers capture and escape process dominates carrier recombination rate. The carrier escape is very efficient which establishes that a sufficient thermal energy is present along with a strong transverse electric field.

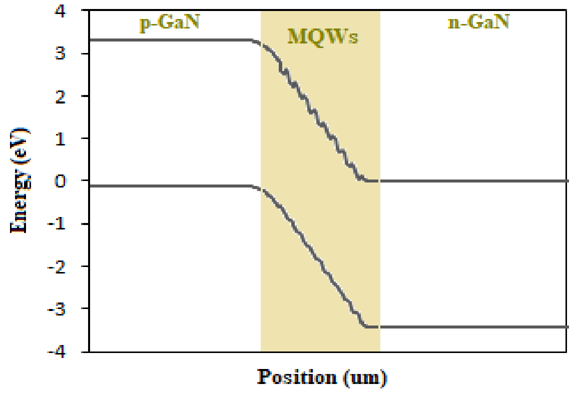

Fig. 2. Energy band diagram of the InGaN/GaN MQW solar cell

Initially the evaluation of the performance of the solar cell is done with the width of the quantum well and the barrier kept constant at 5nm. From the Fig 3 it is evident that an increase in the number of InGaN wells from 5 to 10 improves the performance of the cell significantly. All of the electrical parameters that describe the performance of a solar cell register an increase: the open circuit voltage (V_{OC}) by 0.065%, the short circuit current density (J_{SC}) by 5%, the fill factor (FF) by 0.7% and the efficiency by 5.88% (Table 2). The result is expected, as an increase in the number of quantum well increases the number of electron-hole pairs that escape thermally, favouring the generation and collection of charges. The number of quantum wells has a correlation with the value of J_{SC} and the efficiency because more photons could be absorbed as the number of quantum wells is increased resulting in a larger J_{SC}. In fact, the studies have revealed that J_{SC} increases by 1% for every added quantum well, which shows a weak dependence than expected. But if all the photo-induced carriers produced by photon absorption could reach the contact, the value of J_{SC} should have shown a greater dependence on the number of quantum wells. The result suggests that the recombination process plays an important role affecting the carrier collection process of the InGaN/GaN based MQW solar cell. Therefore, although the J_{SC} is mainly limited by the number of photons absorbed in the MQW layer, the recombination process of the photo-induced carriers must be taken into account while determining the performance of a solar cell.

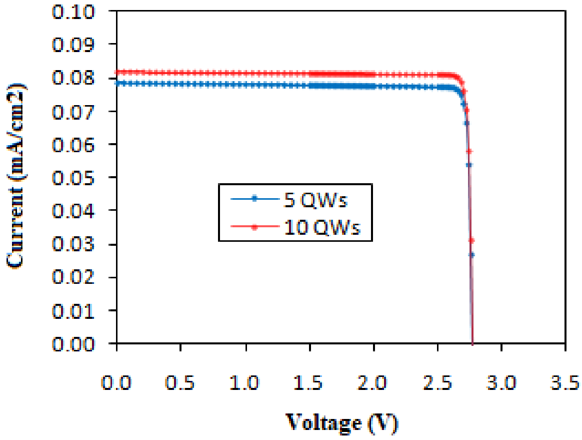

Fig. 3. Current-Voltage characteristics of the MQW solar cells for 5 and 10 periods of InGaN

Table 2. Electrical parameters of the InGaN MQW solar cell as a function of the number of wells

No. of Quantum Wells	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	Efficiency (%)
5	2.7692	0.0785	93.2016	0.2025
10	2.7710	0.0824	93.8491	0.2144

3.2. *Dependence of performance on the width of the Quantum Wells*

The dependence of performance on the width of the quantum well can be expained on the basis of the carrier lifetime in the MQW structure. The carrier lifetime (τ) in a semiconductor is governed by the recombination mechanism which has two components: radiative recombination (τ_R) and non-radiative recombination (τ_{NR}). The increasing InGaN quantum well thickness has an effect on both the radiative and non-radiative carrier lifetimes. The value of τ is given as:

$$1/\tau = 1/\tau_R + 1/\tau_{NR} \qquad (4)$$

The non-radiative recombination in the InGaN quantum well decreases for an increase in the well thickness. Therefore, the thickness of the well has an inverse effect on τ_{NR} [17]. In contrast, for an InGaN quantum well having a small thickness the separation between the elctrons and holes is small, therefore radiative recombination occurs between the charge carriers in the same quantum well layer. Because the radiative recombination rate is very large in this case, the carrier lifetime is very short. The current-voltage characteristics of the solar cell for various values of well thickness is shown in Fig.4. It is evident fom the plot that the increase in short-circuit current density is greater than the increase in open-circuit voltage. The extracted electrical parameters of the MQW solar cell are shown in Table 3.

