GaInN/GaN – Ni/Au Transparent Conducting Oxide Schottky Barrier Solar Cells

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***Abstract* — Schottky barrier solar cells made from two different GaInN/GaN material structures combined with Ni/Au transparent conducting oxide films are demonstrated herein. The GaInN/GaN multiple quantum well structure has a short-circuit current density of 0.062 mA/cm^2, open-circuit voltage of 0.468 V, and fill-factor of 69.8%. The GaInN/GaN double-heterostructure exhibits a 51% reduction in short-circuit current density, 47% lower open-circuit voltage, and 27% smaller fill-factor. Preliminary computer simulations indicate that a 10-fold increase in short-circuit current density should be possible for the GaInN/GaN multiple quantum well structure. The Ni/Au layer is responsible for some of this shortfall as its optical transparency varies from a low of 46.4% at 300 nm to a high of 76.8% at 500 nm. There is also evidence that photo-generated carriers are not being collected from the entire illuminated device area. The Ni/Au bi-layer has an electrical resistivity of 2.9 x 10^{-5} Ωcm, but it is very thin and no effort has been made to trade-off its electrical behavior against its optical properties. Work is now underway to increase the open-circuit voltage of these devices by adopting "barrier height enhancement" schemes.**

***Index Terms* — heterojunction, indium gallium nitride, photovoltaic cells, quantum wells, schottky diodes.**

I. INTRODUCTION

Thin film solar cells made from GaInN semiconductor alloys are of considerable interest because this material system covers an unusually wide energy range (from 3.4 eV for GaN to 0.7 eV for InN), has optical absorption coefficients approaching 10^5 cm^{-1} at energies near the band edge, and exhibits better radiation hardness than conventional III-V semiconductors [1]-[3]. Several different material structures have been evaluated over the past ten years, including InGaN homojunctions [4]-[5], InGaN/GaN heterojunctions [6]-[7], and InGaN/GaN multiple quantum well structures [8]-[9]; all of which contain some form of *p-i-n* doping profile to enable collection of photo-generated carriers. The difficulty of making *p-type* GaN and $In_xGa_{1-x}N$ ($x \leq 0.2$) of good electronic quality has been widely documented in the literature on GaN/InGaN LEDs and laser diodes [10]-[12]. Moreover, there have been very few reports on well-conducting *p-type* InGaN with higher indium content [13]-[15], such as would be necessary to make *p-i-n* InGaN solar cells with band gaps in the range 1.9 to 1.0 eV.

In the present work, the issue of p-type doping was circumvented by employing a Schottky diode configuration to collect photo-generated carriers [16]-[19]. More specifically, transparent conducting oxide (TCO) films made of thin Ni/Au bilayers were placed in intimate contact with *n-type* InGaN/GaN heterostructures to demonstrate the viability of InGaN Schottky barrier solar cells [20].

II. EXPERIMENTAL DETAILS

The two GaInN/GaN material structures employed in this study were grown by organometallic vapor phase epitaxy (OMVPE) on c-plane sapphire substrates. The precursor chemicals trimethylgallium, trimethylindium, ammonia, and disilane were employed in a mixed hydrogen/nitrogen ambient at 300 torr. The first structure consists of a 4.0 μm thick, Si-doped GaN ohmic contact layer ($n = 2 \times 10^{18}$ cm^{-3}), followed by a 0.2 μm thick, nominally un-doped GaInN absorber capped by a 40 nm thick, un-doped GaN surface layer. The second structure is nearly identical to the first except the absorber consists of a 15-pair MQW region with 2.5 nm thick GaInN quantum wells and 12 nm thick GaN barriers. The indium content in the InGaN alloy layers is about 10% in both samples. These two material configurations are referred to in the following discussion as *GaInN DH* and *GaInN MQW*, respectively.

