Minimizing shadow losses in III-nitride solar cells

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ABSTRACT

In this work $InGa_{0.85}N p-n$ homojunction solar cells were grown by MOCVD on GaN/sapphire substrates and fabricated using standard techniques. When illuminated from the backside, these devices showed 65.9% improvement in J_{SC} and 4.4% improvement in V_{OC} as compared to identical illumination from the front. These improvements arise from removal of the losses from electrical contact shading on the front of the devices (11.7% of active area), as well as significant optical absorption by the top current spreading layer. These improvements can likely be further enhanced by utilizing double-side polished wafers, which would eliminate scattering losses on the back surface. In addition to improving electrical characteristics of single cells, backside illumination is necessary for the realization of monolithic tandem InGaN solar cells.

Keywords: III-nitrides, solar cells, MOCVD

1. INTRODUCTION

The most promising route to achieving ultra-high efficiency solar cells is with tandem devices which incorporate materials with different bandgaps. Detailed balance calculations have shown that in order to achieve a tandem solar cell with >50% efficiency, the device must include a junction with bandgap > $2.2eV^{1, 2}$. One of the only material systems capable of achieving this is the III-nitride system. The InGaN ternary alloy is particularly interesting, as its bandgap can be tuned to cover almost the entire solar spectrum by varying the In:Ga ratio. This offers the possibility of realizing a monolithic tandem solar cell structure from a single material system. InGaN tandem solar cells have been modeled^{3, 4} but not demonstrated. Several groups have reported single junction InGaN-based solar cells grown by both MOCVD⁵⁻⁸ and MBE⁹, however all of these cells have exhibited very low J_{SC} and thus low efficiency.

In a III-nitride tandem solar cell composed of epitaxial InGaN layers, backside illumination would be necessary in order to collect incident photons in the proper order (i.e. highest energy first). The low indium content films (higher bandgap) are better lattice matched with GaN and also high indium content InGaN (lower bandgap) must be grown at lower growth temperatures and consequently last in order to prevent film degradation. For these reasons an inverted stack sequence is required, as compared to existing tandem solar cell designs. All of the recent world-record holding solar cells have been triple-junction, heteroepitaxial tandem devices, most of which have been grown on Ge ($E_G = 0.66eV$) or other low bandgap substrates with higher bandgap junctions grown on top^{10, 11}. This cell arrangement necessitates front illumination for high efficiency operation of these solar cells. However, due to the inverted stack structure, InGaN-based tandem solar cells will have to be illuminated from the back.

In this paper the improvement in electrical characteristics in InGaN solar cells under backside illumination is presented and compared to front side illumination. InGaN *p-n* homojunction solar cells were grown by MOCVD on sapphire substrates. The epitaxial structures were characterized by high-resolution XRD to determine material composition and quality, after which they were fabricated into devices. The devices were I-V tested under front and backside illumination, with improved V_{OC} and I_{SC} observed under backside illumination

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2. METHODOLOGY

The InGaN solar cell investigated in this paper was epitaxially grown on a GaN template on a single-side polished sapphire substrate. Both the solar cell and GaN template were grown by MOCVD in a vertical reactor. A schematic of the device structure is shown in Figure 1. The GaN template and n-GaN layers were grown at a temperature of 1045°C and pressure of 200Torr, with trimethylgallium (TMG) and ammonia (NH₃) as the gallium and nitrogen precursors, respectively. The InGaN layers were grown at 745°C and 100Torr, with trimethylindium (TMI), triethylgallium (TEG), and NH₃ as the indium, gallium, and nitrogen precursors, respectively. A low-temperature p-GaN capping layer was grown at the same temperature and pressure as the InGaN layers with TEG used as the gallium precursor. This capping layer was added in order to use the improved contact resistance to p-GaN versus that of p-InGaN. The growth conditions were kept the same in order to prevent degradation of the underlying InGaN layers.



Fig. 1. Schematic of solar cell structure used in this work.

