InGaN photovoltaics literature review / Part II


Others: InGaN solar cells| InGaN PV| InGaN materials| InGan LEDs| Nanocolumns and nanowires| Optical modeling of thin film microstructure| Misc.

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Simulation of In$_{0.65}$Ga$_{0.35}$N single-junction solar cell

Modeling of InGaN/Si tandem solar cells

Abstract: Author(s) 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. Author(s) 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.

- derived expression for achieving maximum efficiency by optimizing thickness for InGaN/Si tandem solar cells by using electron and hole current expression.
- matching operating current rather than short-circuit current in multi-junctions solar cell improves the efficiency and fill factor (but operating current is usually within a few percent of short circuit current).
- 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.
- the efficiency rapidly declines with temperature, careful heat sinking of such cells is critical.
- gain achievable with multicrystalline or otherwise low quality Si by adding an InGaN junction on top of Si can result in increases in energy conversion efficiencies of more than 50% compared to Si alone (27% vs. 17%). Such an increase in efficiency could justify the economic cost associated with increased complexity of growing such cells.
- At an alloy composition of In$_{0.46}$Ga$_{0.54}$N, the conduction band of InGaN has the same energy (relative to the vacuum) as the valence band of Si, and so a n-In$_{0.46}$Ga$_{0.54}$N/ p-Si interface should form a low resistance Ohmic junction.
- A two junction InGaN/Si tandem solar cell where the InGaN has an alloy fraction close to In$_{0.46}$Ga$_{0.54}$N 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.
- Within the layers, holes travel toward the surface of the cell and electrons travel toward the back contact of the cell.
- Authors calculation of the short circuit current density explicitly include the absorption coefficients of InGaN and Si, the junction thicknesses, and the diffusion lengths.
- To find the short circuit current density, authors first calculated the short circuit current densities in each layer (p or n) of each junction separately. The mathematical expressions and calculation method of hole and electron current density (for each layer) are discussed thoroughly.
- 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.
- Increasing the thickness increases the number of photons absorbed and therefore the number of carriers generated, but a larger fraction of the carriers are then lost to recombination processes.
The thickness of the layers were determined mathematically so that the thicker layer is the one in which the minority carrier diffusion length is longer.

The reverse saturation current density for each junction was calculated assuming uniform doping of the layers.

Other than crystalline quality, the only difference between high quality and low quality InGaN is the surface recombination velocities.

The optimal InGaN bandgap, and consequently the InGaN alloy fraction, depends on the thickness of the Si junction. 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 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, 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.

The effective optical thickness of the Si junction was taken to be four times larger than the physical thickness.

The fill factor of the tandem cell is roughly 10% better than that of the single junction Si cell.

The InGaN and Si bandgaps decrease with temperature, increasing the intrinsic carrier concentration (causing $J_0$ to increase further) and decreasing the cell voltage.

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%)

Photovoltaic Effects of InGaN/GaN Double Heterojunctions With p-GaN Nanorod Arrays

Abstract: The p-GaN/In0.06Ga0.94N/n-GaN double heterojunctional solar cells with solely formed nanorod arrays of p-GaN have been fabricated on sapphire (0001). The p-GaN nanorod arrays are demonstrated to significantly reduce the reflectance loss of light incidence. A stress relief of the intrinsic InGaN region is observed from high-resolution X-ray diffraction analyses. The electroluminescence emission peak is blue shifted compared with the conventional solar cells. These results are reflected by the spectral dependences of the external quantum efficiency (EQE) that show a shorter cutoff wavelength response. The maximum EQE value is 55.5%, which is an enhancement of 10% as compared with the conventional devices.

Due to the p-type doping difficulty and crystal quality of In-rich InGaN alloys, most studies are being focused on p-i-n heterojunction solar cells using the Ga-rich intrinsic InGaN layer as the absorber.

