Modeling of InGaN/Si tandem solar cells

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We investigate theoretically the characteristics of monolithic InGaN/Si two-junction series-connected solar cells using the air mass 1.5 global irradiance spectrum. The addition of an InGaN junction is found to produce significant increases in the energy conversion efficiency of the solar cell over that of one-junction Si cells. Even when Si is not of high quality, such two-junction cells could achieve efficiencies high enough to be practically feasible. We also show that further, though smaller, improvements of the efficiency can be achieved by adding another junction to form an InGaN/InGaN/Si three-junction cell. © 2008 American Institute of Physics.

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I. INTRODUCTION

Because of the limitations in the ability of a one-junction solar cell to utilize efficiently the photons of the broad solar spectrum, multijunction solar cells have been the focus of much theoretical and experimental work in the past few decades.1 The most successful efforts to date have concentrated on using well-known semiconductors such as Ge, InP, GaAs, GaSb, and various III-V alloys to construct such cells, achieving energy conversion efficiencies of over 30% for two-junction cells2 and over 40% for three-junction cells combined with solar concentrators.3

Recent advances in the growth and doping of InGaN alloys may provide an alternative to traditional III-V materials. The bandgap of InGaN can be varied from 0.7 to 3.4 eV, making it suitable for a wide range of multijunction solar cell designs. These cells would be able to utilize high energy photons with more efficiency than those made from traditional III-V alloys, which are limited to bandgaps of less than 2.2 eV. Such cells would also have the advantage that Si is relatively cheap and plentiful and its processing techniques are well established, in addition to the fact that the Si bandgap of 1.1 eV is ideally suited for the bottom junction of a high efficiency two-junction solar cell.

InGaN/Si solar cells also have one additional benefit over those constructed from traditional III-V materials. As one can see from Fig. 1, at an alloy composition of In0.46Ga0.54N, the conduction band of InGaN has the same energy (relative to the vacuum) as the valence band of Si, and so a n-In0.46Ga0.54N/p-Si interface should form a low resistance Ohmic junction. In fact, this behavior has been observed for an n-In0.46Ga0.54N/p-Si junction.4 Thus, a two-junction InGaN/Si tandem solar cell where the InGaN has an alloy fraction close to In0.46Ga0.54N can be grown without heavy doping of the interface between the two materials, as is required in multijunction cells constructed from traditional III-V materials. As a bonus, the bandgaps of such a cell would be 1.1 eV (Si) and 1.8 eV (In0.46Ga0.54N), close to the bandgap combination predicted to give the maximum energy conversion efficiency for two-junction solar cells.5,6

In this paper, we calculate the characteristics of series-connected, monolithic, two-junction, two-terminal InGaN/Si solar cells under a variety of conditions, including those in which the semiconductor materials are of less than optimal quality. We also briefly discuss results regarding a three-junction cell, consisting of two InGaN junctions grown on Si. The fact that present cells made from conventional semiconductors have efficiencies not far from their theoretically calculated values is an encouraging sign that our results may be experimentally relevant. Significant challenges such as the poor structural quality of nitride materials remain potential obstacles to the practical development of InGaN/Si solar cells. However, because the relatively large density of structural defects has not precluded the commercial use of the nitrides in certain device applications, it remains to be seen whether the issue of good quality growth will pose an insurmountable problem in the creation and development of ni-

![FIG. 1. Energy diagram showing the conduction and valence bands of InGaN as a function of alloy composition. The conduction and valence bands of Si are shown for comparison. At an alloy composition of In0.46Ga0.54N, the bottom of the InGaN conduction band and the top of the Si valence band have the same energy, relative to the vacuum. Thus, an n-In0.46Ga0.54N/p-Si interface forms a low resistance Ohmic junction.](image-url)
tride solar cells. For the time being, we ignore such considerations, as our goal is to investigate whether the theoretically achievable efficiencies warrant further development work on InGaN/Si solar cells.

