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A Review on Indium Gallium Nitride Solar Cells

Mrinmoy Dey[1, 2*], Iffat Tasnim[1], Nazia Rahman[1], Maitry Dey[1,2], N. K. Das[1,2], A. K. Sen Gupta[1,2], M. A. Matin[1,2] and N. Amin[3,4]

[1]Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh
[2]Renewable Energy Laboratory (REL), Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh
[3]Solar Energy Research Institute (SERI), The National University of Malaysia, 43600 Bangi, Selangor, Malaysia
[4]Department of Electrical, Electronic and Systems Engineering, The National University of Malaysia, 43600 Bangi, Selangor, Malaysia
[*]mrinmoycuet@gmail.com

Abstract- *This research work aims to summarize the potentiality of $In_xGa_{1-x}N$ solar cell based on the research that has been carried out in recent times. InGaN is an important III-V semiconductor material best suited for solar cell as it has high absorption coefficient, high resistivity to radiation and a wide tunable band-gap of a range varying between 0.69 eV to 3.4 eV. Recent studies show that $In_xGa_{1-x}N$ has proven its' importance and potentiality as a solar cell material in the field of homo-junction, hetero-junction and also in multi-junction. This research work is an approach to gather information about the properties of various InGaN based solar cells. The research work was also carried out by investigating recent innovative research work that involved fabrication and numerical modeling as well as analysis of $In_xGa_{1-x}N$ based homo-junction, hetero-junction and multi-junction solar cell. This research work also summarizes variation of properties of InGaN solar cells for different cell structure.*

Keywords: InGaN solar cell, single junction, homo- junction, hetero-junction, multi-junction solar cells, absorption coefficient.

1. INTRODUCTION

With the increasing trend of civilization and population the need for energy is also increasing. Thus usage of carbon emitting fossil fuel has come to a critical point where both generation of electricity and environmental balance should be compensated. Besides, fossil fuel will run out of storage because of extreme use of it as a result of extreme energy crisis. Thus renewable energy resources have attracted the attention of the researchers to meet the future energy demand in a sustainable way. Furthermore, renewable energy sources avoid the safety hazards that are incorporated with nuclear power plant [1]. Amongst all the renewable resources solar PV are most preferable as it has low maintenance, wide range of diversity, and low cost. Moreover it is called infinite energy source as sunlight is abundant in nature. Solar cells that are building block of PV panel must be modelled with a material which has high efficiency in converting sunlight into electricity, high photon absorption, free of toxicity and that is available in nature.

Group III-nitride semiconductors have attracted the attention of the researchers because of its' great potentiality and wide range of properties that are suitable for modelling solar cells. They are also important material for semiconductor light emitting device [2]. One of the most suitable property of $In_xGa_{1-x}N$ based semiconductor devices is it's tunable band-gap which can be varied from 0.69 to 3.4eV by varying the content of In in the composition which covers the whole solar spectrum [3]. But the increase in In content is lead by the growth of material by phase separation process which will degrade the quality of InGaN. This degradation increases with the increasing thickness of the layer [4]. Two layers of InGaN solar cell having bandgap in between 1.1 to 1.7 eV can achieve as much as 50% efficiency theoretically whereas multijunction can have efficiency of about 70%. Layers with different bandgap can be fabricated between InGaN as it is not sensitive to lattice defect [5]. The layers of InGaN solar cell can be deposited using the cost effective techniques and which are efficient to fabricate, such as Metal Organic Chemical Vapor Deposition (MOCVD), Metal Organic Vapor Phase Epitaxy (MOVPE), and Molecular Beam Epitaxy (MBE). So, InGaN is a novel material and research on this material can bring about efficient result in case of solar cell.

Many research works have been carried out till now for evolving the highest efficiency of InGaN solar cell in case of homo junction, hetero junction & multi junction. Many techniques have been adapted to enhance their performance. Therefore, it is the purpose of this research paper is to present a detail review on the recent research of the $In_xGa_{1-x}N$ based solar cells for the advancement of new research. Most of the information summarized in this paper is based on recent research and investigations.

