

High Performance InGaN Solar Cell from Numerical Analysis

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Abstract

The InGaN is recently developed a potential thin film solar cell material with the tunable band gap of 0.7 eV to 3.4 eV to utilize the maximum sun spectrum. In this work, InGaN solar cells have been designed and simulated to investigate the hidden potentiality of $In_xGa_{1-x}N$ material. Numerical Analysis for the designed cells has been performed with AMPS (Analysis of Microelectronic and Photonic Structure) simulator targeted for high efficient single junction solar cells. The performance of $In_xGa_{1-x}N$ single junction solar cells with different proportion of In and Ga content, thickness of each layer including various doping concentration and effect of back contact has been explored for a optimized ultra thin cell. A single junction $In_xGa_{1-x}N$ solar cell has been proposed with conversion efficiency of 25.02% ($V_{oc}=0.925$ V, $J_{sc}=30.883$ mA/cm², $FF=0.876$) having doping concentration of 1×10^{16} cm⁻³ with 0.5 μ m p-InGaN layer, 0.1 μ m n-InGaN layer and Nical ($\Phi_{bL}=1.3$ eV) as a final back contact metal. Furthermore, it has been found that the normalized conversion efficiency of the proposed cell were linearly decreased with a gradient of $-0.04/^{\circ}C$ of the operating temperature, which indicate better stability of the InGaN solar cell.

1. Introduction

To sustain the current development we need inexpensive, reliable and sustainable energy source. The Sun which is unlimited sources of renewable energy and photovoltaic (PV) cells still remains the best way yet determined to harness energy from the sun. The early efforts for development of PV cells were directed towards space applications and PV cells are still today the main source of power in space. InGaN based PV cell is one of the most promising candidates for solar

energy conversion due to higher conversion efficiency and the possibilities of low cost. The InGaN has near ideal band gap of 0.7 eV to 3.42 eV [1, 2] and high optical absorption coefficient over 10^5 which indicate the better absorption of the sun spectrum. It is a very potential material for ultra thin solar cells especially for space application. The layers of an InGaN solar cell can be deposited using many cost effective deposition techniques, such as Metal Organic Chemical Vapor Deposition (MOCVD), Metal Organic Vapor Phase Epitaxy (MOVPE), Molecular Beam Epitaxy (MBE) [3].

In 2007 Jani et al. have reported GaN/InGaN solar cell [4]. Xiaobin Zhang et al. published 20.284% conversion efficiency of InGaN single junction solar cell in 2007 [5]. In 2008 same group published 24.95% conversion efficiency of single junction InGaN solar cell [6]. Recently in 2011 S. Ben Machiche has achieved efficiency of 24.88% [7]. The III-V group materials are widely used for tandem solar cells for the space application, such as InGaP/GaAs double junction and InGaP/GaAs/Ge triple junction cells were developed in 2009. Triple junction structure of GaInP/GaAs/Ge shown efficiency of 41.6% [8] but it should be noted that the 0.66 eV indirect band gap energy of Ge is not optimal as the material for the bottom sub cell in a triple junction cell. Recently, in 2012 a new structure of GaInP/GaAs/GaInNAs shows efficiency of 44%, which is the highest [9]. But the problem of this structure is more complex quardinary alloy system of the cell and the toxicity as well as the cost of Arsanite (As) material is the biggest barrier of these material system. However, there are scopes to reduce the thickness to save materials and to increase the conversion efficiency by improving short circuit current density (J_{sc}), open circuit voltage (V_{oc}) and fill factor (FF) with different proportion of x in $In_xGa_{1-x}N$ material system with different doping concentration. All the above ideas were modeled in this work and numerical analysis was done by using AMPS 1D simulator to achieve the best InGaN single junction solar cell for higher efficiency and stability. This proposed cell might be a basic component of tandem solar cells. The conversion efficiency has been found for the proposed InGaN single junction solar cell is 25.02% with the temperature coefficient (TC) of -0.04%/°C.

2. Modelling and Simulation

In solar cell, a cell model is a theoretical structure created to represent real processes and parameters that might influence cell performance. Models are widely used in science and technology to simplify complicated systems, by neglecting the non crucial features. Consideration of important and non important parameters is the most important task for a successful cell model. In a good model all the important parameters are taken into account and the non important ones are omitted. Modeling is widely used in analysis of silicon solar cells. For thin film InGaN solar cells the need for numerical modeling methods is higher due to the complex nature. Numerical modeling would help to understand the solar cells, behaviour and should give the additional ideas to control the fabrication parameters to improve the cell performance.