Although InGaN materials have a high absorption coefficient of up to 105 cm$^{-1}$ at the band edge, due to the critical-thickness issue, there are still many
challenges for the device design

- The thin-film InGaN device showed an enhancement factor of 57.6% in the current density under a standard simulator with the one-sun air mass 1.5 (AM1.5) global light source
- By optimizing the p-contact grid spacing, the short-circuit current density for the devices with a 166-μm grid spacing was 20% higher than that of the 25-μm device under a concentrated AM0 illumination
- Group-III nitrides have a reasonably high refractive index (~2.5), which leads to a reflectance of 18% according to Fresnel's law from reference
- Till date, due to problems such as material selection and thermal expansion, the devices (InGaN) with antireflective coatings are not reported

To obtain a smooth n-GaN surface for the subsequent metal deposition as the n-type contact electrode, two-step etching sequences are used to form the mesa

- The group-III nitride epilayers were grown on c-plane sapphire by metal-organic chemical vapor deposition
- The material structure is composed of a 1.5-μm GaN buffer layer, a 2-μm Si-doped n-type GaN layer, a 150-nm undoped lower bandgap $\text{In}_{0.06}\text{Ga}_{0.94}\text{N}$, and a 150-nm p-type GaN layer
- Vertically oriented nanorod arrays were prepared by the inductively coupled plasma (ICP) etching of the p-GaN film with self-assembled Ni cluster as the etching mask. The depth of etching is about 150 nm, which is approximately equal to the thickness of the p-GaN layer
- The diameter and the density of the nanorods, which are controlled by the Ni annealing conditions, are 100-200 nm and $1 \times 10^9$ cm$^{-2}$, respectively
- A smoother mesa for an electrical contact with the n-GaN layer was formed by the improved two-step ICP processing of the n-GaN mesa
- After the formation of the p-GaN nanorod arrays, the indium tin oxide was directly deposited on the top and the sidewall of the nanorods. Finally, the p-type and n-type ohmic contact layers were formed by depositing 25-nm Ti/200-nm Al/25-nm Ti/300-nm Au to complete the nanostructure solar cells (SC-II) fabrication

- Solely formed p-GaN nanostructures are proposed and explored to reduce the reflectance loss.
- p-GaN nanorod solar cell exhibits a considerably small reflectance of up to less than 1% within the entire wavelength range
- Since no foreign material is involved, the p-GaN nanorod arrays are intrinsically more stable and durable than dielectric coatings. Furthermore, the nanorod arrays can maintain a low reflectance at a variety of incident angles
- The observed significant decrease in the optical reflectance of p-GaN nanorod solar cell is mainly due to the higher absorption in nanorod arrays
- A part of the light can transmit through the nanorods or reach the layer underneath via the space between the p-GaN nanorods, which may be another reason for the decrease in reflectance
The indium content is determined to be 6% from the distance between the InGaN and GaN peaks in the X-ray scanning curves.

The EL emission peaks of the InGaN layers were observed at 394 and 389 nm for p-GaN nanorod and p-GaN solar cells, respectively.

The emission of p-GaN nanorod solar cell shows a blue-shift phenomenon, which is caused by a partial reduction of the piezoelectric field.

The strain in the InGaN/GaN layer caused by the lattice mismatch between the GaN and InGaN layers is partially released because the nanorods can accommodate the misfit more effectively.

Vertically aligned p-GaN nanorod arrays may be useful in improving the conversion efficiency and reducing material consumption.

p-GaN nanorod arrays can effectively reduce optical loss in PV applications.

p-GaN nanorod arrays applied in InGaN/GaN heterojunctional solar cells (author(s) prototype) yielded up to 55.5% peak EQE.

Low reflectance of p-GaN nanorod arrays originated from high surface area and subwavelength scale of the nanorods, can be used effectively for their enhanced antireflection ability.

p-nanorod type solar cell exhibited considerably small reflectance of up to less than 1% within entire wavelength range whereas for p-GaN (planar type) showed reflectivity of 18% as determined by Fresnel's law for air/GaN interface.

Reduction in the piezoelectric field caused by partial strain release induces a blue-shift in p-nanorod solar cell.

This reduction in the piezoelectric field caused by the partial strain release then induces a blue-shift value of 5 nm.

The response of p-GaN nanorod solar cells in the shorter wavelength region (330-360 nm) is enhanced, the maximum EQE value at 380 nm is 55.5%.

The p-GaN nanorod solar cell has a substantial cost benefit if the nanorod arrays are grown by a bottom up process, such as vapor-liquid-solid growth.

