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# Development of $In_xGa_{1-x}N$ Alloys Based Multi-Quantum Well Solar Cells: An Overview

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*Abstract*—**This paper presents an overview of recent developments in Gallium Nitride (GaN) / Indium Gallium Nitride (InGaN) Multi-Quantum well (MQW) based solar cells. $In_xGa_{1-x}N$ alloys, $0 \leq x \leq 1$, are considered as potential candidates for future photovoltaics as they have an ability to cover the wide range of solar spectrum. InGaN based MQW solar cells are reported in the literature as an appropriate alternative of multijunction solar cells. However, significant improvement in power conversion efficiency has not been witnessed through MQW approach. Therefore, this paper has also highlighted those challenges that avoided the development of high efficiency MQW solar cells.**

***Keywords***— ***InGaN, Solar cells, GaN, high efficiency, Multiquantum well***

## I. INTRODUCTION

The bandgap revision of InN (0.65 V) [1, 2] has made the full use of spectrum possible from IR to deep UV simply by tuning the indium concentration in $In_xGa_{1-x}N$ [3]. It has been demonstrated theoretically that the power conversion efficiency (PCE) exceeding 50% could be possible with InGaN-alloys material system with Indium composition of ~40% [4]. Moreover, the captivating properties of $In_xGa_{1-x}N$ such as the high absorption coefficient, radiation resistance, saturation and peak velocities further advocate their suitability for PV applications [5]. Multijunction solar cells scheme often require the design of sophisticated tunnel diodes for the interconnections between the sub cells which highly complicates the design. One the other hand, the efficiency could be improved significantly by the inclusion of wells in absorber region (pin-structure) thereby enhancing short circuit current (Jsc) without affecting open circuit voltage (Voc) significantly [6]. These Quantum Wells (QWs) assist in extending the absorption range of the thin film solar cells into the longer wavelengths. Barnham et al. introduced the concept of QW solar cells in 1990 [7].

However, there are some issues that hinder the development of high efficiency cells. They are briefly described as: 1) the lattice mismatch of InN and GaN causes the solid phase miscibility gap that shuns the attainment of higher In-concentration in $In_xGa_{1-x}N$ [8]. This phase separation induces traps in forbidden region that start behaving like recombination centers and cause malfunctioning like affecting the thermal conductivity and reverse current, if they exceed a certain limit. 2) Higher concentration of p-doping is also challenging to achieve owing to inherent high electron affinity of $In_xGa_{1-x}N$ material system, however high doping is often required by the window layer to have a good ohmic contact. 3) The polarization charges that are developed at the interface of GaN/InGaN introduces a field that work in opposite to the transport of photo generated carriers resulting in reduction of Voc and Jsc [9]. 4) The proper choice of the substrate and the efficient design of solar cell.

The working mechanism of MQWSC is presented in the next section whereas the progress in developments of GaN/ InGaN MQW solar cells is presented in the third section followed by conclusion given in the last section.

## II. WORKING PRINCIPLE OF QUANTUM WELL SOLAR CELLS

In order to examine the performance of MQW solar cells, the dynamics of capture and escape, and the absorption and recombination of the carriers in QWs must be carefully investigated [11]. The incorporation of MQWs assist in additional absorption (i.e., low-energy photons) resulting in an increased short circuit current, however, the open circuit voltage is reduced due to more recombination of trapped carriers in QWs [12]. The MQW Solar cells are also recognized as an alternative to multijunction solar cells [10]. The issues such as lossy interconnections and current mismatch in multijunction solar cells can be addressed by incorporating the quantum wells.