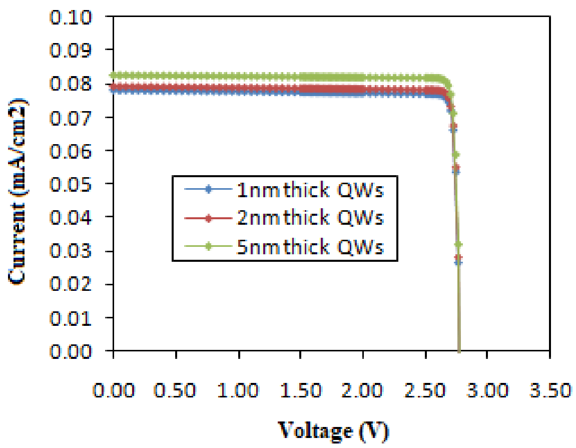

Fig. 4. Current-Voltage characteristics of the MQW solar cell for various width of the wells

Table 3. Electrical parameters of the InGaN MQW solar cell as a function of the width of wells

Width of Quantum Wells (nm)	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	Efficiency (%)
1	2.7692	0.0780	93.2759	0.2014
2	2.7697	0.0791	93.4397	0.2046
5	2.7710	0.0824	93.8491	0.2144

3.3. *Dependence of performance on the doping concentration and width of p-GaN*

The effect of doping concentration is analysed by simulating the structure for different doping concentrations from $1x10^{16}$ to $5x10^{19}/cm^3$ [Fig. 5]. The results of the simulation show that the short-circuit current density is highest for a doping concentration of $1x10^{16}/cm^3$. On the other hand the open-circuit voltage of the cell is the highest for a doping concentration of $5x10^{19}$. The effect of both these factors determine the efficiency plot of the solar cell which resembles that of the V_{OC} curve.

The thickness of p-GaN layer is studied for different values from 0.1µm to 1µm [Fig. 6]. The short-circuit current density increases with the increase in thickness of the p-GaN layer. The increasing thickness has a direct correlation with the increasing photon absorption. This leads to a rise in the electron and hole carrier generation that contributes to an increase in the current density. At the same time, a very thick p-GaN region leads to an increased surface recombination resulting in a decrease of current density. Because the open-circuit voltage and the fill factor are governed largely by the bulk properties of the semiconductor rather than the surface properties, hence their plots show a different trend as compared to the curves of short-circuit current and efficiency.

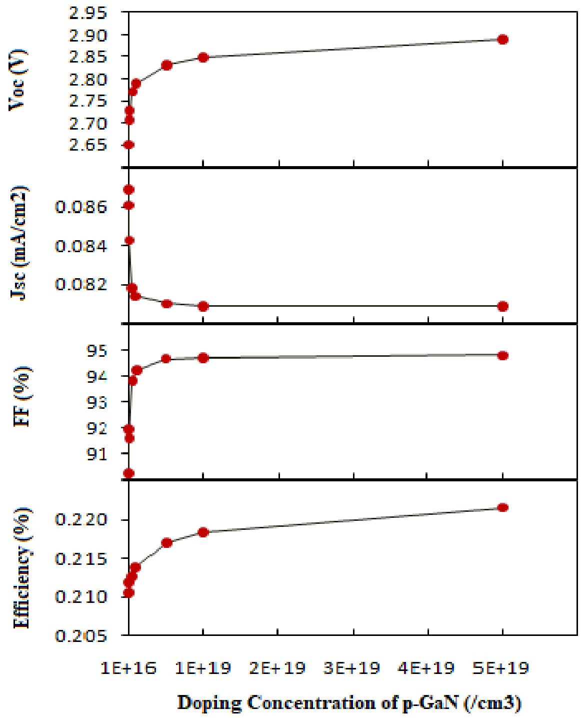

Fig. 5. Effect of doping concentration on the InGaN/GaN MQW solar cell characteristic parameters

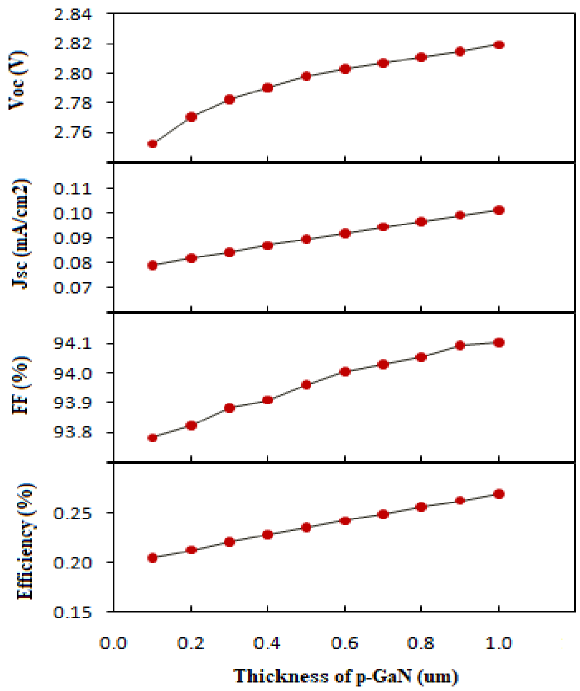

Fig. 6. Effect of thickness on the InGaN/GaN MQW solar cell characteristic parameters

4. CONCLUSION

The dependence of the characteristic parameters, namely, the open-circuit voltage, the short-circuit current, the fill factor and the efficiency were investigated for InGaN/GaN based multiple quantum well (MQW) solar cell. It has been found that increasing the number and thickness of InGaN quantum wells the electrical characteristics of the solar cells improve. However these improvements have a weak dependence on the above factors because the radiative and non-radiative recombination effects play a significant role in determining the performance of MQW based solar cells. Also in this paper, the effect of doping concentration and thickness of the p-GaN layer on the performance was investigated.

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