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Theoretical simulations of InGaN/Si mechanically stacked two-junction solar cell

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ABSTRACT

In this study, potential efficiency of InGaN/Si mechanically stacked two-junction solar cell is theoretically investigated by optimizing the band gap and thickness of the top InGaN cell. Results show that the optimum conversion efficiency is 35.2% under AM 1.5 G spectral illuminations, with the bandgap and thickness of top InGaN solar cell are 2.0 eV and 600 nm, respectively. The results and discussion would be helpful in designing and fabricating high efficiency InGaN/Si mechanically stacked solar cell in experiment.

1. Introduction

InGaN alloys have been focused for their wide applications in optoelectronic devices such as light emitting diodes and solar cells [1–3]. These applications attribute to InGaN material has large absorption coefficient, super radiation resistance and variable band gap ranging from 0.7 to 3.4 eV, which matches well with the energy of solar spectra. Recently, InGaN alloys grown on silicon substrates for the applications of solar cells have drawn a lot of attentions [4,5], due to the advantages of Silicon substrates are cheap, plentiful and easy to be processed. Theoretical calculations indicate that Si is suited for the bottom junction of a high efficiency two-junction solar cell. InGaN can be a top–cell combined with the most used photovoltaic material Si to design InGaN/Si tandem solar cells, which would be able to absorb more photons to produce higher conversion efficiency. Theoretical simulations by L. Hsu showed that InGaN/Si double junction cell can produce an energy conversion efficiency around 30–33% under optimized conditions [6]. The conversion efficiencies of N-InGaN/P-Si single hetero-junction and InGaN/Si double-junction solar cell are estimated to be 29% and 34%, respectively [7]. These calculations indicate that InGaN/Si system has great potential in fabricating of two-junction tandem solar cell.

Although $In_{0.46}Ga_{0.54}N$/Si hetero-junction can form a low resistance Ohmic junction and high conversion efficiency solar cell, the growth of high-quality InGaN films is challenging because of 17% lattice mismatch and 55% difference of thermal expansion between InGaN ternary alloy and Si substrate. Therefore, AlN [8], Si_xN_y [9] and AlGaN/GaN super-lattice are usually used as intermediate layer between GaN and Si substrate to overcome the growth difficulty. However, it is well known that AlN, Si_xN_y and AlGaN/GaN super-lattice has large resistance which would prevent the photo-current between top-cell and bottom cell, so InGaN/Si solar cell is difficult to achieve in experiment.

In this study, we demonstrated and calculated the characteristics of InGaN/Si mechanically stacked multi-junction solar cell (MSMJ) [10] under a variety of conditions. Employ this structure, Gee and Virshup [11], reported a GaAs/Silicon MSMJ with an efficiency of 31%. The difficulties of lattice mismatch of InGaN grown on Si substrate and current mismatch are avoided, because photocurrent matching is no longer required when the two cells are independently operated. The detailed design and simulation are exhibited in this work.

2. Theoretical simulations

The structure of InGaN/Si mechanically stacked two-junction solar cell is shown in Fig. 1, including a top-cell, a bottom-cell and

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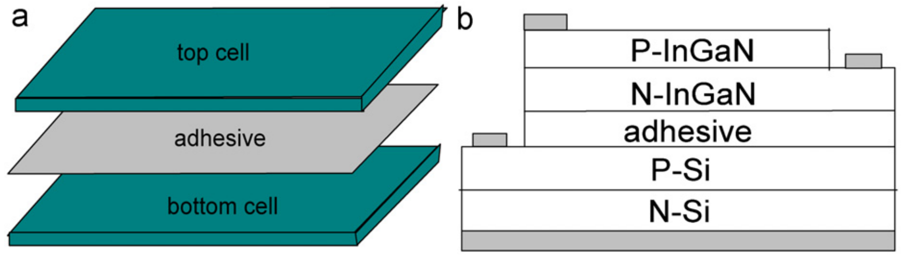

Fig. 1. Schematic of InGaN/Si mechanically stacked two-junction solar cell.