**Improved Conversion Efficiency of GaN/InGaN Thin-Film Solar Cells**

**Abstract:** In this letter, Author(s) report on the fabrication and photovoltaic characteristics of p-i-n GaN/InGaN thin-film solar cells. The thin-film solar cells were fabricated by removing sapphire using a laser lift-off technique and, then, transferring the remaining p-i-n structure onto a Ti/Ag mirror-coated Si substrate via wafer bonding. The mirror structure is helpful to enhance light absorption for a solar cell with a thin absorption layer. After the thin-film process for a conventional sapphire-based p-i-n solar cell, the device exhibits an enhancement factor of 57.6% in current density and an increment in conversion efficiency from 0.55% to 0.80%. The physical origin for the photocurrent enhancement in the thin-film solar cell is related to multireflection of light by the mirror structure.

Crystalline defects commonly observed include v-shaped pits, phase separation, and dislocations, which have been shown to deteriorate device performance by increasing leakage current.

Conventional solar cell with a thin InGaN absorption layer exhibits smaller photocurrent than that with a thick InGaN layer does, the thin-InGaN solar cell shows better performance in open-circuit voltage, fill factor, and shunt resistance.
• Growth of high-In-content InGaN alloy on GaN typically results in the formation of an InGaN film with high defect density. The crystalline defects commonly observed include v-shaped pits, phase separation, and dislocations, which deteriorate device performance by increasing leakage current.
• The superlattice and MQWs schemes showed improved solar-cell performance, but both schemes still have the drawback that the optical absorption layer is too thin to sufficiently absorb the solar spectrum.
• GaN/InGaN p-i-n solar cells were grown on (0001) sapphire substrates by metal-organic chemical vapor deposition (MOCVD).
• The p-i-n structure consisted of a 3-μm n-GaN bottom layer, a thin 150-nm intrinsic In$_{0.1}$Ga$_{0.9}$N absorption layer, and a 150-nm p-GaN top layer.
• Thin-film technique is used to remove the sapphire substrate and transfer the p-i-n structure onto a mirror-coated Si substrate.
• For enhancing light absorption, a highly reflective mirror is employed in thin-InGaN solar cell, which improved current density from 0.33 to 0.52 mA/cm$^2$ and an increment in conversion efficiency from 0.55% to 0.80%.
• Mirror coated Si substrate has another advantage of good heat dissipation as compared with conventional sapphire-based devices.
• The high fill factor in this letter could result from negligible leakage current or large shunt resistance, which could be thought of as the result of good crystalline quality of InGaN.
• The physical origin for the photocurrent enhancement in the thin-film solar cell is related to multireflection of light by the mirror structure.
• In addition to the enhanced light absorption, the mirrorcoated Si substrate still has another advantage of good heat dissipation as compared with the conventional sapphire-based devices.

**High-quality InGaN/GaN heterojunctions and their photovoltaic effects**

**Abstract:** High-quality p-GaN/i-In$_{0.1}$Ga$_{0.9}$N/n-GaN heterojunctional epilayers are grown on (0001)-oriented sapphire substrates by metal organic chemical vapor deposition. The Pendellösung fringes around the InGaN peak in high-resolution x-ray diffraction (HRXRD) confirm a sharp interface between InGaN and GaN films. The corresponding HRXRD and photoluminescence measurements demonstrate that there is no observable phase separation. The improvement in crystal quality yields high-performance photovoltaic cells with open-circuit voltage of around 2.1 eV and fill factor up to 81% under standard AM 1.5 condition. The dark current-voltage measurements show very large shunt resistance, implying an insignificant leakage current in the devices and therefore achieving the high fill factor in the illuminated case.