II. METHOD

The solar cell structure we use to model the performance of an InGaN/Si solar cell is shown in Fig. 2. The tandem cell consists of an InGaN $p/n$ junction grown on top of a Si $p/n$ junction. Each junction is composed of a $p$-type layer grown on top of an $n$-type layer. Within these layers, holes travel upward (toward the surface of the cell) and electrons travel downward (toward the back contact of the cell).

The calculations were performed using a modified version of the standard equations for calculating the electrical characteristics of a tandem solar cell. Previous studies have usually assumed that all photons with energies larger than the bandgap of the cell are absorbed and converted into an electron-hole pair, and that every electron-hole pair created reaches the cell terminals. However, because Si is an indirect gap semiconductor and the Si junction thickness needed to achieve maximum efficiency may be several times larger than the minority carrier diffusion lengths, we do not make such assumptions. Instead, our calculations of the short circuit current density explicitly include the absorption coefficients of InGaN and Si, the junction thicknesses, and the diffusion lengths. As in previous studies, we omit explicit consideration of any reflective and resistive losses in the system and assume that every photon absorbed creates one electron-hole pair.

To find the short circuit current density, we first calculate the short circuit current densities in each layer ($p$ or $n$) of each junction separately. For example, to find the current density generated by the $p$-InGaN layer, we first find the number density of photons of a particular wavelength absorbed by a thickness $dx$ of the $p$-InGaN at a depth $x$ beneath the surface. That quantity is given by the expression

$$\int_0^{x_p} \left( \frac{\text{# incident photons}}{\text{per unit area}} \right) \left( \frac{\text{fraction of photons}}{\text{penetrating to depth } x} \right) \times \left( \frac{\text{fraction of photons}}{\text{absorbed by thickness } dx} \right) \, dx$$

$$= I_0(\lambda) \exp(- \alpha_\lambda(x))(1 - \exp(- \alpha_\lambda(x)dx))$$

$$= I_0(\lambda) \exp(- \alpha_\lambda(x)\alpha_\lambda dx).$$

(1)

All symbols are defined in the nomenclature. Since we assume that each absorbed photon creates one electron-hole pair, this expression also gives the number density of electrons and the number density of holes generated by a thickness $dx$ of $p$-InGaN at a depth $x$ below the surface. The incident photon flux $I_0(\lambda)$ is taken from the air mass (AM) 1.5 global spectrum from the ASTM G-173–03 standard.

Because the layer under consideration is $p$-type, we assume that all holes generated reach the surface. On the other hand, recombination processes might significantly reduce the number of electrons that reach the InGaN $p/n$-junction and so expression (1) must be reduced by the factor $\exp[-(x_p - x)/L_h]$ in that case (the determination of the diffusion length $L_h$ will be discussed later). Thus, the hole current density generated by the $p$-InGaN layer that reaches the surface is

$$e \int_0^{x_p} I_0(\lambda) \exp(- \alpha_\lambda(x)\alpha_\lambda dx)$$

$$= eI_0(\lambda)(1 - \exp(- \alpha_\lambda(x_p))),$$

(2)

and the electron current density generated by the $p$-InGaN layer that reaches the $n$-InGaN layer is

$$e \int_0^{x_p} I_0(\lambda) \exp(- \alpha_\lambda(x)\alpha_\lambda \exp(- \frac{x_p - x}{L_e}) dx$$

$$= eI_0(\lambda) \frac{\alpha_\lambda L_e}{1 - \alpha_\lambda(x_p)\frac{\alpha_\lambda L_e}{\alpha_\lambda(x_p)}} \left( \exp(- \alpha_\lambda(x_p)\frac{\alpha_\lambda L_e}{\alpha_\lambda(x_p)}) - \exp(- \frac{x_p}{L_e}) \right).$$

(3)