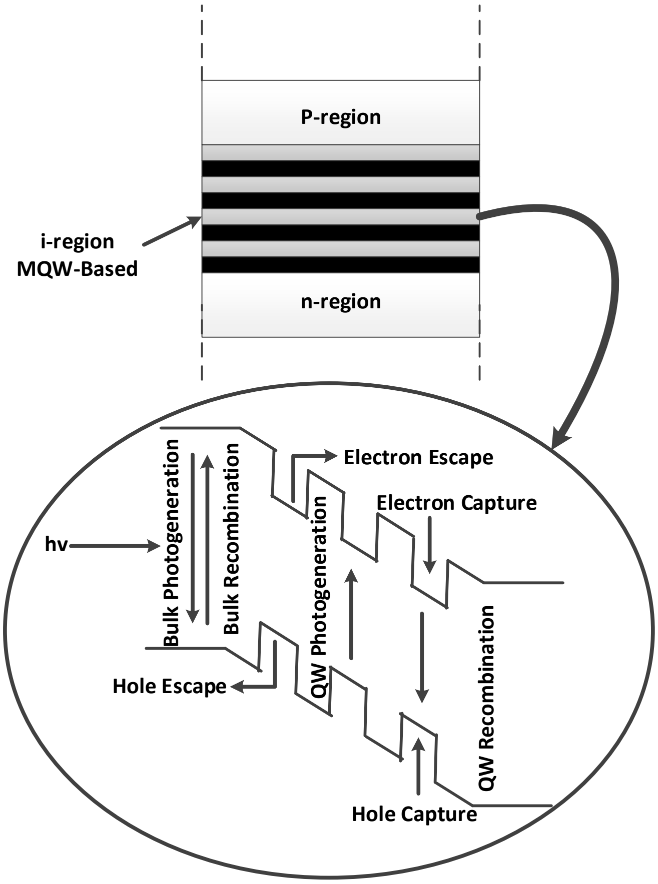

Fig. 1 Schematic of Quantum Well Solar cell with energy band diagram

If the thickness of the QWs becomes comparable to de Broigle wavelength (=plank's constant/momentum of the particle) than the continuous energy levels within the QWs get quantized. The energy of these discrete states within the QWs with infinite barrier is given as follow [13].

$$E_n = \frac{n^2 \pi^2 \hbar^2}{2mL^2} \tag{1}$$

Where n is quantum number, ħ = $h/2\pi$ is reduced Planck's constant, m is the effective electron mass, and L is quantum well thickness. The absorption range of a pin thin film solar cells could be extended into the longer wavelengths by populating the intrinsic region with the quantum wells. This shift is attributed to large overlap of electron and holes wave functions due to one dimensional confinement [14]. Due to the direct bandgap, III-V material systems and their alloy are often preferred for QWSCs.

The Fig. 1 shows a schematic diagram of QWSC, where the wells are developed by alternatively inserting low and high bandgap materials (different $In_xGa_{1-x}N$ alloys) in the intrinsic region. Typical widths of QWs are 60-150A separated by barriers of about 50A [15]. The working principle of QWSC involves many processes that are happening in the intrinsic region following the electrons and hole generation by absorbed photons. A brief description of these processes is discussed as follow.

The escape of photo-generated electrons and holes in the QWS is assisted by tunneling and thermal emission. Both are dependent on the design parameters and material properties. The escape rate via thermionic emission increases with the reduction in the barrier and with the increase in the temperature [16] whereas the tunneling increases with shrinking the thickness of the wells. The carrier may recombine radiatively or non- radiatively or they may relax owing to their scattering with the phonons on their way to contacts. The radiative lifetime decreases with the field and increases with the temperature. The auger recombination is the only considerable non-radiative recombination in QWSC. For effective PV operation, the escape rate must be greater than the capture rate [17]. The strain that is introduced due to lattice mismatch is compensated using strain balanced heterostructures [18].

The QWs have highly studied in reverse biased regime however the forward bias reverse current, more important as far as the PV applications are concerned, are less extensively been studied [19]. A comprehensive theory beyond the conventional existing theories is required that can explain the transport and optical characteristics of an open and interacting non-equilibrium system on microscopic and unified level [17]. Some of the important considerations to develop InGaN/ GaN MQWs solar cells with improved conversion efficiency are summarized as follow.

1. Adjust the active region to control the absorption properties thereby working on the thickness and numbers of QWs and barriers as well as the alloy compositions (In mole fraction) and doping levels.
2. Improve the carrier collection in order to screen the existing piezoelectric field thereby adjusting the doping levels on either side of the active region.
3. Optimize the design to overgrow the defect created at GaN/Sapphire interface and the doping level of p-GaN in order to improve the p-contact without affecting crystal quality.

## III. A REVIEW OF GAN/ INGAN MQW WELL SOLAR CELLS

In this Section an overview of some of the MQW solar cells based on InGaN alloys fabricated by different researchers for the last few years are presented.

