High 400 °C operation temperature blue spectrum concentration solar junction in GaInN/GaN

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Transparent wide gap junctions suitable as high temperature, high flux topping cells have been achieved in GaInN/GaN by metal-organic vapor phase epitaxy. In structures of 25 quantum wells (QWs) under AM1.5G illumination, an open circuit voltage of 2.1 V is achieved. Of the photons absorbed in the limited spectral range of < 450 nm, 64.2% are converted to electrons collected at the contacts under zero bias. At a fill factor of 45%, they account for a power conversion efficiency of 38.6%. Under concentration, the maximum output power density per sun increases from 0.49 mW/cm$^2$ to 0.51 mW/cm$^2$ at 40 suns and then falls 0.42 mW/cm$^2$ at 150 suns. Under external heating, a maximum of 0.59 mW/cm$^2$ is reached at 250 °C. Even at 400 °C, the device is fully operational and exceeds room temperature performance. A defect analysis suggests that significantly higher fill factors and extension into longer wavelength ranges are possible with further development.

The results prove GaInN/GaN QW solar junctions a viable and rugged topping cell for concentrator photovoltaics with minimal cooling requirements. By capturing the short range spectrum, they reduce the thermal load to any conventional cells stacked behind. © 2014 AIP Publishing LLC.

A high energy conversion efficiency in wide bandgap GaInN/GaN-based heterostructures has enabled gigawatt electric power savings in lighting by solid state light emitting diodes (LEDs) and a stable and reliable technology manufacturing base. The strongly absorbing direct bandgap of Ga$_{1-x}$In$_x$N can be tuned from 370 to 1770 nm, in Ga$_{1-x}$In$_x$N/GaN heterostructures photo charges are effectively separated by built-in piezoelectricity, and thermionic emission should help carrier extraction through the 3 eV GaN pn-junction. Respective solar cells have been demonstrated using GaInN homojunctions, GaInN/GaN double heterojunctions, and GaInN/GaN quantum well (QW) structures.

High performance multi-junction concentration cells utilize AlGaInP compounds of various compositions but severely suffer performance loss and destruction under elevated operating temperature. Therefore, active cooling precautions are being devised, which disallows their integration with solar thermal collectors. In contrast, GaInN/GaN-based solar junctions have shown a high and monotonic increase in power conversion efficiency up to 200 suns, the highest concentration applied, without any cooling provisions. In separate work, output power was found to increase with temperature from 22 °C to 70 °C. But above that, performance dropped again, reverting to that of 40 °C at 115 °C, the highest temperature applied.

Here we report short wavelength ($\lambda < 450$ nm) solar junction performance under concentration up to 150 suns and, separately, up to chuck temperatures of 400 °C. A set of three different structures was grown on c-plane (0001) sapphire substrate (0.3 mm) by metal-organic vapor phase epitaxy (MOVPE). Common to all, in sequence of growth, is a 2 $\mu$m thick n-GaN, 2.5 nm thick unintentionally doped GaN QWs separated by 20 nm thick GaN barriers, 20 nm thick p-AlGaIn, and 200 nm thick p-GaN layers. The number of GaInN/GaN QWs was varied to 8, 25, and 40. By help of an x-ray diffraction analysis of the (0002) superlattice fringes, an InN-fraction $x = 0.08 \pm 0.01$ was determined for the Ga$_{1-x}$In$_x$N layers. Wafers were fabricated into 350 $\times$ 350 $\mu$m$^2$ mesas by reactive-ion etching. Semitransparent Ni/Au (5 nm/5 nm) was then deposited as p-contact, Ti/Al/Ti/Au (20 nm/100 nm/45 nm/55 nm) was deposited as n-contact by electron beam evaporation. No efforts were yet made to enhance light coupling into the structure by any of the well-known methods.

Current-voltage performance of the junctions was measured by a source meter and simulated solar illumination (150 W Xenon arc lamp with AM1.5G filter). The external quantum efficiency (EQE) spectrum was measured by the same lamp dispersed by a monochromator. The monochromatized excitation light was focused on the sample, or a calibrated silicon photodiode, both under zero bias voltage. The photocurrent was measured by a lock-in amplifier due to small sample size. The excitation light spectrum and EQE in absolute units were obtained by scaling to the known photocurrent response curve of the silicon photodiode. The absorption spectrum was obtained as the difference of incident, transmitted, scattered, and reflected spectral powers. The internal quantum efficiency (IQE) spectrum is calculated from the ratio of EQE spectrum to the absorption spectrum. All efficiency values are obtained by standard laboratory equipment and intended for qualitative scientific purposes only. They have not been verified by independent parties.

