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Properties of nitride-based photovoltaic cells under concentrated light illumination

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We investigated the properties of nitride-based solar cells under concentrated light illumination from 1 to 200 suns. The conversion efficiency of our solar cells increased with increasing concentration up to 200 suns. The short-circuit current density, open-circuit voltage, fill factor, and conversion efficiency were 510 mA/cm^2, 1.9 V, 70%, and 3.4%, respectively, under an air mass filter of 1.5G at 200 suns and room temperature.

1 General Since the band gap of GaInN ternary alloys covers a broad range from 0.65 to 3.43 eV [1], these alloys are suitable for solar cell applications. So far, we have succeeded in fabricating GaInN-based solar cells [2, 3]. By reducing the pit density in the GaInN active layer using freestanding *c*-plane GaN substrates and applying GaInN superlattice structures, the conversion efficiency of our nitride-based solar cells has reached 2.9% [4].

One of the disadvantages of compound semiconductor solar cells is their high cost compared with that of Si or organic solar cells. This problem can be solved by using a condenser lens system. In general, a low-cost material can be used for the condenser lens system. Thus, if the solar cells can operate at 200 suns, for example, the cost per chip would be reduced almost 200-fold. In addition, the performances of solar cells using Si, InP, and GaAs are improved by focusing the sunlight [5], although the improvement in performance is limited depending on a material, a junction quality, a cell configuration, and an electrode pattern. The maximum efficiencies of Si and InP solar cells have been reported to be obtained at 90–95 suns [5]. In contrast, the maximum efficiency of GaAs solar cells has been reported to be obtained at over 200 suns [5]. On the other hand, photovoltaic cell characteristics of GaInN-based solar cells have been investigated in concentration up to 30 suns only [6]. Details of nitride-based solar cell characteristics in concentration above 30 suns are still unknown.

In this study, we investigate the focusing properties of nitride-based solar cells up to 200 suns. We also discuss the dependence of the concentration ratio on the solar cell characteristics.

2 Sample structure Nitride-based solar cells were grown by metal organic vapour phase epitaxy. Trimethylindium, trimethylaluminium, trimethylgallium, triethylgallium, and ammonia were used as the source gases.

Figure 1 schematically shows the structure of the devices prepared in this study. We grew 50 pairs of unintentionally doped $Ga_{0.83}In_{0.17}N$ (3 nm)/$Ga_{0.93}In_{0.07}N$ (0.6 nm) superlattice layers as active layers on freestanding GaN substrates. Another 10 pairs of Si-doped $Ga_{0.90}In_{0.10}N$ (3 nm)/GaN (3 nm) superlattice layers were inserted beneath the active layers. The Si concentration in the 10 pairs of superlattice layers was 3×10^{18} cm^{-3}. The role of the additional Si-doped superlattice layers was to reduce the dislocation density and to obtain high-quality active layers with a higher InN mole fraction while maintaining a low

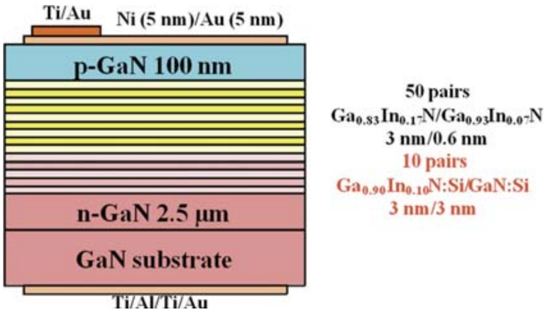

Figure 1 (online colour at: www.pss-rapid.com) Schematic view of sample structure of nitride-based solar cells.

series resistance (R_S) [3]. In addition, the numbers of superlattice layers are experimentally obtained. Dislocation density was reduced also by using the GaN substrate. A semitransparent Ni (5 nm)/Au (5 nm) ohmic contact and a Ti (30 nm)/Al (100 nm)/Ti (20 nm)/Au (150 nm) ohmic contact were formed on p-GaN (the surface of the device) and on n-GaN (the reverse side of the device) by electron beam evaporation, respectively. The devices had a vertical structure.