Photoluminescence (PL) measurements were made at room-temperature to assess the relative "quality" of the two samples in their *as-grown* states. As evidenced in Fig. 1, the local PL maximum near 365 nm has a narrow spectral line-width (in both structures), which is indicative of good quality n-type GaN. The sample with the MQW absorber exhibits its maximum luminescence intensity at the wavelength (λ_p) of 438 nm with a corresponding spectral-line-width ($\Delta\lambda$) of 14 nm. In contrast, for the DH absorber, the luminescence peak occurs at shorter wavelength (λ_p = 420 nm) and the spectral line-width is considerably broader ($\Delta\lambda$ = 24 nm). Moreover, the DH absorber exhibits a very broad luminescence signal with maximum intensity around 560 nm, which is likely attributable to optical transitions mediated by point defects with energy levels within the band-gap of the bulk InGaN layer.

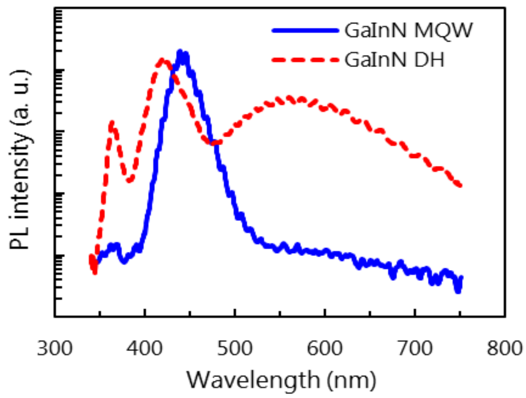

Fig. 1. Photoluminescence spectra (recorded at 300 K) for both GaInN material structures. The measurements were made using an Accent RPM 2000 wafer mapping system equipped with a 30 mW HeCd laser excitation source and low-noise Si photo-detector.

Individual device mesas were formed by inductively-coupled plasma etching down through the GaN capping layer and GaInN absorber region to expose the n-type GaN ohmic contact layer. The device structure depicted in Fig. 2 has a square-shaped mesa with an active area of roughly 9.6 x 10^{-3} cm^2 surrounded by a 200 μm wide Ti/Al metal trace that serves as the bottom-side electrode. After dry etching and ohmic contact formation, the mesa surface is coated via electron-beam evaporation with a Ni (5 nm) / Au (5 nm) metal bi-layer and then annealed at 500 °C for 10 minutes in air to convert this composite film into a transparent conducting oxide. This Ni/Au TCO film forms a *broad-area* Schottky barrier with respect to the un-doped GaN capping layer. A top-side electrode consisting of a thick Ni/Ag composite formed in a grid pattern was employed to lower the series resistance associated with the TCO side of the Schottky diode and to facilitate either probe contact measurements or wire bonding.

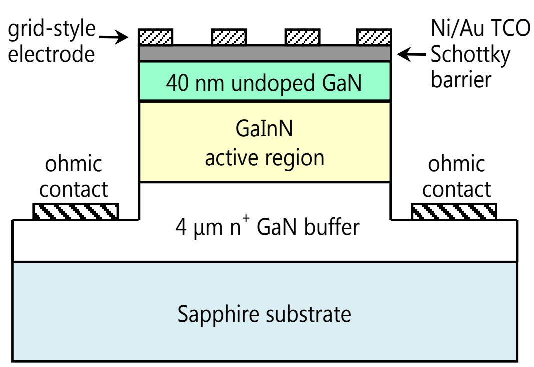

Fig. 2. Schematic cross-section of fabricated GaInN/GaN – Ni/Au TCO Schottky barrier solar cell.

III. Results and Discussion

Current-voltage (*I-V*) characteristics were acquired using a Newport solar simulator with an AM0 spectral filter and a Keithley *I-V* sweep tool. The solar simulator intensity was calibrated to 100 mW/cm^2 using a calibrated Si photovoltaic cell. These data were converted into current density vs. voltage (*J-V*) curves by dividing the measured current by 70% of the device mesa area (30% of the mesa is covered by the opaque Ni/Ag grid electrode). No attempt was made to correct for optical losses associated with reflection off the device surface.