Junction current-voltage performance under variable concentration up to 150 suns was performed by focusing the AM1.5G spectrum with a fused silica lens. The concentration ratio was scaled by the known response function of the silicon photodiode. The sample was placed on a black aluminum chuck at room temperature. There was no active cooling. Junction current-voltage performance under
variable chuck temperature from 25 °C up to 400 °C was performed on a controlled hot plate in the dark and under direct Xenon lamp illumination (no concentration, no solar spectrum filter) in air.

Current-voltage of all samples (8, 25, and 40 QWs) under AM1.5G illumination and in the dark at room temperature is shown in Fig. 1(a). Short circuit current density $J_{SC}$ and open circuit voltage $V_{OC}$ are shown in the inset. With the increase of the QW number, $J_{SC}$ is found to increase monotonically from 0.26 over 0.51 to 1.35 mA/cm$^2$. $V_{OC}$, however, is found to drop in parallel (2.12 V, 2.07 V, 0.81 V). Under reverse bias, the 40 QW structure shows a significantly higher leakage current than the structures of fewer QWs (Fig. 1(a)). This sample therefore was further analyzed in scanning electron microscopy (SEM). From the cross-section view (Fig. 1(b)), V-defects are apparent that emerge around the 20th QW and propagate to open defects at the top surface. In the top view image they appear as hexagonal pits (Fig. 1(c)). The existence of such defects is the likely reason of the high reverse leakage current in this sample similar to the case reported by Mori et al.\textsuperscript{19} The controlled avoidance of V-defect formation is a well-practised development goal in the epitaxy of GaInN/GaN heterostructures\textsuperscript{17} and likely can be solved with further development. From such improved devices it would be reasonable to expect a performance of $J_{SC} > 1$ mA/cm$^2$ at $V_{OC} > 2$ V from within that narrow spectral range.

Absorption, EQE, and IQE spectra of the 8 and 25 QW structures at room temperature are shown in Fig. 1(d) (no light concentration). (Data for the 40 QW structure appears strongly affected by the presence of V-defects and therefore is not helpful in this analysis). Both, EQE and absorption increase with the QW number and we extrapolate that some 40 QWs are indeed needed for full absorption. IQE, i.e., the ratio of EQE and absorption $A$, in both structures shows a maximum in the 390 nm to 540 nm spectral range. The 8 QW structure peaks at a spectral IQE of 95% at 434 nm, the 25 QW structure shows a broader plateau of spectral IQE of 75%. These very high values for the narrow-spectrum quantum efficiency provide important evidence of the potential of the materials system.

For an individual junction, as part of a multijunction system, conversion efficiency in relation to the actually absorbed (in contrast to the transmitted) spectrum is a meaningful performance measure. In this way, the overall IQE of the solar junction is determined as

$$
\text{IQE} = \frac{\int \text{EQE}(\lambda) \times \frac{P(\lambda)}{h c} d\lambda}{\int A(\lambda) \times \frac{P(\lambda)}{h c} d\lambda},
$$

where $P(\lambda)$, $h$, and $c$ are the spectral irradiance, Planck’s constant, and speed of light, respectively. We so obtain overall IQE values of 49.8% for the 8 QW and 64.2% for the 25 QW structures. The deviation of these numbers from the peak IQE values reflects the spectral variation of IQE as caused by a spectrally varying photocarrier extraction probability. Nevertheless, with overall IQE values reaching beyond 50% these QW systems prove extremely efficient in converting absorbed photons to extracted charge carriers.

In a similar fashion, the maximum electrical output power can be related to the actually absorbed spectral power portion of this individual junction. This internal power conversion efficiency ($\eta_{\text{int}}$) is obtained as

$$
\eta_{\text{int}} = \frac{P_m}{\int A(\lambda) \times \frac{P(\lambda)}{h c} \times d\lambda},
$$

where $P_m$ is the maximum output power obtained from the $I$-$V$ measurement under AM1.5G irradiance. Accordingly, we find values of $\eta_{\text{int}} = 42.0\%$ for the 8 QW structure and $\eta_{\text{int}} = 38.6\%$ for the 25 QW structure. The high internal power conversion efficiency value proves the GaInN/GaN QW based solar cells as highly efficient at photovoltaic conversion.

Analysis of the 25 QW junction under variable concentrated AM1.5G illumination up to 150 suns is shown in Fig. 2. The sample is only passively cooled by the aluminium chuck. The current-voltage behavior (Fig. 2(a)) is analyzed for $V_{OC}$ and $J_{SC}$ in Fig. 2(b). Both increases monotonically with concentration ratio $X$. While $J_{SC}$ scales linearly, $V_{OC}$ increases logarithmically. This is well described by the standard diode equation\textsuperscript{20,21}

$$
V_{OC}(X) = \frac{m k_B T}{q} \ln \left( \frac{X J_{SC}}{J_0} + 1 \right)
\approx V_{OC}(X = 1) + \frac{m k_B T}{q} \ln(X),
$$
where $m$, $k_B$, $T$, $q$, and $J_0$ are ideality factor of the diode, Boltzmann constant, temperature, elementary charge, and reverse saturation current, respectively.