- crystalline defects commonly observed include v-shaped pits, phase separation, and dislocations, which have been shown to deteriorate device performance by increasing leakage current.
- fabricated high quality p-i-n type solar cell using MOCVD by adjusting the layer thickness using critical thickness calculations.
- leakage current density increases with area/periphery ratio of diode, revealing leakage current as one of main components degrading photovoltaic performance.
- A high-quality p-GaN/ i-In$_{0.1}$Ga$_{0.9}$N/n-GaN double heterojunction with no observable phase separation and relaxation is obtained using metal organic chemical vapor deposition (MOCVD)
- Epitaxial layers of GaN and InGaN were grown on c-plane sapphire substrates by MOCVD using the conventional two-step growth process
- The p-i-n junction for photovoltaic effect consists of a 3 um thick bottom Si-doped n-type GaN (n-GaN), 0.15 um thick intrinsic In$_{0.1}$Ga$_{0.9}$N layer (i-InGaN), and 0.15 um thick top p-GaN
- Pendellösung fringes phenomenon is frequently used to judge heterojunction quality as the figure-of-merit
- A sharp single peak corresponding to near-band edge transition in the epitaxially grown InGaN phase appears at 393 nm (~3.15 eV) in the PL spectrum. Induced broadening of the primary InGaN peak which implies phase separation is not observed. These results confirm a good suppression of phase separation in the InGaN epilayers
- Due to the good crystal quality and interface property in InGaN/GaN heterojunction, devices may exhibit low reversed saturation current density
- The limited Voc in this study could be ascribed to the relatively smaller built-in potential caused by the lower doping concentration in GaN and/or less incident light due to the adsorption in the Ni/Au contact layer
- The relatively high fill factor (81%) could result from the negligible leakage current or large shunt resistance in the fabricated solar cells. The cause of the improved shunt resistance or leakage current could be thought of as the reduction of defects such as dislocations in the bulk portion or interface of the heterojunctions
- The devices display the poorer photovoltaic effect (especially the low fill factor, data are not shown here), which could be attributed to worse crystal quality caused by a relaxation of InGaN layer which generates dislocations (increasing leakage current and recombination) because the growth thickness exceeds the critical thickness of InGaN on GaN

Growth, fabrication, and characterization of InGaN solar cells

Abstract: The InGaN alloy system offers a unique opportunity to develop high efficiency multi-junction solar cells. In this study, single junction solar cells made of In$_x$ Ga$_{1-x}$N are successfully developed, with $x = 0$, 0.2, and 0.3. The materials are grown on sapphire substrates by MBE, consisting of a Si-doped InGaN layer, an intrinsic layer and an Mg-doped InGaN layer on the top. The I–V curves indicate that the cell made of all-GaN has low series resistance (0.12 Ω cm$^2$) and insignificant parasitic leakage. Contact resistances of p and n contacts are 2.9 × 10$^{-2}$ Ω cm$^2$ and 2.0 × 10$^{-3}$ Ω cm$^2$, respectively. Upon illumination by a 200 mW/cm$^2$, 325 nm laser, Voc is measured at 2.5 V with a fill factor of 61%. Clear photoresponses are also observed in both InGaN cells with 0.2 and 0.3 Indium content when illuminated by outdoor sunlight. But it is difficult to determine the solar performance due to the large leakage current, which may be caused by the material defects. A thicker buffer layer or GaN template can be applied to the future growth process to reduce the defect density of InGaN films.
good control of p-type doping in InGaN is one of most critical issues. Due to unusual low position of the conduction band edge at 0.9 eV below Fermi level stabilization energy (EFs), p-type doping of InGaN has proved extremely difficult. Evaluation of p-type doping with Magnesium (Mg) as an acceptor still remains a challenge because strong surface accumulation of electrons exists throughout most of the Indium (In) composition range. Surface accumulation represents a possible significant parasitic conductivity path between p and n contacts on solar cell structures. Suggested that a thicker buffer layer or GaN template can be applied to reduce defect density of InGaN. Devices with high In compositions have much higher leakage current, which cause difficulty to determine turn-on voltage and output power of cells. High In mole fraction alloy has a strong surface electron accumulation which can also contribute to the leakage in InGaN cells. Leakage current density goes up as area/ periphery ratio of the diode increases, which tell that bulk leakage is one of main component in leakage current in devices. High defect density in InGaN materials may cause the abnormal bulk leakage current in devices.

Due to the unusual low position of the conduction band edge at 0.9 eV below the Fermi level stabilization energy (EFs), p-type doping of InGaN has been proved extremely difficult.