The dopants used were silicon for n-type and magnesium for p-type with precursors of silane (SiH₄) and bis(cyclopentadienyl)magnesium (Cp₂Mg), respectively. The p-type layers were activated in a rapid thermal annealer (RTA) at 650°C for 20 minutes under N₂ flow in order to drive-off passivating hydrogen bonded to the magnesium dopants. Carrier concentrations were measured in calibration films by Hall Effect measurement in the Van der Pauw configuration using an Ecopia HMS-3000 system with a 0.51Tesla magnet.

High resolution X-ray diffraction (HRXRD) and optical transmission were used to verify the indium content and crystalline quality of the solar cell structure. Reciprocal space maps (RSM) and ω -20 XRD measurements were performed using a Phillips X'Pert Pro MRD featuring a four-bounce hybrid monochromator with CuK_{a1} monochromatic radiation and a Ge(220) three-bounce analyzer in triple-axis alignment. Optical transmission-reflection measurements were performed using a PerkinElmer Lambda 1050 UV/Vis/NIR system in the 250 to 700nm range.

After material characterization the structure was fabricated into devices. First a layer of Ni/Au (5nm/5nm) was deposited by e-beam evaporation then oxidized in an RTA at 550°C for 5 minutes to form a transparent NiO_x current spreading layer. Next a 100nm layer of indium-tin-oxide (ITO) was deposited by e-beam evaporation. Then $(350\mu m)^2$ mesas were etched using an inductively coupled plasma with the pattern defined by standard photolithography. Finally, electrical contacts were deposited by e-beam evaporation with the pattern defined by a liftoff process. The p-contact pad consisted of Ni/Au (50nm/150nm), and the n-contact pad consisted of Ti/Al/Ti/Au (10nm/30nm/10nm/150nm). The contact/mesa pattern is shown in Figure 2. The total un-etched area of the device is 0.1048 mm², 11.7% of which is shaded by the p-contact. The n-contact does not cover any of the active area of the device.



Fig. 2. Contact (grey) and mesa (blue) pattern used for the solar cells reported here.

Once the structure was fabricated into devices, dark and illuminated I-V measurements were performed. The I-V measurements were performed using a software-controlled Keithley 2400 source-meter. The illumination source was a 300W broadband Xe-lamp in an Oriel housing with an AM0 filter installed. A GaN template grown on double-side polished sapphire was also installed as a filter to mimic the absorption of the GaN template underneath the solar structure, which would affect backside illumination measurements.

3. RESULTS AND DISCUSSION

The composition of the InGaN layers was confirmed to be ~15% based on the InGaN peak position in the ω -2 θ XRD scan shown in Figure 3.



Fig. 3. XRD (0002) ω-2θ scan of as-grown InGaN solar cell structure. Indium composition is 15%.

The thickness of the InGaN layers was kept low in order to keep them strained and thus avoid relaxation-induced crystal defects. The strained condition was confirmed by asymmetric RSM (Figure 4), which showed that the InGaN structure was strained to the GaN template lattice constant as indicated by the vertically aligned GaN and InGaN peaks. Optical transmission characterization of the structure (Figure 5) confirmed the indium content of the films calculated from XRD. Hall effect measurements indicated hole concentrations of 5×10^{16} cm⁻³ in the p-GaN and 5×10^{18} cm⁻³ in the p-InGaN. The electron concentration was measured to be 1×10^{18} cm⁻³ in both the n-GaN and n-InGaN.



Fig. 4. Asymmetric $(11\overline{2}4)$ reciprocal space map of as-grown InGaN solar cell structure showing that the structure is strained to the GaN template.



Fig. 5. Optical transmission sepctrum of as-grown InGaN solar cell structure.

The I-V data is shown in Figure 6, and there is a dramatic improvement in J_{SC} as well as improvement in V_{OC} for backside illumination. Under front illumination, $V_{OC} = 783.56$ mV and $J_{SC} = 0.0123$ mA/cm² with a fill factor of 0.437.