Once the cell is produced, it needs to be characterized to determine the performance and losses. Analysis of characterization curves indicates the nature and source of losses. Modeling techniques can provide physical explanation of the mechanism behind the cell performance. Numerical modeling may predict the changes in material properties on the solar cell performances and could suggest ways to change the fabrication process to improve the cell performances. Modeling would be a valuable tool to improve the performance, interpretation of modeling results requires great carefulness.

Numerical simulation of solar cell is an important way to predict the effect on cell performance [10] and to test the feasibility of the proposed structure. Due to complex and very costly fabrication methods of solar cells; the need for numerical modelling method is higher. Fig. 1 illustrates the proposed structure of InGaN based single junction solar cell. It is clear from Fig. 1 that this structure consists of TCO as front contact and back contact to achieve thin InGaN layer. The doping concentration of $5 \times 10^{17} \text{ cm}^{-3}$ has been used in the earlier InGaN solar cell, it has been changed to $1 \times 10^{16} \text{ cm}^{-3}$ which is practically achievable values for higher efficiency [11]. Higher watt function metals such as Au/Ni/Pt need to be used for back contact as InGaN has high electron affinity. In this work, AMPS-1D simulator was used to investigate the $In_xGa_{1-x}N$ cell performance. The Table 1 show all material parameters used in this work, which were determined based on literature, theory or in some cases reasonable

Table 1.
Parameters for simulation of single junction solar cell

Parameter	p-InGaN	n-InGaN
x	0.64	0.64
E_g	1.34	1.34
ϵ_r	13.09	13.09
χ (eV)	5.54	5.54
$N_c 10^{18} \text{ cm}^{-3}$	1.40	1.40
$N_v 10^{19} \text{ cm}^{-3}$	4.04	4.04
$N_A \text{ cm}^{-3}$	10^{16}	0
$N_D \text{ cm}^{-3}$	0	10^{16}
μ_n	955	955
μ_p	169.8	169.8
D (μm)	0.5	0.1

estimations. In this analysis p-InGaN absorber layer thickness from 0.1 μm to 1.2 μm , n-InGaN layer thickness from 30 nm to 0.15 μm were varied by keeping all other parameters at the fixed values as shown in Table 1 aiming to achieve the highly efficient single junction solar cells. Back contact selection and doping concentration of the proposed cell was optimized.

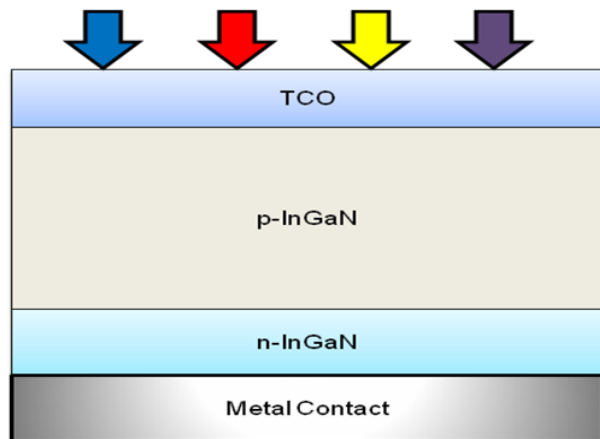


Figure 1. Proposed structure of InGaN single junction solar cell

3. Result and Discussion

This numerical analysis has been done aiming to improve the cell performance of the InGaN single junction solar cell structure. The dependency of the cell performance on the p-InGaN and n-InGaN layers thickness from 0.1 μm to 1.5 μm , with doping concentration of $1 \times 10^{14} \text{ cm}^{-3}$ to $5 \times 10^{17} \text{ cm}^{-3}$ and back contact barrier of 0.5 eV to 1.5 eV which corresponds to Ag, Al, Ti, Mo, Cu, Ni and Pt has been simulated by employing AMPS simulator. Finally, temperature effect from 25°C to 100°C has been simulated to explore the stability of the proposed cell at higher operating temperature.