The fill factor (FF) and maximum output power density per sun as functions of the concentration ratio are interpreted in Fig. 2(c). With increasing concentration, FF shows a slight decrease from 45% to 41%. The maximum output power density per sun, on the other hand, increases from 0.49 mW/cm² to 0.51 mW/cm² when $X$ increases from 1 to 40. It then decreases to 0.42 mW/cm², when $X$ further increases from 40 to 150. Nevertheless, with a value above 0.4 mW/cm² and an overall loss of not more than 14% for the partial spectrum performance (350–450 nm) up to concentrations of 150 suns without any active cooling, these results demonstrate the strong potential of the material system as an actively collecting junction and spectral filter for a lower thermal load in secondary conventional solar junctions.

The junction current-voltage behavior under variable chuck temperature up to 400 °C under illumination is shown in Fig. 3(a) for the 25 QW structure. It is noteworthy that the solar junction is still operating well at the highest temperature applied, i.e., 400 °C. This emphasizes the system’s potential superiority to conventional compound solar junction systems. With the increase of temperature, we find $V_{OC}$ to decrease monotonically from 2.08 V (25 °C) to 0.96 V (400 °C). $J_{SC}$, on the other hand, increases from 0.51 mA/cm² (25 °C) to 0.89 mA/cm² (400 °C). Fig. 3(b) shows the output power density vs. voltage curves at various temperatures. Their analysis for maximum output power density and fill factor as functions of temperature are shown in Fig. 3(d).

We find a monotonic increase of the maximum output power density up to 250 °C, from 0.46 mW/cm² (25 °C) to 0.59 mW/cm² (250 °C). It then drops to 0.48 mW/cm² at 400 °C, but still remains 7% higher than at 25 °C. We see this as the product of a decreasing $V_{OC}$ but increasing $J_{SC}$ with temperature. Both are deemed the consequence of a temperature induced shift of the cell spectral sensitivity into the higher intensity longer wavelength range. Our maximum at 250 °C, however, suggests better high temperature performance than other work reaching a maximum at a mere 70 °C. Also, the fill factor here increases with temperature from 47.2% (25 °C) to the maximum of 57.1% at 300 °C.

In subsequent experiments, the dark and leakage current-voltage behavior under variable chuck temperature up to 400 °C was measured (Fig. 3(c)). The data are well described by the standard diode equation and an ideality factor varying between 4 at 25 °C and 3 at 400 °C. Such
elevated values are frequently observed in GaInN/GaN multi-QW LEDs and have been attributed to multiple regions of piezoelectric depletion. On the other hand, Sang et al. propose to distinguish contributions of thermoelectric emission and carrier tunneling from such data up to 100 °C. A further analysis will be subject of forthcoming work. The leakage current is well below 200 nA, similar to our prior LED work.

The series (R_s) and shunt (R_sh) resistances versus sample temperature are analyzed in Fig. 3(d). R_s decreases monotonically while R_sh keeps constant over the whole temperature range. The constant value of R_sh suggests that leakage paths are not temperature activated. The decrease of R_s is expected by an increase in the free hole concentration but cannot explain the overall increase in output power density. Instead, the decrease in bandgap energy with temperature and associated spectral capture gain is the dominant factor in current increase, while it cannot fully account for the decrease in V_OC. The maximum at 250 °C is likely controlled by an increase in loss mechanisms, such as an increase in internal recombination at temperatures higher than that. A combination of the high voltage of the low QW-count structures with the high current density achieved in the 40-QW sample for additional big efficiency improvements seems attainable with better epitaxial growth control. The ability to operate the junction at such elevated temperatures allows for a wider portion of the solar spectrum to be converted and thereby increase the output power.

In conclusion, we demonstrated the growth and fabrication of GaInN/GaN high operation temperature solar cell junctions suitable for the short wavelength spectral range. An overall IQE as high as 64.2% is achieved and demonstrated. This implies that GaInN/GaN multi QW junctions can be a key component of tandem or hybrid multijunction solar cells to efficiently convert the short wavelength portion of the solar spectrum. With an almost constant value of power conversion efficiency under concentrated solar illumination up to 150 suns, and a monotonically increasing power conversion at elevated temperature up to 250 °C, we proved that the great potential of GaInN/GaN multi QW junctions in concentrated photovoltaics. In particular, as a system of technological proven long-term stability and product worthiness in volume production it can provide both, a missing link to more conventional systems and a motivation for further GaInN materials development throughout the entire solar spectral region. We expect that substantial further improvements are possible with a dedicated effort in epitaxial growth and device research.

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