A similar calculation for the $n$-InGaN layer, under the assumption that recombination processes do not significantly reduce the number of electrons traversing the layer but do reduce the number of holes, gives

$$e \int_0^{x_n} \left( I_0(\lambda) \exp(- \alpha_\lambda(x_p)) \exp(- \alpha_\lambda(x)\alpha_\lambda dx$$

$$\times \exp\left(- \frac{x}{L_h}\right) dx$$

$$= eI_0(\lambda) \exp(- \alpha_\lambda(x_p)\alpha_\lambda \exp\left[- \frac{x}{L_h} \left( \alpha_\lambda(x) + \frac{1}{L_h} \right) \right].$$

(4)

for the hole current density generated by the $n$-InGaN layer that reaches the $p$-InGaN layer (and consequently the surface of the cell) and

$$e \int_0^{x_n} \left( I_0(\lambda) \exp(- \alpha_\lambda(x_p)) \exp(- \alpha_\lambda(x)\alpha_\lambda dx$$

$$= eI_0(\lambda) \exp(- \alpha_\lambda(x_p))(1 - \exp(- \alpha_\lambda(x_p)))$$

(5)

for the electron current density generated by the $n$-InGaN layer that reaches the InGaN/Si interface.
Finally, the total hole current density generated by the InGaN junction that reaches the top contact can be found by adding expressions (2) and (4) and integrating over all incident photon wavelengths,

\[ e \int_0^\infty I_0(\lambda) \left[ (1 - \exp(-\alpha_\lambda x_p)) \right. \]
\[ + \frac{\exp(-\alpha_\lambda x_p) \alpha_\lambda L_h}{1 + \alpha_\lambda L_h} \exp(-x_n \left( \alpha_\lambda + \frac{1}{L_h} \right)) \left. \right] d\lambda. \tag{6} \]

Similarly, the total electron current density generated by the InGaN junction is obtained by adding expressions (3) and (5) and integrating over all incident photon wavelengths,

\[ e \int_0^\infty I_0(\lambda) \left[ \exp(-\alpha_\lambda x_p) (1 - \exp(-\alpha_\lambda x_p)) \right. \]
\[ + \frac{\alpha_\lambda L_e}{1 - \alpha_\lambda L_e} \exp(-\alpha_\lambda x_p - \exp(-x_n \left( \alpha_\lambda - \frac{x_p}{L_e} \right)) \left. \right] d\lambda. \tag{7} \]

Maximum efficiency is achieved when the thicknesses of the n-InGaN and p-InGaN layers are adjusted so that the electron and hole currents are equal. However, because the effect of changing the thickness of a layer is not straightforward (increasing the thickness increases the number of photons absorbed and therefore the number of carriers generated, but a larger fraction of the carriers are lost to recombination processes), the optimization process is nontrivial. As a simplification, we take the thicknesses of the p-InGaN and n-InGaN layers to be

\[ x_p = t_p L_e / (L_e + L_p), \quad x_n = t_n L_h / (L_h + L_e), \tag{8} \]

so that the thicker layer is the one in which the minority carrier diffusion length is longer. The short circuit current density for the top (InGaN) junction \( J_{\text{SC}T} \) is then the smaller of the resulting electron and hole current densities [expressions (6) and (7)]. An analogous calculation gives the short circuit current density for the bottom (Si) junction \( J_{\text{SC}B} \).

Following the work in Ref. 5, we maximized the cell efficiency by adjusting the thickness of the InGaN junction \( t_p \), whenever possible, so that \( J_{\text{SC}T} \) and \( J_{\text{SC}B} \) differed by less than 1 \( \mu \text{A/cm}^2 \). When such an adjustment was not possible (for instance, if \( J_{\text{SC}B} \) was larger than \( J_{\text{SC}T} \) for any top junction thickness), the short circuit current of the two-junction cell was taken to be the smaller of \( J_{\text{SC}T} \) and \( J_{\text{SC}B} \), and \( t_p \) was set to the value that maximized \( J_{\text{SC}T} \). Strictly speaking, one should match the operating currents of the two junctions rather than the short circuit currents. However, this would have complicated the calculations without a significant increase in accuracy since the operating current is usually within a few percent of the short circuit current.