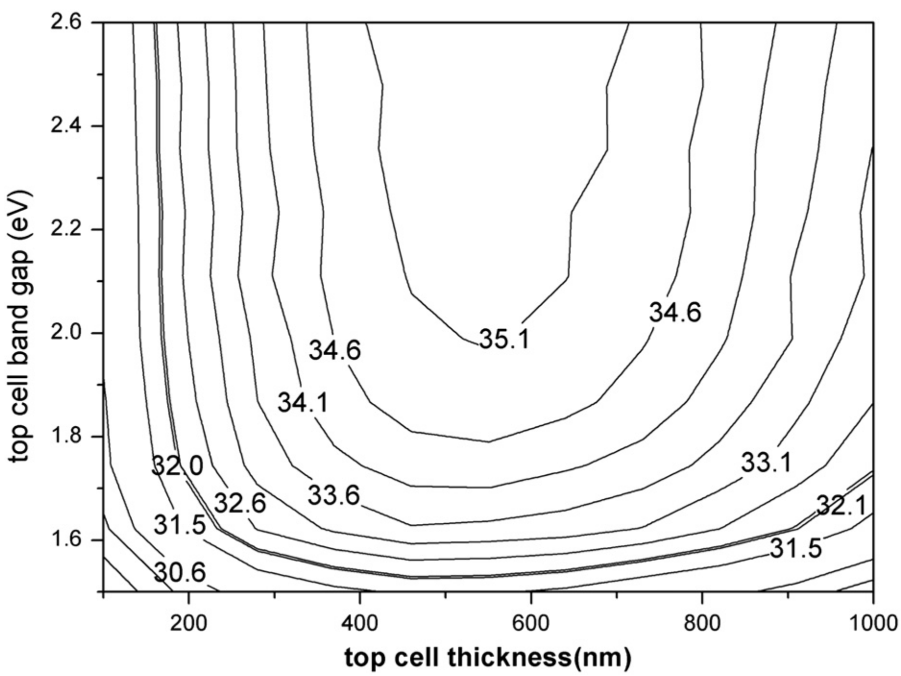

Fig. 2. Is efficiency curve of InGaN/Si mechanically stacked two junction solar cells as a function of the band gap and thickness of the to-cell (InGaN layer).

an adhesive layer. In this simulation, the thickness of Si junction is 500 μm, the calculation is based on five assumptions:

(1) The majority carrier concentration is taken equal to 10^{18} cm^{-3} in each sub-cell.
(2) The reflection loss of the solar cell is zero.
(3) The transparency of the adhesive layer is 100%.
(4) The effects of series resistance is ignored.
(5) Internal quantum efficiency (IQE) is consider as unit one.

The tunnel junction and current match can be ignored which are necessary in traditional tandem solar cell. The sub-cells are separated with each other and work individually. For terrestrial application, the efficiencies of InGaN/Si mechanically stacked solar cells were calculated at room temperature under AM 1.5 G spectra.

The band gap of $In_xGa_{1-x}N$ is expressed as [12]

$$E_g(In_xGa_{1-x}N) = 0.7x + 3.42(1-x) - 1.43x(1-x) \tag{1}$$

The bowing parameter is 1.43 eV. For simplicity, assume that each absorbed photon creates an electron and a hole, the photo-generated current density of the top-cell can be written as [6,13]

$$J_T = e\int_0^{\lambda_T} I(\lambda)\{1-\exp[-\alpha_{InGaN}(\lambda)t_T]\}d\lambda, \tag{2}$$

and bottom cell as

$$J_B = e\int_0^{\lambda_T} I(\lambda)\exp[-\alpha_{InGaN}(\lambda)t_T]\{1-\exp[-\alpha_{Si}(\lambda)t_B\}d\lambda + e\int_{\lambda_T}^{\lambda_B} I(\lambda)\{1-\exp[-\alpha_{Si}(\lambda)t_B\}d\lambda, \tag{3}$$

where $I(\lambda)$ is the incident flux density of AM 1.5 G solar spectra, t_T and t_B are the thicknesses of top-cell and bottom cell, respectively. Parameters λ_T and λ_B are expressed as $\lambda_T = hc/E_{gT}$ and $\lambda_B = hc/E_{gB}$, E_{gT} and E_{gB} are the band gaps of the top and bottom cells, respectively. For InGaN materials, the absorption coefficient is a function of energy and can be expressed as [12]