2. Status of Research on $In_xGa_{1-x}N$

Research has been done on various $In_xGa_{1-x}N$ homojunction, heterojunction and multijunction solar cell. Based on recent research and investigation different InGaN solar cell with different Indium content, single and multiple junctions are summarized below.

2.1 Homo-junction $In_xGa_{1-x}N$ Solar Cell

Many $In_xGa_{1-x}N$ solar cells has been modelled and simulated to gain higher efficiency. The content of Indium in $In_xGa_{1-x}N$ is varied from 25% to 100% to get higher efficiency. The mole fraction has an impact on the solar cell as the band gap of the material depends on it. Yang demonstrated fabrication of a p-n homo-juction InGaN cell by MOVPE with 18% indium content and 320nm thickness. He achieved V_{oc} of 430mV and very low Jsc of 0.04 mA/cm^2 [6]. Jani et al. investigated two different cell by MOVPE process with different In content of 0.28 and 0.12 with thickness of 100nm and 300 nm respectively and found V_{oc} of 1.5-2V and J_{sc} same as the previous one [7, 8]. A InGaN homo-junction cell was fabricated by MPE process with an intrinsic layer which gives a standard V_{oc} of 2.5V and J_{sc} of 30 mA/cm^2 with 30% In content and 800nm thickness by Chen [9,10]. Similar p-i-n junction of InGaN was formed by MOVPE process with 2-15% of indium content and 400nm of layer thickness by Cai et al. but found a poor J_{sc} of 1.4-1.87 mA/cm^{-2} at xenon lamp [11, 12]. Misra demonstrated fabrication of a homo-junction cell with 0.31 mole fraction of indium and it's V_{oc} and J_{sc} was measured in AM0 at 1 sun and 3 sun. It was proposed to be manufactured by Molecular beam epitaxy and showed V_{oc} of 0.55V at AM0 1 sun and V_{oc} of 0.78V at AM0 3 sun [13]. In 2010 a p-n homojunction InGaN solar cell was proposed by Jampana by MOVPE and calculated it's V_{oc} and J_{sc} at AM0 and AM1.5 [14]. Open circuit voltage of 1.73V and short circuit current density of 0.91mA/cm^{-2} was found at AM0 but at AM1.5 both V_{oc} and J_{sc} came down to a lower value of 1.47V and 0.26 mA/cm^{-2} respectively [14]. Recent research on fabrication was done in 2011 by Bonny who measured the open circuit voltage and short circuit current density under xenon lamp which was 1.8-0.2 V and 1-2.2 V respectively. It should be noted that the thickness was varied from 0.4µm to 1 µm [15] .

All of the homojunction cell discussed so far was based on fabricating p-n junction by various method and experimentally calculating the outcome under different circumstance. Now our investigation will move forward to the numerical analysis of homojunction InGaN solar cell. Researches usually carry out simulation work by different simulating software by variation of indium content on p-n layer of the cell and investigating it's feasibility and exploring it's efficiency and other characteristics.

In 2013 Dennai simulated a simple p-n junction solar cell by simulating software AMPS-1D with In content of 0.52 and explored it's potentiality by varying p-layer thickness and doping concentration. p-layer is varied from 100nm to 2µm and doping concentration was varied between 1×10^{15}cm^{-3} to 1×10^{19} cm^{-3} . Finally the result of 22.46 mA/cm^2 short circuit current density , 1.14 of V_{oc} , 89.4% of fill factor and a optimum power conversion efficiency of 22.99% was achived at 600nm p-layer thickness, 230 nm of n-layer thickness and 1×10^{15} cm^{-3} doping concentration [16]. A.K Das investigated different $In_xGa_{1-x}N$ solar cell by varying indium content from 42% to 74% and measured the performance parameters of each cell at AM1.5. Simulation was carried out with and without an intrinsic layer of $In_xGa_{1-x}N$ having bandgap of 1.4eV and 230 nm of thickness. Without i-layer mole fraction of 0.62 power conversion efficiency of 28.088% and with i-layer mole fraction of 0.46 PCE of 27.411% was achieved [17]. Later in 2015, Mesrane investigated InGaN based single junction solar cell with bandgap of 1.39eV by ATLAS software and found J_{sc} =32.6791mA/cm^{-2}, V_{oc}=0.94091 volts, FF=.886 and efficiency =25.5056% [18]. Lastly, a high efficiency p-n junction InGaN solar cell was modelled and simulated by N. Akter at In content of 64% and the back contact was optimised at back contact barrier height=1.3 eV which indicate the metal contact should be nical. p-layer thickness was varied from 100nm to 1µm and was optimized at 500nm. n-layer thickness was varied from 30nm to 120 nm and then was optimized at 100nm. The highest efficiency was found at doping concentration of 1×10^{16} cm^{-3}. By keeping all the parameters fixed at optimization J_{sc}=30.883mA/cm^2, V_{oc}=0.925V, FF=0.876 and efficiency of 25.02% was found [19].