We note that the optical thicknesses \( t_p \) and \( t_n \) of the InGaN and Si junctions are not necessarily the same as the physical thicknesses. The most efficient solar cells are designed such that internal reflections can increase the cell’s effective thickness by as much as a factor of 40. In our calculations, we assume a much more modest enhancement of the effective thickness, using a factor of 4 for the Si junction (since its surface cannot be textured in the “inverted pyramids” used in very high efficiency one-junction Si solar cells) and a factor of only 1 for the InGaN junction since the structural quality of this material is expected to be poor.

The reverse saturation current density for each junction was calculated assuming uniform doping of the layers. Because we aim to estimate maximum efficiencies of a tandem cell, the contributions of the space charge layer recombination current and the tunneling current were ignored, as it is in most other calculations. The magnitude of this reverse saturation (or injected) current density is

\[ J_0 = \frac{e D_e n_i^2}{L_e N_A} \left( \frac{S J e L_e \sinh \left( \frac{x_e}{L_e} \right)}{D_e} + \frac{S J e L_e \cosh \left( \frac{x_e}{L_e} \right)}{D_e} \right) \]
\[ + \frac{e D_h n_i^2}{L_h N_D} \left( \frac{S J h L_h \sin \left( \frac{x_h}{L_h} \right)}{D_h} + \frac{S J h L_h \cos \left( \frac{x_h}{L_h} \right)}{D_h} \right). \tag{9} \]

The intrinsic carrier concentration \( n_i \) can be calculated in the usual way using

\[ n_i^2 = N_c N_V \exp \left( \frac{-E_a}{k_BT} \right), \tag{10} \]

where \( N_c \) and \( N_V \) are given by \( 2M_{\text{C}}(2\pi k_B T m_e^*/h^2)^{3/2} \) and \( 2M_{\text{V}}(2\pi k_B T m_e^*/h^2)^{3/2} \), respectively.

The diffusion constants \( D_e \) and \( D_h \) can be calculated from the Einstein relationships

\[ D_e = \frac{k_B T}{e} \mu_e \quad \text{and} \quad D_h = \frac{k_B T}{e} \mu_h. \tag{11} \]

The diffusion constants and the diffusion lengths \( L_e \) and \( L_h \) are related by \( L_e = \sqrt{\tau_e D_e} \) and \( L_h = \sqrt{\tau_h D_h} \), where the minority carrier lifetimes \( \tau_e \) and \( \tau_h \) are given by

\[ \frac{1}{\tau_e} = \frac{1}{\tau_{\text{SRH}}} + B N_A \quad \text{and} \quad \frac{1}{\tau_h} = \frac{1}{\tau_{\text{SRH}}} + B N_D. \tag{12} \]

The voltage of a two-junction cell under normal operating conditions is simply the sum of the voltages of the individual junctions,

\[ V = \frac{k_B T}{e} \ln \left( \frac{J + J_{\text{SC}T}}{J_{0T}} + 1 \right) + \ln \left( \frac{J + J_{\text{SC}B}}{J_{0B}} + 1 \right). \tag{13} \]

The maximum power per unit area that the cell can produce is calculated by finding the voltage and current density that maximize the product \( JV \), found by setting its derivative equal to zero,

\[ \left. \frac{d(JV)}{dJ} \right|_{J=J_{\text{max}}} = 0. \tag{14} \]

The efficiency of the cell is equal to the ratio of this maximum power to the power incident on the cell calculated directly from the solar spectrum (1000 W/m² for the AM 1.5 global spectrum).
Table I shows the values of the material parameters used in our calculations. A few of the parameters, such as the band-to-band recombination coefficient and the Shockley–Read–Hall scattering time, are poorly known. In those cases, we have used the generic values found in Ref. 5. In the Si case, the “high quality” parameters along with an optical enhancement factor of 12 predict an energy conversion efficiency of 25.8% for a 10 μm thick one-junction Si cell, close to the record observed efficiency of 24.7%. For InGaN, the high quality parameters give a short circuit current and open circuit voltage close to the ones reported for an InGaN/GaN solar cell as described in Ref. 11. Because of the uncertainties in the parameters and the factors ignored in the assumptions, we do not attempt to match the real-world operating characteristics closely, instead aiming only for reasonable agreement. For those same reasons and because of the difficulty in making it quantitative, we also have not attempted to account for the effect that passivation of the Si interfaces would have on the open circuit voltage of the cell.