For backside illumination $V_{OC} = 818.12 \text{mV} (4.4\% \text{ improvement})$ and $J_{SC} = 0.0204 \text{ mA/cm}^2 (65.9\% \text{ improvement})$ with a fill factor of 0.447.



Fig. 6. I-V data for dark, front, and backside illumination conditions.

It is expected that the improvement in J_{SC} would be much more dramatic than the improvement in V_{OC} , as J_{SC} is directly proportional to the photon flux density entering the cell, while improvement in V_{OC} is related to J_{SC} improvement by the diode equation¹²:

$$V_{\rm OC} = \frac{kT}{q} \ln \left(\frac{J_{\rm SC}}{J_{\rm o}} + 1 \right) \tag{1}$$

However the J_{SC} improvement greatly exceeds the 11.7% shading from the p-contact. In addition to the shading from the p-contact, the optical absorption of the "transparent" current spreading layer must be considered and is shown in Figure 7. The current spreading layer was measured to have very high absorption levels in the applicable spectral range, which would greatly reduce the number of sufficiently energetic photons reaching the active region.

The average absorption (weighted to the AM0 spectrum) of the current spreading layer in the spectral region between the $In_{0.15}Ga_{0.85}N$ bandgap (2.68eV) and the GaN bandgap (3.44eV) is 59.56%. With front illumination, the total optical loss from contact shading and current-spreading layer absorption is given by:

$$Total loss = (contact area) \times (contact shadow loss) + (remaining area) \times (absorption loss)$$
(2)

Total loss =
$$(.117) \times 100\% + (0.883) \times 59.56\% = 64.3\%$$

The expected improvement for backside illumination is given by:

$$Improvement = [J_{SC}(back)/J_{SC}(front)] - 1 = [1/(1 - Total loss)] - 1$$
(3)

Improvement =
$$[1/(1-0.643)] - 1 = 180\%$$

In other words, the J_{SC} from backside illumination would be expected to be 2.80 times that from front illumination. This is much higher than the observed 1.66 times improvement. This discrepancy is most likely due to scattering losses through the rough backside surface of the single-side polished sapphire substrate.



Fig. 7. Optical absorption of NiO_x/ITO stack.

4. CONCLUSIONS

This work has demonstrated dramatic improvement in the photoresponse of an InGaN solar cell by using backside illumination. This consisted of a 65.9% improvement in J_{SC} and a 4.4% improvement in V_{OC} as compared to front illumination, both of which could be improved upon greatly by using a double-side polished sapphire substrate which would eliminate scattering. Backside illumination is necessary for the eventual realization of monolithic InGaN tandem solar cells and can ease the fabrication process of III-nitride solar cells by removing shadowing constraints from the design of contact patterns. The only other method of reducing contact shading is to reduce the aerial coverage of the contact, which results in an undesirable increase in the series resistance (R_S) of the cell¹³. Backside illumination removes contact shading loss without affecting R_S .

What makes backside illumination feasible for III-nitride solar cells is the sapphire substrate, which has a very high bandgap and very low optical absorption across the solar spectrum. The benefits of backside illumination would be compromised by a SiC substrate, which has a bandgap of 3.26eV for 4H and 3.03eV for 6H. Thus under backside illumination a SiC substrate would result in significantly higher UV absorption than what is already caused by the GaN template ($E_G = 3.44eV$).

The dramatic improvement in J_{SC} presented here due to backside illumination is very promising, as all of the InGaN solar cells reported to date have suffered from very low current densities. Many of these cells have utilized some type of "transparent" current spreading layer^{5, 7, 8}, which is a practice carried over from III-nitride LED fabrication. However, based on the results presented here, it is clear that such layers can absorb a great deal of light in the solar spectrum, contributing to the poor solar cell performance. If these layers are necessary for making Ohmic or tunneling contact to the p-GaN layer, then backside illumination is the most obvious way to avoid the associated losses.

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