3 Experimental conditions The conversion efficiencies of the devices were measured using a solar simulator with an air mass (AM) filter of 1.5G (Asahi Spectra HAL-302). In this solar simulator, the infrared light was eliminated with a filter. Both the irradiation area and the photon density were changed to adjust the concentration of the light from 1 to 200 suns. The current density versus voltage characteristics of the devices were measured from 1 to 200 suns at room temperature (RT). No active temperature control of the devices was performed.

4 Experimental result Figure 2 shows the current density versus voltage characteristics of the nitride-based solar cells under the solar simulator (1 to 200 suns) at RT. We found that the open-circuit voltage (V_{OC}) of the nitride-based solar cells was increased with increasing concentration ratio and appeared to saturate above 50 suns. V_{OC} is plotted as a function of concentration ratio in Fig. 3.

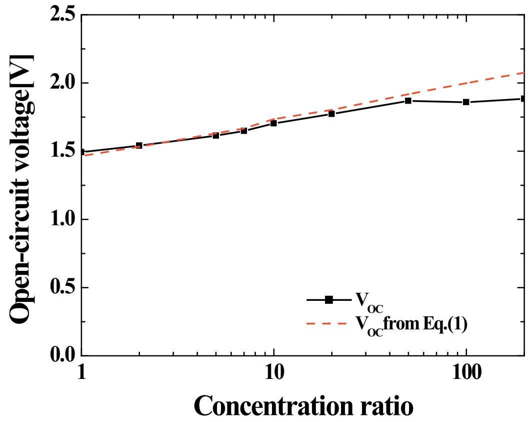

Figure 3 (online colour at: www.pss-rapid.com) V_{OC} as function of concentration ratio. The red dashed line was obtained using Eq. (1).

In general, V_{OC} can be expressed as [7]

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{J_{SC}\mathrm{CR}}{J_0} + 1\right), \quad (1)$$

where J_{SC}, CR, J_0, n, k, T, and q are the short-circuit current density, concentration ratio, reverse saturation current, n-value (a correction value of the diode equation), Boltzmann constant, temperature, and elementary charge, respectively. Equation (1) shows that V_{OC} should increase logarithmically with increasing light intensity. The dashed line in Fig. 3 almost matches the experimental results for 1 to 200 suns.

Figure 4 shows the fill factor (FF) and J_{SC} as functions of the concentration ratio. FF only changed slightly, from 72 to 70%, when the concentration was increased from 1 to 200 suns. In general, FF under concentrated sunlight is affected by the enhanced carrier recombination in the inter-

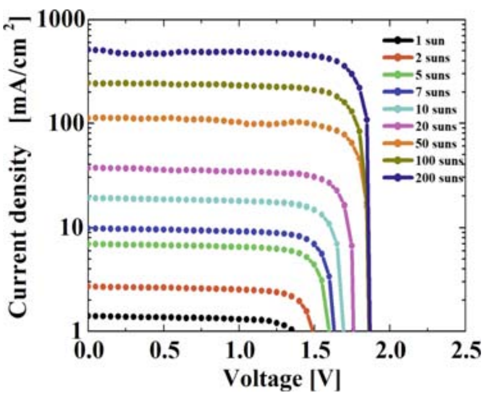

Figure 2 (online colour at: www.pss-rapid.com) Current density versus voltage characteristics of nitride-based solar cells under the solar simulator (AM of 1.5G, 1 to 200 suns) at RT.