$$\alpha_{InGaN}(E) = \alpha_0\sqrt{\frac{E-E_g(x)}{E_g(x)}} \tag{4}$$

where $E_g(x)$ is the band gap of $In_xGa_{1-x}N$ and α_0 is about 2×10^5 cm^{-1} for InGaN. The absorption coefficient used for Si is given as [6]

$$\alpha(E) = -0.425(E-E_g)^3 + 0.757(E-E_g)^2 - 0.0224(E-E_g) + 10^{-4}(1.1eV < E < 1.5eV) = 0.0287\exp[2.72(E-E_g)](E > 1.5eV), \tag{5}$$

In this study, the reverse saturation current density for bottom cell is given by [14,15]

$$J_0 = en_i^2\left(\frac{D_P}{N_D L_P}\frac{S_P L_P/D_P \cosh x_n/L_P + \sinh x_n/L_P}{S_P L_P/D_P \sinh x_n/L_P + \cosh x_n/L_P} + \frac{D_n}{N_A L_n}\frac{S_n L_n/D_n \cosh x_p/L_n + \sinh x_P/L_n}{S_n L_n/D_n \sinh x_P/L_n + \cosh x_P/L_n}\right), \tag{6}$$

Where D_n and D_p are the diffusion coefficients of electrons and holes, L_n and L_p are the diffusion lengths for electrons and holes, S_n and S_p are the surface recombination velocities in the materials, N_A and N_D are the acceptor and donor concentrations, x_n and x_p are the thicknesses of the n and p type layers, respectively.

The reverse saturation current density of InGaN solar cell is expressed as [16]

$$J_0(In_xGa_{1-x}N) = 2.481\times10^{11}\exp\left[\frac{-E_g(x)}{kT}\right], \tag{7}$$

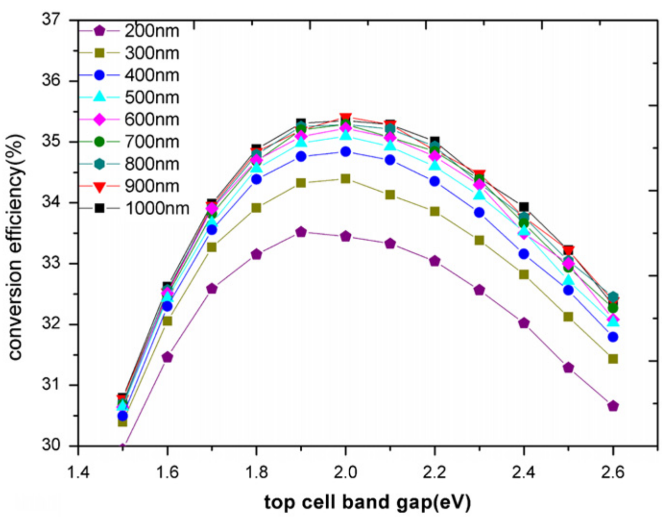

Fig. 3. Energy conversion efficiencies as a function of top-cell band gap with different thicknesses of top-cell layer (InGaN).

the intrinsic carrier concentration is calculated from

$$n_i^2 = N_C N_V \exp\left(-\frac{E_g}{kT}\right), \tag{8}$$

where N_C and N_V are the effective densities of states, k is Boltzmann constant and T is absolute temperature.

For each sub-cell, the open circuit voltage, V_{oc}, can be expressed as

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{J_{SC}}{J_o}+1\right) \tag{9}$$

The energy conversion efficiency is given by [17]

$$\eta = \frac{P_{max}}{P_{in}} = \frac{J_{max}V_{max}}{P_{in}} = \frac{FFJ_{SC}V_{OC}}{P_{in}} \tag{10}$$

Where P_{in} is the total input power under AM 1.5 G illumination, FF is fill factor of solar cell, which is expressed as an empirical equation [16]

$$FF = \frac{V_{OC} - kT/q\ln(qV_{OC}/kT + 0.72)}{V_{OC} + kT/q} \tag{11}$$

3. Results and discussion

As stated previously, the thickness of bottom Si cell is a constant in our calculation model. We just optimize the parameters of top InGaN sub-cell. Fig. 2 shows the isoefficiency curve of InGaN/Si mechanically stacked two junction solar cells as a function of the band gap (E_{gT}) and thickness (t_T) of the top-cell (InGaN layer). It is seen that: (a) the efficiency increases with InGaN layer thickness; (b) the efficiency increases from the periphery to the center along the horizontal axis. The simulated conversion efficiency of InGaN/Si (MSMJ) in our study is more than 35%, which is higher than 31% calculated by Hsu and Walukiewz [6], since their configuration is a serial tandem solar cell which is influenced by current mismatch.