In this work, simulations were done for different proportion of Indium in $\text{In}_x\text{Ga}_{1-x}\text{N}$ from 0% to 100% and found the efficiency of 15.75%, 19%, 20%, 22%, 23%, 24% for In ratio 52%, 57%, 60%, 62%, 63%, 64% respectively. It has been observed from this analysis that $\text{In}_x\text{Ga}_{1-x}\text{N}$ single junction solar cell shows better performance in the band gap range of 1.2 eV to 1.5 eV and was optimized at 1.34 eV that indicate $\text{In}_{0.64}\text{Ga}_{0.36}\text{N}$, which is illustrated in Fig. 2.

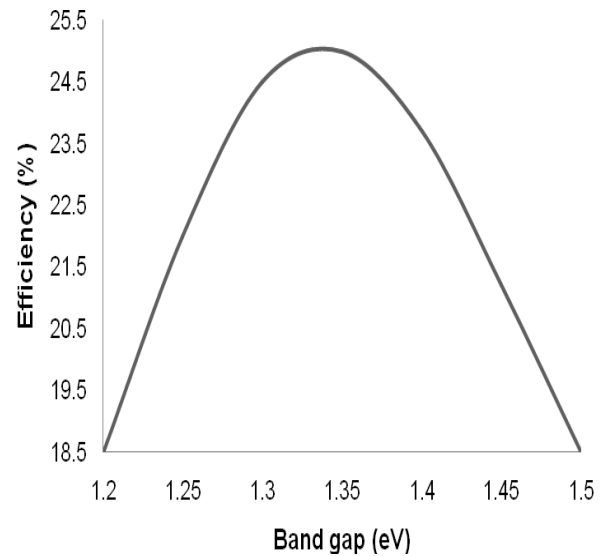


Figure 2 Selection of band gap for single junction InGaN solar cell

The effects of p-InGaN absorber layer thickness variation from 0.1 μm to 1.5 μm on the cell output parameters are shown in Fig. 3, with all other parameters of Table 1. From Fig. 3, it is clear that solar cell efficiency is affected by the absorber layer thickness of p-InGaN. However, V_{oc} and FF are not affected and J_{sc} is increased with the increment of cell p-InGaN absorber layer thickness. Thus, from the combined effect, the efficiency is increased with increment of layer thickness until 0.5 μm but above 0.5 μm it shows a decreasing trend. It might be attributed to weaken of electric field above 0.5 μm of p-InGaN layer.

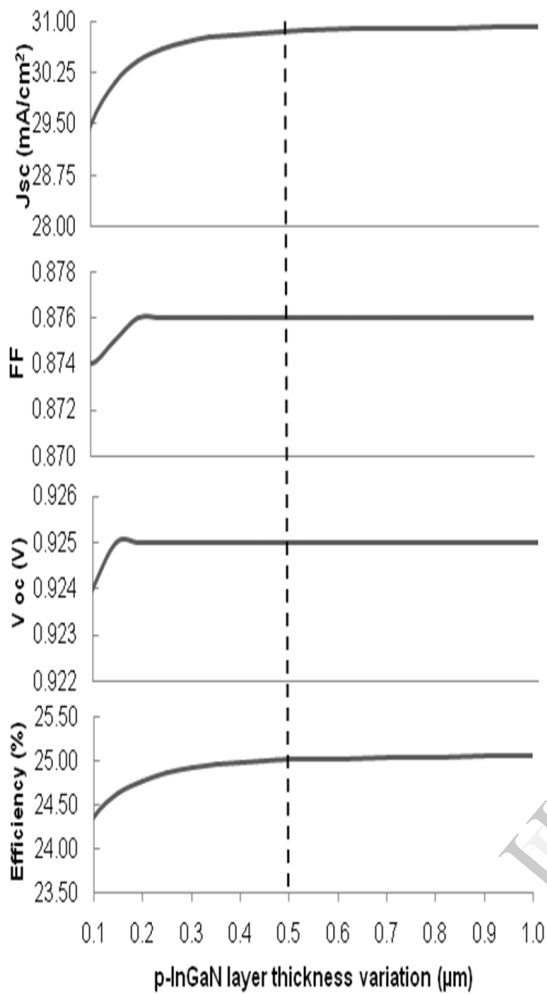


Figure. 3 Selection of band gap for single junction InGaN solar cell

Moreover, the electrical field distribution in the p-InGaN absorber layer was found to diminish within 0.5 μm of InGaN thickness. Thus, generation of carrier after 0.5 μm of InGaN will not contribute to the cell output rather would be lost by recombination. Electric field distribution and generation rate of InGaN single junction solar cell has shown in Fig. 4 and Fig. 5 respectively.