The "illuminated" *J-V* characteristics for both GaInN material structures are shown in Fig. 3. The GaInN MQW solar cell exhibits a short-circuit current density (J_{sc}) of 0.062 mA/cm^2, open-circuit voltage (V_{oc}) of 0.468 V, and fill-factor (*FF*) of 69.8%. The GaInN DH solar cell yields J_{sc} = 0.041 mA/cm^2, V_{oc} = 0.321 V, and *FF* = 54.9%.

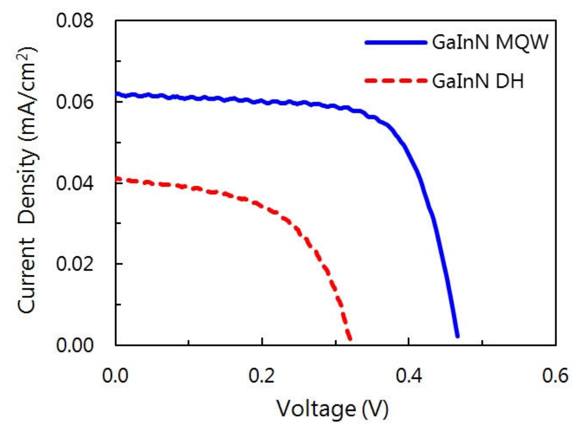

Fig. 3. Illuminated *J-V* characteristics for GaInN MQW (solid line) and GaInN DH (dashed line) Schottky barrier solar cells. The raw *I-V* data were acquired at room temperature under simulated AM0 (1x) solar radiation. *J-V* curves were obtained from the *I-V* data using the procedure outlined in the text.

It is interesting that J_{sc} is roughly 51% larger for the GaInN MQW solar cell even though the total GaInN thickness is only 37.5 nm in this structure compared to 200 nm in the GaInN DH case. Notwithstanding this result, the optical transmission spectra in Fig. 4 demonstrate that the GaInN DH structure more strongly absorbs solar radiation at wavelengths longer than 365 nm (as expected given its 5.3x greater GaInN thickness). These observations suggest that the GaInN DH device suffers from substantial trapping of photo-generated carriers at the GaInN/GaN heterojunctions on the bottom-side (electrons) and top-side (holes) of the GaInN absorber layer.

It is also significant that V_{oc} is approximately 47% larger for the GaInN MQW solar cell than for the GaInN DH device. High-resolution x-ray diffraction measurements (data not shown) indicate the GaInN layer in the DH structure is in a "partially relaxed" strain state and thus probably has a higher density of threading dislocations (i.e., larger concentration of

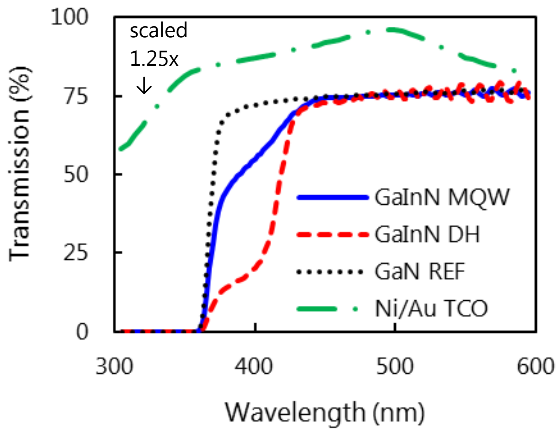

Fig. 4. Optical transmission spectra at room-temperature for both GaInN material structures, a GaN reference sample, and a Ni/Au TCO film deposited on sapphire. The GaInN and GaN spectra are plotted in *as measured* form (i.e., raw data). The transmission data for the Ni/Au TCO film has been normalized by the signal from a bare sapphire substrate, and then scaled by 1.25x for illustration purposes (i.e., to avoid overlaps with the other curves).