To obtain the parameters for “low quality” Si, such as that used in commercial Si solar cells that are not single crystals, we arbitrarily reduced the electron and hole mobilities and the Shockley–Read–Hall recombination time by a factor of 2. Surface recombination velocities of reasonable magnitudes (Ref. 7, p. 15) were then chosen so that our calculations, using an optical enhancement factor of 2, predict an efficiency of 17.0% for a 20 μm thick Si cell, similar to the efficiency of commercially available one-junction multicrystalline Si solar cells. Because the structural quality of currently grown InGaN is invariably quite poor, the only difference between high quality and low quality InGaN is the surface recombination velocities, which again were chosen to have a reasonable order of magnitude (Ref. 7, p. 15).

The absorption coefficients for InGaN and Si were obtained by fitting a function to published absorption curves for each material. The absorption coefficient used for Si was

\[
a(\mu m^{-1}) = -0.425(E-E_g)^3 + 0.757(E-E_g)^2 - 0.0224(E-E_g) + 10^{-4} (1.1 \text{ eV} < E < 1.5 \text{ eV})
\]

\[
= 0.0287 \exp[2.72(E-E_g)] \quad (E > 1.5 \text{ eV}),
\]

using the absorption curve in Ref. 12. The absorption coefficient used for InGaN was

\[
a(\mu m^{-1}) = 7.91(E-E_g)^4 - 14.9(E-E_g)^3 + 5.32(E-E_g)^2 + 9.61(E-E_g) + 1.98 \quad (E > E_g),
\]

using the absorption curve in Ref. 13. For simplicity, we ignored any effects of the InGaN alloy composition on the shape of the absorption curve (changing only the value of the bandgap \(E_g\)). Although this is not strictly correct, the error introduced by this simplification is likely to be smaller than the errors from the uncertainty in the other InGaN material parameters.

### III. RESULTS

Figure 3 shows the efficiency of a tandem InGaN/Si solar cell as a function of InGaN bandgap for different Si junction thicknesses. As stated previously, the thickness of the InGaN junction was chosen to match the short circuit currents of both cells, thereby maximizing the efficiency. The material parameters used for Si and InGaN in this calculation are those from the high quality columns in Table I. The slight bumpiness in the curves shown in Fig. 3 is due to the irregularity of the AM 1.5 spectrum, which includes dips in intensity due to atmospheric absorption lines. As the bandgap of the InGaN junction is changed, the rate at which additional photons become available or unavailable for absorption changes in an irregular fashion, leading to a waviness in the curves.

As might be expected, the optimal InGaN bandgap, and consequently the InGaN alloy fraction, depends on the thickness of the Si junction. Recall that maximum efficiency is achieved when the operating currents of the InGaN and Si junctions are matched. As the Si thickness increases up to 20 μm, its short circuit current density increases because it absorbs a larger fraction of the photons with energies larger than the bandgap of the InGaN layer.
than 1.1 eV. Therefore, one must decrease the bandgap of the InGaN junction so that it also absorbs more photons. As the Si thickness becomes larger than 20 μm, however, the short circuit current density of the Si junction decreases due to the loss of carriers through recombination and thermalization and the optimal InGaN bandgap increases in order to let more photons through the InGaN junction to be absorbed by Si to compensate.