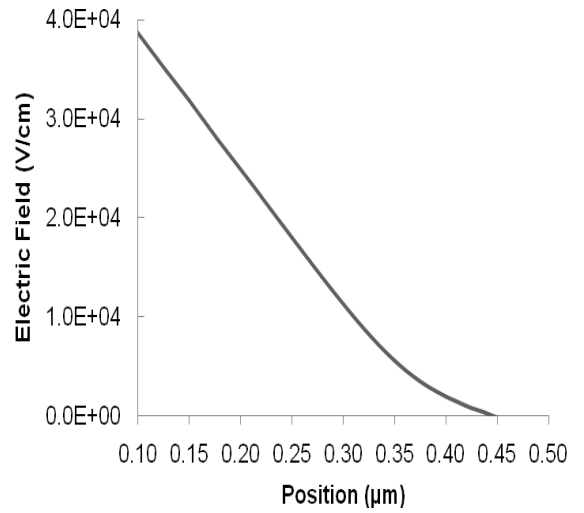


Figure 4. Electric field distribution of InGaN solar cell

The carrier generation rate of 0.5 μm thick InGaN cells are calculated and found to be in the order of $5 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}$ in the vicinity of InGaN junction as shown in Fig.5. From the Fig. 5, it is evident that the carrier generation drastically decreases within just 0.5 μm of InGaN absorber layer thickness.

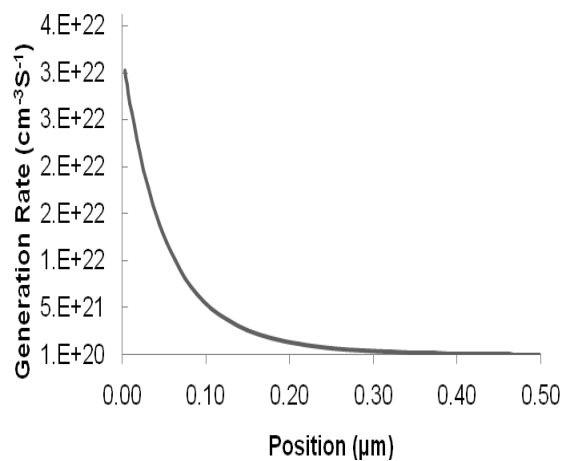


Figure 5. Generation rate of InGaN single junction solar cell

A numerical simulation was done to investigate the layer thickness of n-InGaN in the range of 30 nm to 0.12 μm . The simulation results are shown in Fig. 6. It is clear from the Fig. 6 that the cell performance has increased from 30 nm to 0.1 μm and above 0.1 μm it has no significant change. The cell performance is better in 0.1 μm n-InGaN when all other parameters are constant as the Table 1.

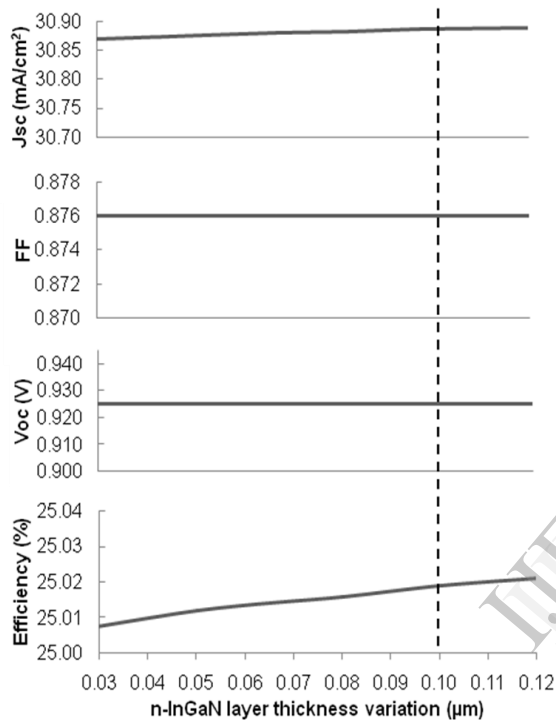


Figure 6. The n-InGaN layer thickness variation of InGaN solar cell

To investigate the dependency of the cell performance on the doping concentration of InGaN, a numerical simulation was conducted from $1 \times 10^{14} \text{ cm}^{-3}$ to $5 \times 10^{17} \text{ cm}^{-3}$. The simulation results are shown in Fig. 7. It is clear from Fig. 7 that the cell efficiency is highest in the doping concentration of $1 \times 10^{16} \text{ cm}^{-3}$ which is more effective and today's practically achievable.