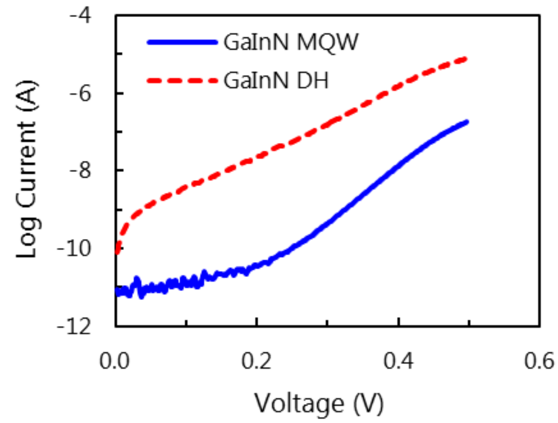

Fig. 5. Dark *I-V* characteristics for GaInN MQW (solid line) and GaInN DH (dashed line) Schottky barrier solar cells. The measurements were preformed at room-temperature in the absence of optical illumination.

non-radiative recombination centers) than the *pseudomorphic* GaInN MQW active region. The "dark" current-voltage characteristics plotted in Fig. 5 support this hypothesis – the GaInN DH structure has a much higher leakage current at low forward voltage than the GaInN MQW device. The combination of lower J_{sc} and higher leakage (dark) current work together to suppress V_{oc} for the GaInN DH solar cell relative to the GaInN MQW case.

It is not possible at this time to make quantitative comparisons between the results presented here and values reported in the literature. To our knowledge there has been only one other report on InGaN Schottky barrier solar cells [21]; but, this work did not employ a calibrated solar illumination source. It is clear, however, that the J_{sc} and V_{oc} values demonstrated in this work are inferior to those of the best *p-i-n* InGaN/GaN devices [4-9]. Nevertheless, the fill factors reported here are on par with literature values.

Preliminary computer simulations indicate that a 10-fold increase in J_{sc} should be possible for the GaInN MQW device structure. The Ni/Au TCO layer is responsible for some of this shortfall, as evidenced by the optical transmission data plotted in Fig. 4. The optical transparency of the TCO film varies from a low of 46.4% at λ = 300 nm to a high of 76.8% at 500 nm. Furthermore, it is likely that some of the photo-generated holes are trapped at the TCO/GaN interface; thereby reducing the carrier collection efficiency.

There is also evidence that photo-generated carriers are not being collected from the entire illuminated device area. The Ni/Au TCO has an electrical resistivity of 2.9 x 10^{-5} Ωcm, but it is only 10 nm thick and no effort has been made to trade-off its electrical behavior against its optical properties (e.g., increasing film thickness to reduce lateral resistance at the expense of optical transparency).

Finally, it is recognized that V_{oc} for *conventional* Schottky barrier solar cells should be considerably smaller than for *p-i-n* junction devices. Nevertheless, others have demonstrated substantial barrier height increases in both metal-Si [22] and metal-GaAs [23]-[24] Schottky diodes by incorporating novel doping or alloy interlayers. In fact, this approach was used long ago to significantly improve the performance of an Au-(AlGaAs)-GaAs solar cell [25]. Work is now underway to adopt such "barrier height enhancement" schemes to the case of GaInN – TCO Schottky barrier solar cells.

IV. Summary and Conclusions

This work demonstrates the viability of GaInN/GaN – Ni/Au TCO Schottky barrier solar cells. Two different GaInN/GaN material structures were evaluated and the multiple quantum well solar cell proved to be superior to the double-heterostructure device. Considerable work remains to bring J_{sc} and V_{oc} for the Schottky barrier solar cells described here in line with the best *p-i-n* InGaN/GaN devices, but avenues for improvement have been identified and are now under evaluation.

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