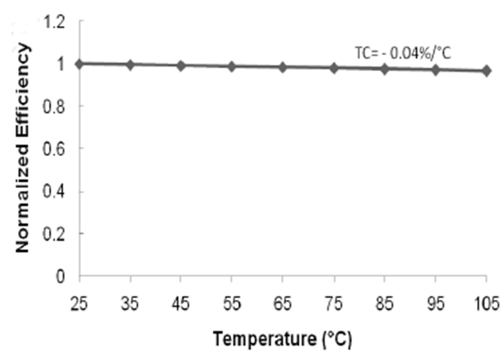

Fig.01 Effect of temperature on the efficiency of single junction InGaN solar cell [19].

Effect of temperature on the cell was also investigated and it was found that the performance parameter of the cell degrades with operating temperature with a gradient of 0.04%/°C. Fig .01 shows how the normalized efficiency of the cell decays with temperature.

2.2 Heterojunction Solar Cell

Most solar cells based on group III nitrides that have been researched are heterojunction. InGaN heterojuction solar cells that have been modelled so far has the common structure of p-GaN/ i-InGaN/n-GaN. The researche work that had been done to model high efficient InGaN solar cell for the past few years are discussed below.

In 2007 design and characterization of GaN/InGaN has been performed by O.Jani which shows open circuit voltage of 2.4V and internal quantum efficiency as high as 60% by MOCVD fabrication process [20]. In 2008 a research paper published by X. Zheng on GaN/InGaN heterojunction structure which shows open circuit voltage of 2.1V and fill factor up to 81% [21]. The main structure of this solar cell was p-GaN/ i-$In_{0.1}Ga_{0.9}N$/ n-GaN. In 2009 A. Melton reported the result for MOCVD growth of high In content InGaN film on Zno substrate for optimized structural and optical properties [22]. In 2010 J. Phill Shim published a paper on InGaN/GaN p-i-n solar cell where 10.8% indium was confirmed within an i-InGaN layer [23]. The solar cell with ITO shows a short circuit current density of 0.644 mA/cm^2, an open circuit voltage of 2.0V,a fill factor of 79.5%,a peak external quantum efficiency of 74.1%,and a conversion efficiency of 1.0%. In 2011 a high internal and external quantum efficiency of InGaN/GaN has been reported by E. Matioli [24]. The internal quantum efficiency was found as high as 97% and a peak external quantum efficiency of 72%, a fill factor of 79%, a short-circuit current density of 1.06 mA/cm^2, and an open circuit voltage of 1.89 V were achieved under 1 sun air-mass 1.5 global spectrum illumination conditions. In 2013 Mahfizul Islam published a paper showing the influences of interdot distance, quantum dot size and indium content of $In_xGa_{1-x}N$/GaN QD–IBSC on the position and width of the intermediate bands are investigated [25].The results reveal that the $In_xGa_{1-x}N$/GaN quantum dot intermediate band solar cell gives much larger power conversion efficiency than that of conventional solar cells. The maximum efficiency for one intermediate band is 54.41 % and it can be increased to 62.79 % if two bands are formed in the potential well. In 2013 Wang reported a research paper on the characteristic of non polar double heterojunction GaN/$In_xGa_{1-x}N$ solar cell for different In content [26].