The surface accumulation represents a possible significant parasitic conductivity path between p and n contacts on solar cell structures. The buffer layer used in the design is a 250 nm AlN layer grown at about 800 °C followed by a 1 μm GaN layer. Due to the surface electron accumulation, most of the Mg-doped InGaN films exhibit strong n-type Hall polarity. The devices with high In compositions have much higher leakage current, which cause the difficulty to determine the turn-on voltage and output power of the cells. It is anticipated that high In mole fraction alloy has a strong surface electron accumulation which can also contribute to the leakage in InGaN cells. The electroluminescence peak of In0.2Ga0.8N cell overlaps with the absorption edge of the device, which indicates relative lack of localized states. The cell consisted of all-GaN composition has low series resistance and insignificant parasitic leakage. A thicker buffer layer or GaN template can be applied to the future growth to reduce the defect density of InGaN.

Characteristics of InGaN designed for photovoltaic applications [6][6][6]

Abstract: This work addresses the required properties and device structures for an InGaN solar cell. Homojunction InGaN solar cells with a bandgap greater than 2.0 eV are specifically targeted due to material limitations. These devices are attractive because over half the available power in the solar spectrum is above 2.0 eV. Using high growth rates, InGaN films with indium compositions ranging from 1 to 32% have been grown by Molecular Beam Epitaxy with negligible phase separation according to X-ray diffraction analysis, and
better than 190 arc-sec ω-2θ FWHM for ~0.6 μm thick In0.32Ga0.68N film. Using measured transmission data, the adsorption coefficient of InGaN at 2.4 eV was calculated as \( \alpha \approx 2 \times 10^5 \text{ cm}^{-1} \) near the band edge. This results in the optimal solar cell thickness of less than a micron and may lead to high open circuit voltage while reducing the constraints on limited minority carrier lifetimes.

- suggested that InN films must be grown at low temperatures, such as 360-550 °C because of low dissociation temperature of InN
- at low substrate temperatures, it is difficult to achieve p-type InGaN while maintaining good crystalline structures
- InGaN has phase separation for high In composition due to the immiscibility of InN in GaN
- phase separation also affects the bandgap of material, creating localized regions of different composition materials, seriously limiting efficiency of solar cell
- phase separation can be suppressed by increasing growth rate, author(s) successfully grew InGaN films with various In compositions by Molecular Beam Epitaxy (MBE) at rates in excess of 0.6-1.3 μm/hr.
- absorption coefficient of InGaN at 2.4 eV was calculated to be \( \alpha \approx 2 \times 10^5 \text{ cm}^{-1} \), near the band edge
- InN films must be grown at low temperatures, such as 360-550 °C because of the low dissociation temperature of InN
- At low substrate temperatures, it is difficult to achieve p-type InGaN while maintaining good crystalline structures
- InGaN has a well documented phase separation for high In composition due to the immiscibility of InN in GaN
- The phase separation also affects the bandgap of the material, creating localized regions of different composition materials, seriously limiting the efficiency of the solar cell. Such localization of the electron and hole wave functions makes current collection more difficult and to date has lead to decreased conversion efficiency
- A polarization induced discontinuity in the conduction-band edge of GaN – GaN heterojunctions is formed, which negatively affects the photocurrent of the device by preventing minority carrier collection
- A heterojunction device has defects arising from lattice mismatch directly at the collection junction - the most sensitive region of the device
- Phase separation can be suppressed by increasing the growth rate
- As the III/V ratio is increased in InGaN, phase separation minimizes. The growth rate increased with increasing III/V ratio and phase separation diminished
- Optical transmission measurements of MBE grown samples with a film thickness of ~1 um found very sharp bandgap edges, indicative of minimal phase separation
- Relatively sharp transition for lower In composition materials but slightly less sharp transition for higher In composition InGaN, resulting from slight phase separation was observed
Growth of InGaN self-assembled quantum dots and their application to photodiodes[7][7][7]

Abstract: Nanometer-scale InGaN self-assembled quantum dots (QDs) have been prepared by growth interruption during metalorganic chemical vapor deposition growth. With a 12 s growth interruption, author(s) successfully formed InGaN QDs with a typical lateral size of 25 nm and an average height of 4.1 nm. The QD density was about 2×10¹⁰ cm⁻². In contrast, much larger InGaN QDs were obtained without growth interruption. InGaN metal-semiconductor-metal photodiodes with and without QDs were also fabricated. It was found that the QD photodiode with lower dark current could operate in the normal incidence mode, and exhibit a stronger photoresponse.