For a deeper insight into Fig. 2, the energy conversion efficiencies as a function of E_{gT} with different thicknesses of InGaN layer are shown in Fig. 3. As can be seen that all curves have a similar trend, conversion efficiency increases at the beginning and

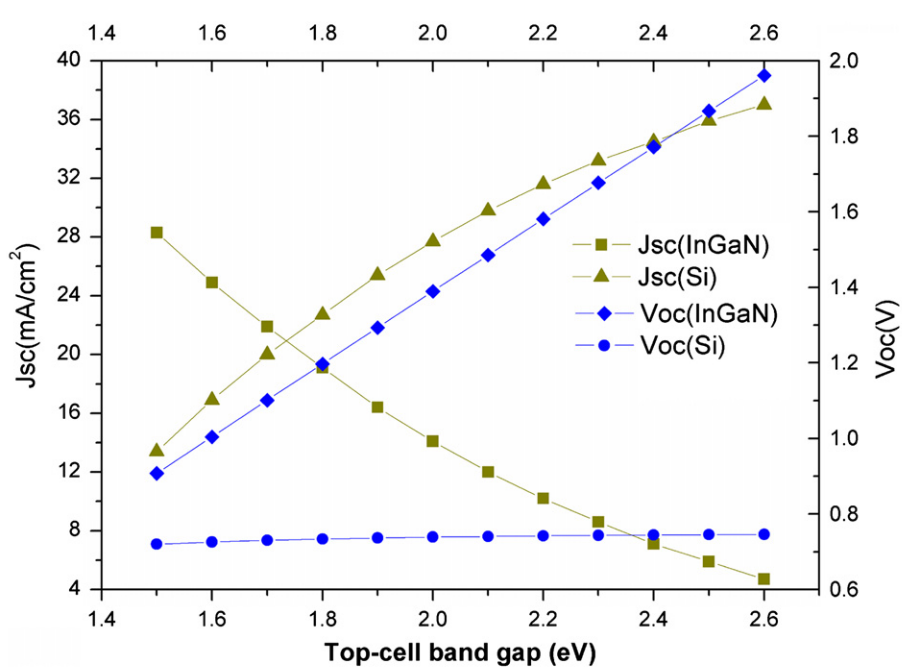

Fig. 4. The dependences of the short circuit current (J_{SC}) and open circuit voltage (V_{oc}) on top–cell band gap.