The maximum conversion efficiency was found 24.32 % with 65% In composition. In the same year Z. Ren published a paper which shows increased performance of GaN/InGaN solar cell with an thin i-layer of $In_{0.05}Ga_{0.95}N$ between GaN barrier and $In_{0.2}Ga_{0.8}N$ well. the open-circuit voltage was increased from 1.4 V to 1.7 V, short-circuit current density was increased by 65% and external quantum efficiency was increased by 59% [27]. In 2014 Zahra Arefinia published a paper at the 22nd Iranian Conference on Electrical Engineering (ICEE 2014) on modeling of grapheme based schottky barrier InGaN solar cell. A new graphene based Schottky barrier solar cells with low Indium contents (x <0.45) is proposed [28]. Then, their solar power conversion efficiency simulated and optimized using an analytical model. Also, the effect of the temperature and doping concentration of $In_xGa_{1-x}N$ on the performance of the G/ $In_xGa_{1-x}N$ solar cells is evaluated.

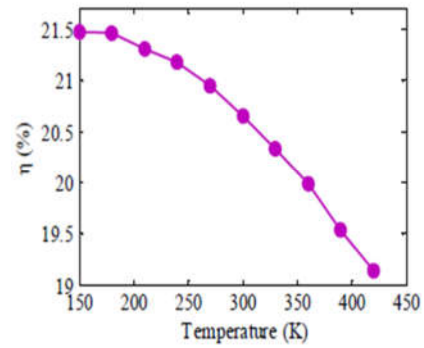

Fig.02 Effect of temperature on Graphene/InGaN solar cell [28].

Fig.02 shows the how the efficiency of the modeled cell decreases with operating temperature. The output performance parameter of the cell was compared with similar structure of Graphene/Si solar cell and it has been observed that the modeled cell has a better performance than the compared cell. The temperature of the solar cell was varied from 150K to 443K . A Voc Of 3.1V, Jcs of 6.9mA/cm^2, FF of 96.2% and conversion efficiency of 20.67% has been reported on graphene/$In_{0.3}Ga_{0.7}N$ solar cell simulation [28].

In 2015 a paper in Algeria by L. Boudaude presented a GaN/InGan which was simulated using SCAPs software. the maximum efficiency of a p-n GaN/InGaN heterojunction solar cell with 0.2 indium composition is 2.78%, above an indium composition of 20%, the modeled heterojunction devices do not operate as solar cells [29]. In the same year A.M Fabien demonstrated the growth, characterization, and testing of large area InGaN/GaN solar cells with 50nm and 200nm thick InGaN films with 10% and 20%. This work presents the InGaN/GaN duel junction with the highest In content (22%) [30].

2.3 Multijunction Solar Cell

Although many research work and advancement has been done on homojunction and heterojunction InGaN solar cell specially on GaN/$In_xGa_{1-x}N$ but their performance is still low because of their theoretical limits and transparency loss for higher bandgap energy. So, research work has been carried out based on multijunction solar cell for high quantum efficiency and high temperature tolerance.

In 2008 a high performance GaN/InGaN p-i-n double heterojunction solar cell with 2.95 bandgap with external quantam efficiency of 63% was reported by Neufeld [31]. The solar cells have a fill factor of 75%, short circuit current density of 4.2 mA/cm^2, and open circuit voltage of 1.81 V under concentrated AM0 illumination. In 2010 J.Y Wang published paper on enhancing InGaN based solar cell efficiency through localized surface plasmon interaction by embedding Ag nanoparticles in the absorbing layer having efficiency of about 27% [32]. In 2011 F. Bouzid explored the potential of $In_xGa_{1-x}N$ tandem cells. Calculation indicates that the attainable efficiency can be enhanced up to 34 % and 37% for tandems with double and triple junctions respectively, obtained under 1 sun AM1.5 illumination and at ambient temperature, using realistic material parameters [33].

K.J Singh has carried out numerical simulation of compositionally graded optimized radiation hard InGan multijunction solar cell that achieved high theoretical efficiency upto 39.02% for space application using TCAD [34]. In 2013 simulation of multijunction was carried out by D.Benmoussa using AMPS-1D and found that the efficiency can be improved from 10.09% for a single junction up to 40.05% for six junctions obtained [35]. Fig.03 represents how the efficiency of the cell increases when the number of junction is increased.