R. Dahal et al. reported the fabrication of InGaN/GaN MQW based solar cells, grown on GaN (epilayer)/sapphire template by MOCVD [4]. To reveal the cell operation at longer wavelengths (>420 nm) and try to alleviate the issues of phase separation, the Indium (In) content was varied from 0.3-0.4. The performance of device with In 0.4 is found to be poor as compared to that of 0.3 because of the reduced material quality. The results of $In_{0.3}Ga_{0.7}N$/GaN MQWs are given in the table I. The low value of external quantum efficiency (EQE) is attributed to the lower crystalline InGaN quality with higher In

TABLE I. A REVIEW OF SOME OF THE MQW SOLAR CELLS BASED ON INGAN ALLOYS BY DIFFERENT RESEARCHERS OVER THE YEARS.

| **Authors, References and Year** | **MQW Structure** | **Fabrication Process** | **Performance Parameters** |
|---|---|---|---|
| R. Dahal et al [4]<br>(2009) | In$_{0.3}$Ga$_{0.7}$N/GaN | MOCVD | Voc=2V, FF=60%, EQE=40% at 420nm and 10% at 450nm<br>Under white light source |
| K. Y. Lai et al [20]<br>(2010) | In$_{0.3}$Ga$_{0.7}$N /GaN | MOCVD | Voc=1.95V, Jsc=0.83mA/cm2, FF=30%, η =0.48%<br>Under AM 1.5 |
| Zhang Xiao-Bin [21]<br>(2011) | In$_{0.15}$Ga$_{0.85}$N/GaN | MOCVD | Voc = 2.22 V Jsc=0.7 mA/cm$^2$, FF= 0.40, EQE=36% at 388 nm and7% at 430 nm<br>Under illumination of a Xe lamp |
| Noriyuki Watanabe et al [22]<br>(2012) | In $_{0.14}$Ga$_{0.86}$ N/GaN | MOCVD | With 3nm BT<br>Voc=1.64V, Jsc=0.69 mA/cm$^2$, FF=53% η=0.60%<br>With 9nm BT<br>Voc=1.89V, Jsc=0.61 mA/cm$^2$, FF=49%, η=0.57%<br>Under 1.5 AM |
| Jing Liang et al [23]<br>(2013) | In$_{0.25}$Ga$_{0.75}$N/GaN | MOCVD | CSS Sample<br>Voc=0.62V, Jsc=0.33 mA/cm$^2$, FF=63%, η=0.13%<br>PSS Sample Voc=0.56V<br>Jsc=0.54 mA/cm$^2$, FF=60%, η=0.18%<br>Under AM1.5 |
| Seung Hwan Kim et al [24]<br>(2014) | In$_x$Ga$_{1-x}$ N/(Al)GaN<br>With x=0.05,0.15,0.28 | MOCVD | With In 5%<br>Voc=0.56V, Jsc=0.54 mA/cm$^2$, FF=60%, η=0.18%<br>With In 15%<br>Voc=0.56V, Jsc=0.54 mA/cm$^2$, FF=60%, η=0.18%<br>With In 28%<br>Voc=0.56V, Jsc=0.54 mA/cm$^2$, FF=60%, η=0.18%<br>Under AM 1.5G |
| Der-Hsien Lien [25]<br>(2014) | GaN/In $_{0.15}$ Ga $_{0.85}$ N | MOCVD | At 300K<br>Voc=2.28V, Jsc=0.46 mA/cm$^2$, FF=60%, η=0.18%<br>At 700K<br>Voc=1.43V, Jsc=1.36 mA/cm$^2$, FF=74%, η=0.18%<br>Under AM1.5G |
| Ezgi Dogmus et al [26]<br>(2015) | In$_x$Ga$_{1-x}$ N/GaN<br>With x=0.15,0.19,0.24 | MOCVD | With In 15%<br>Voc=1.66V, Jsc=0.65mA/cm$^2$, FF=49.6%, η=0.52%<br>With In 19%<br>Voc=1.47V, Jsc=0.48mA/cm$^2$, FF=26.7%, η=0.19%<br>With In 24%<br>Voc=0.81V, Jsc=0.56mA/cm$^2$, FF=35.6%, η=0.16%<br>Under AM 1.5G |
| Pramila Mahala et al [27]<br>(2016) | GaN/In $_{0.19}$ Ga $_{0.81}$ N | MOCVD | Voc=1.69V, Jsc=0.30mA/cm$^2$, FF=41.3%, η=0.21%<br>Under AM 1.5G |
| Zhaoying Chen et al [28]<br>(2016) | GaN/ In$_{0.30}$Ga$_{0.70}$N | MOCVD | With PSS<br>Voc=2.01V, Jsc=0.97mA/cm$^2$, FF=59.4%, η=1.16%<br>With Sapphire<br>Voc=2.06V, Jsc=0.71mA/cm$^2$, FF=64.43%, η=0.94%<br>Under AM 1.5G |
| Xuanqi Huang et al [29]<br>(2017) | ~GaN/In $_{0.2}$ Ga$_{0.80}$ N | MOCVD | m-plane<br>Voc=2.32V, Jsc=0.803mA/cm$^2$, FF=55.5%<br>(20$\bar{2}$1) plane<br>Voc=1.92V, Jsc=0.736mA/cm$^{2,}$ FF=43.2%<br>c-plane<br>Voc=0.33V, Jsc=0.644mA/cm$^2$, FF=21.5%<br>Under AM 1.5G and 1 sun condition |