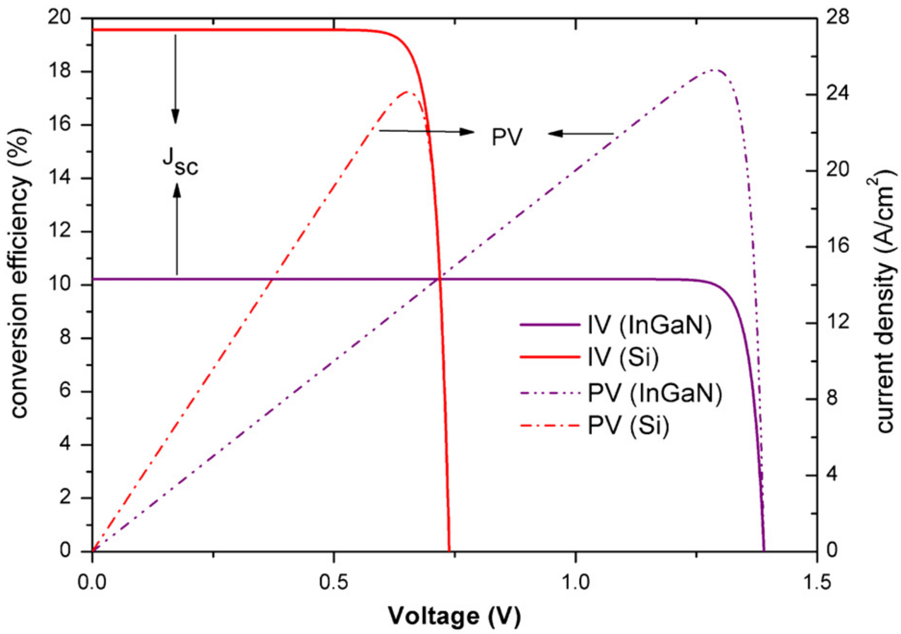

Fig. 5. Simulated IV and PV characteristics of InGaN/Si mechanically stacked two-junction solar cell. The band gap and thickness of top InGaN cell is 2.0 eV and 600 nm, respectively.

Table 1
Simulated *IV* performance of Incan/Si mechanically stacked solar cell(InGaN layer band gap is 2.0 eV and thickness is 600 nm).

Cell types	J_{sc} [mA/cm^2]	V_{oc} [V]	*FF* [%]	η [%]
InGaN top-cell	14.1	1.39	0.908	17.8
Si bottom cell	27.7	0.74	0.851	17.4

then decreases with the increase of E_{gT}, the conversion efficiency is maxium with the top-cell band gap of 2.0 eV, and enhances with the increase of the thickness of top-cell layer. However, if the t_T exceeds 600 nm, the enhancement of conversion efficiency is very small and can be ignored. For this reason, only the thickness from 100 nm to 1000 nm is calculated, the optimized thickness and band gap of top-cell are 600 nm and 2.0 eV, respectively.

Short circuit current density and open circuit voltage are very important factors in influencing the conversion efficiency. Fig. 4 shows the short circuit current density and open circuit voltage of the two junctions as a function of E_{gT}. The short current density (J_{sc}) of InGaN decreases with broadening of the E_{gT}, but J_{sc} of the silicon sub-cell presents an increase tendency. This results from the reasons that with the increase of top-cell band gap, the number of absorbed photons by InGaN layer becomes lesser, and short circuit current density decreases for the case of E_{gT} broadening. In this calculation, the reflection loss has been ignored, so the number of photon transmitting through the top-cell increase and are absorbed by the bottom Si cell, so J_{sc} of bottom cell becomes greater. The open circuit voltage (V_{oc}) of InGaN keeps increasing with the enhancement of E_{gT} because of the reduction of J_{0T}, which drops as an exponential relationship with band gap. Meanwhile, V_{oc} of bottom cell slightly increases along with the horizontal axis. This is contributed to the increment of J_{sc} of Si bottom cell.

Fig. 5 shows the simulated voltage–current (*IV*) and voltage–efficiency (*PV*) curves for InGaN top–cell and Si bottom cell, with the band gap and thickness of top–cell at 2.0 eV and 600 nm, respectively. It is seen that the short circuit current densities are 27.7 mA/cm^2 and 14.1 mA/cm^2 for Si bottom cell and InGaN top-cell, and the open circuit voltages are 0.74 V and 1.39 V, respectively. As it is shown in table 1, the energy conversion efficiency is 17.8% for InGaN top-cell and 17.4% for Si bottom cell. According to the optimized parameters of InGaN layer, the efficiency of InGaN/Si mechanically stacked solar cell is calculated to be 35.2%

4. Conclusion

In this study, we have investigated theoretically the energy conversion efficiency that might be achieved by InGaN/Si mechanically stacked two-junction solar cell. According to numerical simulations, we determined the optimized band gap and thickness of top InGaN layer to be around 2.0 eV and 600 nm, respectively. The optimal conversion efficiency was 35.2%, which is higher than that of single junction Si solar cell and conventional InGaN/Si tandem solar cell in theory. Furthermore, the structure utilized in this work not only has high potential energy conversion efficiency, but also avoids the difficulties encountered in the process of InGaN grown on Si substrate and the technical difficulties of fabricating the tunnel junction. The calculations would contribute to designing and fabricating high efficiency InGaN/Si mechanically stacked solar cell, and this structure can be a new research direction in InGaN/Si two-junction solar cells.

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