Figure 4 shows the optimal InGaN bandgap as a function of the physical thickness of the Si junction. Results where both the Si and InGaN are of high quality and low quality are shown. Figure 5 shows the energy conversion efficiencies corresponding to the InGaN bandgap/Si-thickness combinations plotted in Fig. 4. The predicted efficiencies using high quality material are comparable to those of two-junction solar cells made from high quality traditional III-V semiconductors such as GaInP and GaAs. Because the material parameters corresponding to high quality InGaN reflect that of currently grown InGaN, there is a reason to believe that the expected efficiencies might climb even higher as growth techniques for III-nitride alloys improve.

While the calculated energy conversion efficiencies for low quality InGaN/Si two-junction cells are several percentage points lower than those for high quality cells, the maximum efficiencies are still nearly 10 percentage points higher than the efficiencies of commercial one-junction Si solar cells (the maximum efficiency of a low quality one-junction Si solar cell is 17.0% using our calculations). The simple addition of a thin layer of InGaN increases the energy conversion efficiency of the cell by more than 50%. Although the InGaN/Si tandem cell has a short circuit current much smaller than that of the bare one-junction Si cell (16 mA/cm² vs 40 mA/cm²), the much larger bandgap of InGaN gives this cell an open circuit voltage almost four times larger than that of the simple Si cell (1.9 V vs 0.53 V). In addition, the fill factor of the tandem cell is roughly 10% better than that of the single junction Si cell (88% vs 81%). Although series resistances and reflective losses have not been explicitly incorporated into this calculation, such losses are partially accounted for implicitly since the values used in our calculations give results that are close to those measured for real-world devices. Our results suggest that even in non-ideal situations, significant gains could be achieved by the addition of an InGaN junction to one-junction Si solar cells.

As mentioned previously, one of the advantages of the InGaN/Si combination is that for a certain InGaN alloy fraction ($In_{0.46}Ga_{0.54}N$, $E_g = 1.8$ eV), the InGaN conduction band and Si valence band line up, eliminating the need for a heavily doped interface in order to produce a low resistance Ohmic junction between the two materials. However, moving away from this particular InGaN alloy composition increases the resistance and a different solution is necessary to produce a heterojunction with an acceptably low resistance. Furthermore, it is evident from Fig. 4 that the InGaN alloy fraction that produces a low resistance junction is significantly different from the InGaN alloy fraction that is predicted to maximize the energy conversion efficiency of the cell. Figure 6 shows the efficiencies that could be expected from an $In_{0.46}Ga_{0.54}N$/Si tandem cell. The maximum predicted efficiencies in this case are only a few percentage points lower than those obtained by choosing InGaN alloys to optimize the energy conversion efficiency, 29.4% vs 31% for high quality material and 26.4% vs 27% for low quality material.

Figure 7 shows the calculated voltage-current and voltage-efficiency curves for an $In_{0.46}Ga_{0.54}N$/Si tandem cell made from low quality material. The IV curve looks reasonably good even given the low quality of the materials used. Because the conversion efficiency of the cell is a sharp func-
tion of the voltage, care must be taken to keep the operating voltage close to its optimum value for peak performance. The optimum value of the operating voltage corresponds to a current that is about 99% of the short circuit current.

As with other multijunction solar cells such as the InGaP/GaAs or InGaP/GaAs/Ge, the increased costs of fabrication make InGaN/Si cells most practical when used in conjunction with light concentrating systems. Figure 8 shows calculated efficiencies of some tandem InGaN/Si cells under a 500 times concentration of the AM 1.5 global spectrum. At room temperature, a 500 times concentration of the incident radiation increases the efficiency of such cells by 5%–6%. However, because such concentrations of sunlight are also likely to raise the cell’s operating temperature, we have also calculated efficiencies at temperatures up to 200 °C, taking into account only the increase in the reverse saturation current and ignoring the temperature dependence of the material parameters. The loss in efficiency shown occurs primarily through a reduction of the cell’s operating voltage due to an increase in $J_0$ of nearly eight orders of magnitude over the temperature range shown. In fact, Fig. 8 likely underestimates the reduction in efficiency because the InGaN and Si bandgaps decrease with temperature, increasing the intrinsic carrier concentration (causing $J_0$ to increase further) and decreasing the cell voltage. These results indicate that even a modest increase in the cell temperature has a considerable detrimental effect on the cell performance. Therefore good heat sinking of such cells is necessary for maintaining a high energy conversion efficiency when using concentrating optics.