thin absorber layer and to the absorption losses in p contact (semitransparent). K. Y. Lai reported that high In content (>0.15) lead to fluctuations due to the lower InN/GaN miscibility, resulting in a lower Fill Factor (FF) and PCE [20]. Moreover, they explicated that high In content (30%) results in QWs with varying barrier heights and the overall result is the limited photocurrent. They found that the Efficiency (η) and FF increase with temperature is due to the additional photocurrent attributed by the carriers (thermally activated) from the shallow wells. Zhang Xiao et al. reported InGaN/GaN MQW based Solar cell with enhanced open circuit voltage [21]. The low Jsc because of reduced photons absorption in MQW is attributed to the thinner absorption layer and wider bandgap. The poor FF is credited by the large series resistance owing to high p-contact resistance and lower crystal quality of MQW. The thinner absorption layer and high series resistance is also culprit of low value of the EQE. Noriyuki Watanabe et al. inspected the effect of thickness of the barrier of InGaN/GaN MQW based Solar cell and found a reduction in $V_{OC}$ and an improvement in Jsc with the reduction of barrier thickness (BT) [22]. The lower $V_{OC}$ is ascribed to the larger ideality factor and leakage current of the diodes whereas the higher Jsc is due to longer lifetime of the carriers. Jing Liang et al. reported that InGaN/GaN MQW based Solar cell grown on patterned sapphire substrates (PSS), having GaN nucleation (~30nm) on sapphire, has improved performance in term of Jsc and η than cell grown on conventional sapphire substrate (CSS) [23]. The improved JSC is attributed to better light absorption because of scattering due to textured surface and reduced density of edge dislocation.

The lower Voc in both cases is ascribed to the deteriorated crystal quality and higher Indium content. Seung Hwan Kim et al. investigated the carrier transport as function of composition of Indium in vertical type InGaN based solar cells and found increased JSC and reduced FF with increasing Indium composition [24]. It is because of the reduced tunneling of carrier because of stronger piezoelectric field and increased height of the barrier. Der-Hsien Lien et al. fabricated InGaN/GaN MQWSCs on c-plane (sapphire) substrate by MOCVD to investigate their applicability for the harsh environment and found that they have an excellent reliability [25]. The high radiation robustness was attributed to their direct bandgap and atomic bonding is strong.

Ezgi Dogmus et al. fabricated and investigated InGaN/GaN MQW based Solar cells with varying Indium composition [26]. The EQE analysis revealed that spectral cut-off λ of 24% In-sample extends up to 530nm. They also revealed that the high density of dislocation due increasing Indium content degrades the $V_{OC}$ and η. The highest PCE was achieved with 15% Indium sample. Pramila Mahala et al [27] have fabricated and analyse InGaN/GaN MQW based Solar cells and the results are tabulated in Table 1. The low value of Jsc and FF is attributed to the series resistance, which for the most part was contributed by p-contact/p-GaN interface region. Zhaoying Chen et al. investigated InGaN/GaN based MQW solar cell fabricated on the patterned sapphire substrate (PSS), in form of hexagonal array of conical protrusions, and compared to that grown on (0001) sapphire [28]. They found an improvement of PCE (~23.4%) and a positive temperature coefficient of PV efficiency up to 423K. The high PCE is attributed to better crystal quality that led to reduced density of threading dislocation. They also indicated the potential of III-N for the applications of concentrator PV. Xuanqi Huang et al. demonstrated the potential of semi-polar and non-polar bulk GAN substrate for high efficiency future PV [29]. They grew MQWSCs on $20\bar{2}1$ plane (semi-polar) and m-plane (non-polar) GaN substrates and compared them with convention c-plane substrate. The best performance was achieved by non-planer substrate which is due to the reduction in polarization induced effects, resulting in a better collection and transport of the carriers.

## IV. CONCLUSION

This paper presents the recent developments in the Multi Quantum Well solar cells based on InGaN alloys. It is found that although the $In_xGa_{1-x}N$ material system has a potential to achieve a theoretical efficiency of more than 50 percent, however up till now this is not achieved in fabrication. It is largely attributed to the poor crystal quality at higher indium composition. Moreover, other issues such as high p-doping, suitable choice of substrate, polarization and optimum design are also responsible for not achieving the desired results. Therefore, it is evident that still there is a long way to go to achieve better efficiency of solar cell.

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