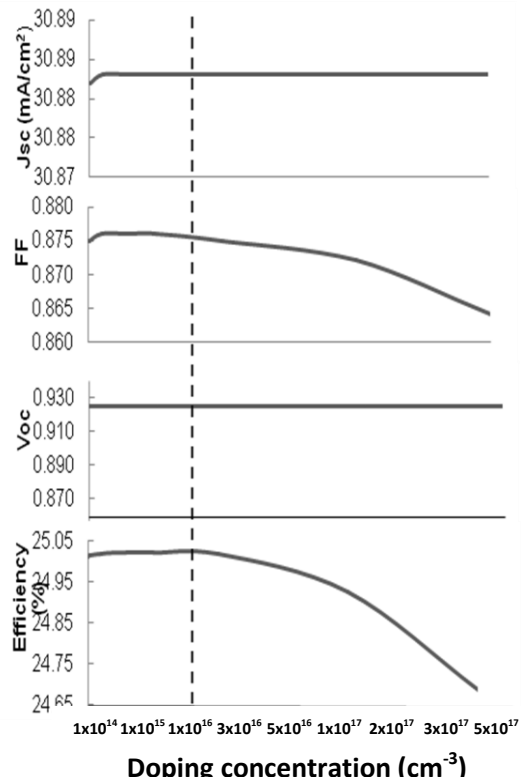


Figure 7. Doping concentration (cm^{-3}) of InGaN solar cell

The formation of a stable, low resistance, non-rectifying back contact to InGaN is one of the major and critical challenges of efficient and stable solar cells. Metals with a high work function ($\phi_m \geq 6.8 \text{ eV}$) are required to make an ohmic backcontact but most of the metals do not have such high work functions to make good ohmic contacts to InGaN, instead tend to form Schottky, or blocking barriers. Due to the high electron affinity of InGaN, the non ohmic contacts usually show high resistance and thus make a significant contribution to the high series resistance (R_s) of the solar cells which in turn badly affect the fill factor (FF) of the cell. A numerical simulation was conducted to find the effect of back contact on the InGaN single junction solar cell and the results are shown in Fig. 8.

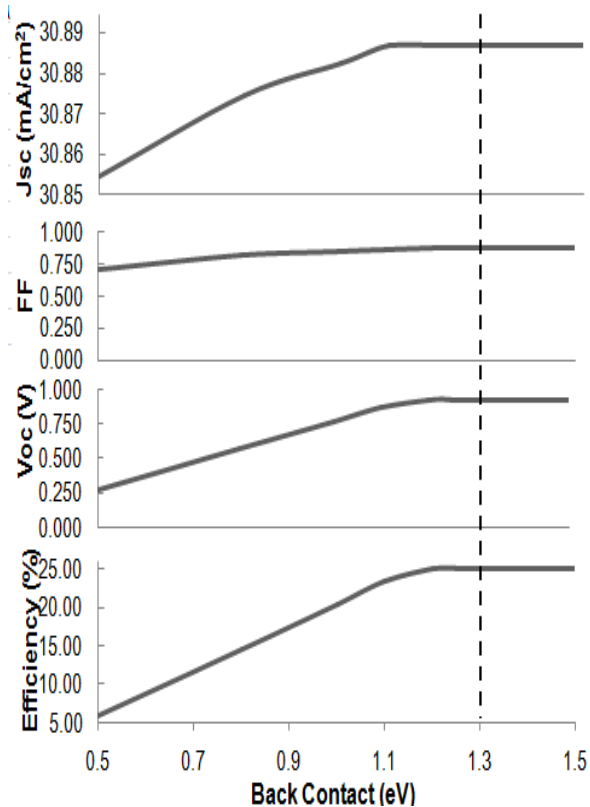


Figure 8. Effect of back contact on InGaN single junction solar cell

In this numerical analysis, simulation was started with Al ($\Phi_{bL}=0.5$ eV) as a good metal contact and then it was modified to Ti, Mo, Cu, Ni, Pt as the final back contact. It has observed from the Fig. 9 that the cell conversion efficiency is higher with Ni ($\Phi_{bL}=1.3$ eV) as the back contact.