Finally, we consider the efficiencies achievable by three-junction InGaN/InGaN/Si solar cells where the two InGaN junctions have different alloy compositions and bandgaps. Figure 9 shows the efficiency of such a solar cell, where the Si layer is 20 μm thick and the two InGaN junctions have thicknesses that produce the maximum short circuit current density for the corresponding one-junction InGaN cells. The use of high quality Si and InGaN was assumed. Because of the nonmonotonic relationship between the thickness of the junctions and their short circuit currents, the three-junction cells represented in the figure are not optimized for maximum energy conversion efficiency. However, the calculated maximum efficiency of 35% puts a lower bound on the true maximum value. The improvement in efficiency achieved by adding two InGaN junctions to Si as opposed to one (31%–35%) is smaller than the improvement from adding a single InGaN junction to a bare Si solar cell (25%–31%). However, for a three-junction cell, 1.1 eV is no longer the optimal bandgap for the bottom junction.

**IV. CONCLUSION**

We have investigated theoretically the possible energy conversion efficiencies that might be achieved by growing an InGaN junction on top of a conventional one-junction Si solar cell. InGaN is an appealing candidate to be paired with Si in a tandem solar cell not only because the bandgaps of the upper and lower cells can then be set to the values for which the theoretical maximum energy conversion efficiency would be achieved for a two-junction solar cell, but also because the alignment of the Si valence band with the In$_{0.46}$Ga$_{0.54}$N conduction band eliminates the need for heavy doping at the InGaN/Si heterointerface for cells using InGaN.
near that alloy composition. However, the generally poor structural quality of epitaxial layers of InGaN and of nitride materials in general poses a potential problem to the practical construction of such devices.

We have found that two-junction InGaN/Si solar cells can have significantly higher efficiencies than one-junction Si solar cells, with energy conversion efficiencies of slightly more than 31%. Even more impressive and perhaps surprising is the gain achievable with multicrystalline or otherwise low quality Si. In such cases, adding an InGaN junction on top of Si can result in increases in the energy conversion efficiencies of more than 50% compared to Si alone (27% vs 17%). Such an increase in the efficiency could justify the economic cost associated with the increased complexity of growing such cells.

The performance of InGaN/Si tandem cells under a 500 times concentrated AM 1.5 global solar spectrum is similarly impressive, with predicted efficiencies higher than 36% with times concentrated AM 1.5 global solar spectrum is similarly growing such cells. Finally, adding a second InGaN junction with idle declines with temperature, careful heat sinking of such high quality material. However, because the efficiency rapidly declines with temperature, careful heat sinking of such materials in general poses a potential problem to the practical construction of such devices.

List of Symbols

\[ M_c, M_v \] Number of equivalent minima in the conduction, valence band
\[ m_e^*, m_h^* \] Effective mass of electron, hole
\[ \mu_e, \mu_h \] Mobility of electrons, holes
\[ N_A, N_D \] Doping concentration of p-, n-type layer of junction
\[ N_c, N_v \] Density of states in the conduction, valence band
\[ n_i \] Intrinsic carrier concentration
\[ S_c, S_h \] Surface recombination velocity of minority electrons, holes
\[ T \] Temperature
\[ t_b, t_f \] Optical thickness of bottom, top junction
\[ \tau_e, \tau_h \] Lifetime of minority electrons, holes
\[ \tau_{SRH} \] Shockley-Read-Hall lifetime
\[ V \] Voltage
\[ V_{OC} \] Open circuit voltage
\[ x_n, x_p \] Thickness of n-, p-type layer of junction

8. NREL (http://feed.nrel.gov/solar/spectra/am1.5).