- Author(s) could achieve a much larger photocurrent to dark current contrast ratio from MSM photodiodes with nanoscale InGaN SAQDs

III–V nitride semiconductor materials have a wurtzite crystal structure

- At room temperature, the band gap energy of AlInGaN varies from 0.7 to 6.2 eV depending on its composition
- MSM photodiodes have an ultra low intrinsic capacitance and their fabrication process is also compatible with field-effect transistor (FET)-based electronics
- Nitride quantum dots (QDs) can be self-organized using the strain-induced Stranski-Krastanov growth mode and also by applying growth interruption during metalorganic chemical vapor deposition (MOCVD) growth
- Small circular InGaN self assembled quantum dots (SAQDs) were formed by the interrupted growth mode with diameter in the range of 20–38 nm, average height of 4.1 nm and density to be around 2X10¹⁰ cm⁻²
- Large oval InGaN islands were found in sample grown without growth interruption with width in the range of 140 nm-70 nm, average height of 1.7 nm density about 3.5X10⁸ cm⁻²
- The surface morphology of MOCVD grown InGaN can be varied by using interrupted growth rate
- Growth interruption could release the partial strain energy of InGaN epitaxial layer when InGaN was grown more than the critical thickness 0.8 nm
- The introduction of growth interruption resulted in a PL blueshift as large as 67 meV that can be attributed to the lateral size effect of nanostructures
- The subband transition energies increase when the size of nanostructure becomes smaller
- The QW (2.4nm thick InGaN) detectors are not sensitive to radiation that is incident perpendicularly, while the QD detector can operate in the normal incidence mode showing better photoresponse
- A larger photoresponse was observed from photodiodes with In-GaN nanostructures

InGaN/GaN multiple quantum well concentrator solar cells[8][8][8]

Abstract: Author(s) present the growth, fabrication, and photovoltaic characteristics of Inx Ga1–xN/GaN(x ~ 0.35) multiple quantum well solar cells for concentrator applications. The
open circuit voltage, short circuit current density, and solar-energy-to-electricity conversion efficiency were found to increase under concentrated sunlight. The overall efficiency increases from 2.95% to 3.03% when solar concentration increases from 1 to 30 suns and could be enhanced by further improving the material quality.

- requirements of an active material system for obtaining solar cells with a conversion efficiency greater than 50% can be fulfilled by InGaN alloys with In-content of about 40%.
- large lattice mismatch between InN and GaN, results in phase separation and as a consequence reported values of open circuit voltages (Voc) for different In contents in general are significantly lower than theoretical values (thermodynamic limit)
- strain could suppress phase separation in InGaN
- used strain to suppress phase separation for In(x)Ga(1-x)N (x~0.3) based multiple quantum well
- advantages of low dimensional InGaN MQW solar cells include (i) crystalline quality of thin light absorption layers (InGaN wells) embedded between GaN barriers is higher than that of InGaN epilayers with thickness exceeding the critical thickness, (ii) with incorporation of MQW structure in the i-region, Voc and Jsc can be independently optimized. (iii) MQW solar cells are expected to outperform bulk i-layer solar cells under concentrated sunlight
- described Voc as a function of concentrated sun light by mathematical expression

Lower Voc values in InGaN solar cells with higher In contents are not only caused by the lowering of the band gaps but are also related to reduced crystalline quality By directly depositing on GaN or AlN epitemplates without buffer layers, single phase InGaN epilayers across the entire alloy range can be produced by MOCVD

- Strain can suppress phase separation in InGaN
- In the MQW model the crystalline quality of the thin light absorption layers (InGaN wells) embedded between GaN barriers is higher than that of InGaN epilayers with thickness exceeding the critical thickness. Also in the i-region, Voc and Jsc can be independently optimized
- Voc is primarily determined by the wider band gap barrier material while spectral response is determined by the width and depth of the lower band gap material of QWs
- MQW solar cells are expected to outperform bulk i-layer solar cells under concentrated sunlight
- The overall solar to electrical power conversion efficiency of the device is 2.95%, which is still much lower than the theoretically expected value of a single junction solar cell of about 8% at the experimented optical energy band gap can be attributed to the insufficient thickness of the light absorbing layer in InGaN wells
- The decrease in FF with increasing C is related to the enhanced carrier recombination at the interface region due to high carrier densities under concentrated sunlight
Optimization of GaN window layer for InGaN solar cells using polarization effect \[9\] [9] [9]