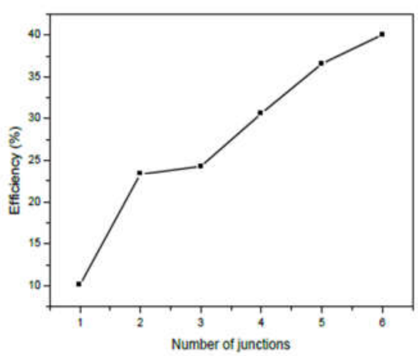

Fig.03 Variation of efficiency with number of junction [35].

R.M Farrell discussed the unique advantages and challenges of fabricating hybrid InGaN-GaAs multi junction cells for ultrahigh efficiency device designs in 2013 [36]. The external quantum efficiency increased across the entire spectral range of the InGaN QWs and the peak EQE increased from 45.7% to 68.1%. Likewise, the short circuit current density increased from1.13 mA/cm^2 to 1.64 mA/cm^2, the open circuit voltage increased slightly from 2.05 V to 2.06 V, the fill factor decreased slightly from 63.2% to 62.0%, and the peak power density increased corresponding to a relative increase of 43.2% following the application of the optical coatings.

In 2014, F.Bouzid designed a $In_{0.53}Ga_{0.47}N/GaAs$ photovoltaic dual junction tandem using GaAs/AlAs bragg reflector and achieved conversion efficiency of 29% under 1 sun AM 1.5G illumination . In addition, they have analyzed the temperature effect of the structure and found that the increase in temperature causes a degradation of the cell performance [37]. N. Akter designed and simulated a high efficiency InGaN multijunction tandem solar cell. The best conversion efficiency of the single junction, double junction and triple junction solar cells are 25.019%, 35.45% and 42.34% respectively. Effect of tunnel junction for the tandem cells also investigated and found that required thickness for tunnel junction is around 25 nm. It has been found that the TC of InGaN cells is about -0.04%/°C, which indicate the higher stability of the proposed cells [38] .

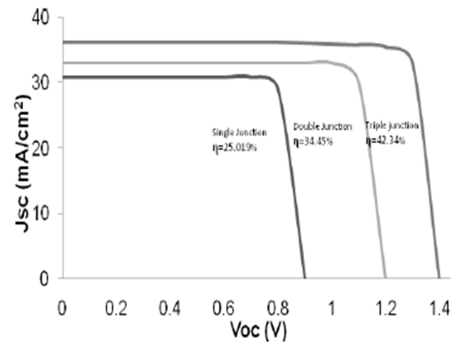

Fig.04 J-V curves for single, double and triple junction cells [38].

Y.Fang desingned a high temperature InGaN double junction solar cell using TCAD. The theoretical conversion efficiency of the best devices can be 30% at 450 °C with an incident solar radiation concentration of 200 suns [39].

Many efficient research works has been done in the recent year 2016 on multijunction InGaN solar cell. A MQW device with 40 periods of $In_{0.12}Ga_{0.88}N/GaN$ quantum well stack is simulated by Y.Fang using TCAD [40]. Both IQE and J-V characteristic are simulated at room temperature and 450^oC. Polarization effect is modeled and proved to carrier collection inside quantum wells. They also showed that the device is suitable as a concentrator solar cell for solar thermal systems. An InGaN/GaN solar cell including a dual multiple quantum wells structure is investigated by Zhen Bi. It shows an obvious advantage over the conventional InGaN/GaN cell, which only contains a single MQW structure. Because the short current density (Jsc) increases, the 1 sun power conversion efficiency significantly improves from 0.62% (single cell) to 1.02% (dual cell) [41].

3. CONCLUSION

In this research work various fabrication process and numerical analysis that has been done on InGaN single and multijunction in recent times. The property of those solar cells has also been investigated and the output performance parameter variation in different condition has been discussed. It has been found that homojunction of InGaN material has a record efficiency of 25.02% with better thermal stability. InGaN heterojunction solar cell has achieved 24.32% with In content of 65% till now. Finally, for InGaN multijunction solar 35.45% and 42.34% PCE was reported for duel and triple junction respectively.

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