The J-V curve of the proposed cell has shown in Fig. 9. This simulation has shown higher efficiency over 25.02% ($V_{oc}=0.925$ V, $J_{sc}=30.883$ mA/cm², FF=0.876) which is higher than any other reported InGaN based cells. The reputed results are 20.284% [5], 24.95% [6] and 24.88% [7]. The 0.5 μ m p-InGaN with 0.1 μ m n-InGaN and doping concentration of 1×10^{16} cm⁻³ with Ni as the back contact shows the highest conversion efficiency of 25.02% ($V_{oc}=0.925$ V, $J_{sc}=30.883$ mA/cm², FF=0.876).

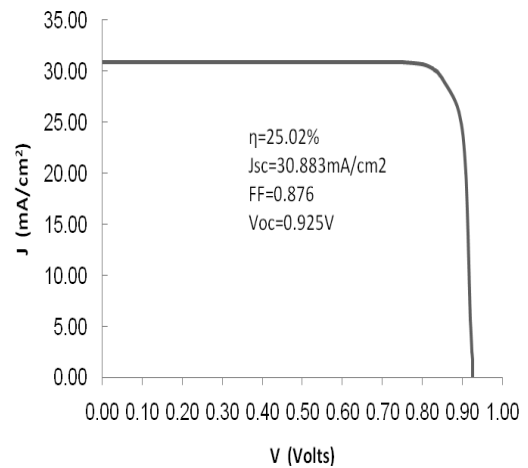


Figure 9. J-V curve of the proposed InGaN single junction solar cell

The improvement in efficiency came from the improved J_{sc} with the reduction of doping concentration, which eliminated the phase separation among InGaN layer and from the optimization of layer thickness with back contact.

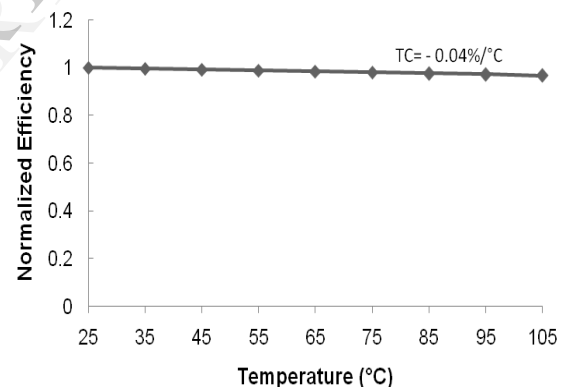


Figure 10. Effect of operating temperature on InGaN solar cell

In practical cases the operating temperature plays a very important role that affects the performance of the solar cells especially in space application. At higher operating temperature, parameters such as the effective density of states, absorption coefficients, electron and hole mobility, carrier concentrations and band gaps of the materials are affected significantly. An investigation has been done on normalized efficiency of the final cell to understand the effect of temperature on InGaN single junction solar cell with operating temperature ranged from 25°C to 105°C as shown in Fig. 10. It is evident from the Fig. 10 that the conversion efficiency of the cell linearly decreases at the temperature gradient of -

0.04%/°C, with increase of operating temperature, which also indicates the higher degree of stability of the final proposed cell at higher operating temperature or in stressed conditions [10, 12].

4. Conclusion

In this work, bangaps of single junction $\text{In}_x\text{Ga}_{1-x}\text{N}$ solar cell was optimized at 1.34 eV, in order to achive the higher conversion efficiency. Layer thickness of the cell were simulated regorously and optimized at 0.5 μm for p-InGaN and 0.1 μm for n-InGaN layer. Doping concentration of the designed cell was optimized at $1 \times 10^{16} \text{ cm}^{-3}$ which is practically achievable value to improve the cell performance. Back contact barrier of the designed cell was optimized and found that Ni with $\Phi_{\text{BL}}=1.3$ eV can be used as the final back contact for higher performance. The optimized InGaN single junction solar cell has shown the cell conversion efficiency of 25.02% ($J_{\text{sc}}=30.883 \text{ mA/cm}^2$, $V_{\text{oc}}=0.925 \text{ V}$, $\text{FF}=0.876$) which is highest for any reported InGaN single junction solar cells. Finally, the degree of stability of the designed cell has been investigate and found that the temperature coefficient is - 0.04%/°C which indicates the higher stability of the proposed cell.

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6. References

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