**Abstract:** The III-nitride material system offers substantial potential to develop high-efficiency solar cells. Theoretical modeling of InGaN solar cells indicate strong band bending at the top surface of p-InGaN junction caused due to piezoelectric polarization-induced charge at the strained p-GaN window interface. A counterintuitive strained n-GaN window layer is proposed, modeled and experimentally verified to improve performance of InGaN solar cells. InGaN solar cells with band gap of 2.9 eV are grown using MOCVD with p-type and n-type strained GaN window layers, and fabricated using variable metallization schemes. Fabricated solar cells using n-GaN window layers yield superior VOC and FF compared to those using p-GaN window layers. The VOC’s of InGaN solar cells with n-GaN window layers are further enhanced from 1.5 V to 2 V by replacing the conventional NiOX top contact metal with Ti/Al, which also verifies the tunneling principle.

- net polarization and consequent internal electric fields have detrimental effect on performance of optoelectronic devices due to polarization-induced potential barriers and band bending.
- demonstrated counterintuitive design, fabrication and optimization of the GaN window layer for InGaN solar cells mediated by polarization effects
- thin GaN window layers, designed in a 2 – 10 nm thickness range, are typically strained due to lattice mismatch with the underlying InGaN layer and hence, generate substantial piezoelectric polarization.
- simulations indicated that tunneling contacts using n-type material can potentially provide superior Ohmic characteristics to p-type GaN or InGaN contacts.
- due to lower resistivity and ease of forming Ohmic contacts to n-GaN compared to p-GaN, tunneling contact using n-type material indicates a viable alternative
- Strained n-GaN window layers enhance tunneling of holes from the p-InGaN junction due to piezoelectrically induced sheet charge and strong band bending at heterointerface
- Fabricated InGaN solar cells with band gap of 2.9 eV and n-GaN window layer demonstrate a superior performance compared to those with p-GaN window layers
- The III-nitrides are highly polar molecules due to non-centrosymmetry of charge in the wurtzite structure and the large ionicity of the covalent bonds
- The net polarization and consequent internal electric fields have been shown to be detrimental to the performance of optoelectronic devices due to polarization-induced potential barriers and band bending
- Window layers serve to passivate the top junction surface and generate a front-surface field to minimize front surface recombination
- Thin GaN window layers, designed in a 2 - 10 nm thickness range, are typically strained due to lattice mismatch with the underlying InGaN layer and hence, generate substantial piezoelectric polarization
- The downward bending of bands at the strained-p-GaN/p- InGaN heterointerface tends to develop a potential well that accumulates a 2-Dimensional Electron Gas (2DEG)
- InGaN solar cells with p-GaN window layers demonstrate very low Open-Circuit Voltages (Voc) and Fill Factors (FF)
The combination of strong polarization charge at the p-GaN/p-InGaN interface with a non-ideal NiOx/p-GaN contact substantially reduces the Voc and FF of the solar cell.

**Simulation of In_{0.65}Ga_{0.35}N single-junction solar cell**

**Abstract:** The performances of In0.65Ga0.35N single-junction solar cells with different structures, including various doping densities and thicknesses of each layer, have been simulated. It is found that the optimum efficiency of an In0.65Ga0.35N solar cell is 20.284% with $5 \times 1017$ cm$^{-3}$ carrier concentration of the front and basic regions, a 130 nm thick p-layer and a 270 nm thick n-layer.

- When carrier concentrations of front and basic regions are $5 \times 1017$ cm$^{-3}$, thickness of p-layer and n-layer are 130 nm and 270 nm, respectively, optimum efficiency calculated is 20.284% (AM1.5G, 100mWcm$^{-2}$, 0.32–1.32μm)
- Summarized expression for efficiency, minority carrier, diffusion length, open circuit voltage short-circuit current and other experimentally measured properties of GaN and InGaN
- **Authors used the analysis of microelectronic and photonic structures (AMPS) to analyses InGaN PV cells. It uses the first-principles of continuity and Poisson’s equations approach to analyze the transport behaviour of semiconductor electronic and optoelectronic device structures**