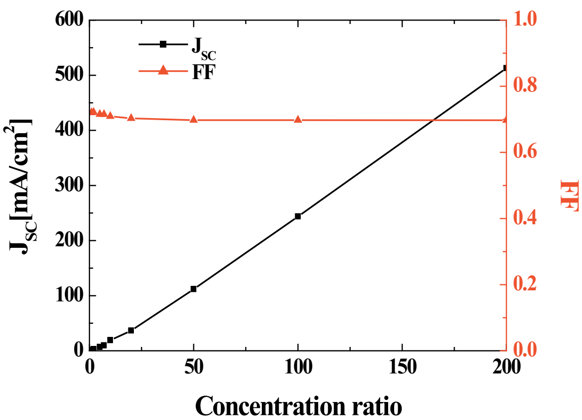

Figure 4 (online colour at: www.pss-rapid.com) J_{SC} and FF as functions of concentration ratio.

Table 1 Device performance characteristics of nitride-based solar cells under the solar simulator (AM of 1.5G, 1 and 200 suns).

	V_{OC} [V]	FF [%]	J_{SC} [mA/cm^2]	η [%]	R_S [Ω cm^2]	R_{SH} [Ω cm^2]
1 sun	1.5	72	1.4	1.5	110	12000
200 suns	1.9	70	520	3.4	0.53	18

face region due to the high carrier density under concentrated sunlight [7].

In Ref. [6], FF decreased from 64% to 57% when the concentration ratio increased from 1 to 30 suns, whereas for the samples used in this study, FF did not decrease significantly when the concentration ratio increased. Previous reports concluded that the significant decrease in FF with increasing concentration was due to the poor crystal quality of the sample [6]. Our samples with the GaN substrate and superlattice structure have high crystallinity [3]. The dislocation density of this sample was approximately 5×10^7 cm^{-2}. Therefore, a high FF was maintained up to 200 suns.

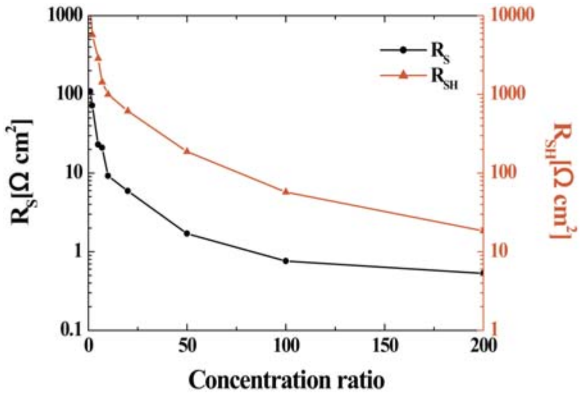

Figure 5 (online colour at: www.pss-rapid.com) R_S and R_{SH} as functions of concentration ratio (1 to 200 suns).

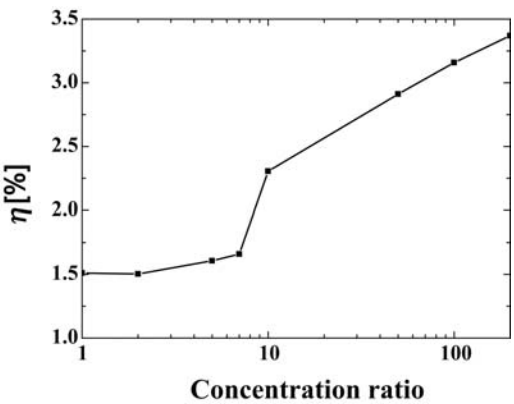

Figure 6 η as a function of concentration ratio.

J_{SC} was approximately proportional to the concentration ratio and increased 370-fold when the concentration ratio was increased from 1 to 200 suns (cf. Table 1).

Figure 5 shows the measured series resistance (R_S) and shunt resistance (R_{SH}) as functions of the concentration ratio. We calculated R_S and R_{SH} from the slope of the *I–V* curves [8]. R_S and R_{SH} rapidly decrease with increasing concentration ratio. Because the photo current of this solar cell is very small at low sun, R_S and R_{SH} appear larger. Thus, R_S and R_{SH} are rapidly reduced due to an increase in the photo current with high concentrated light illumination.

Figure 6 shows the power conversion efficiency η as a function of concentration ratio. We also summarize the values of J_{SC}, V_{OC}, R_S, R_{SH}, FF, and η at 1 and 200 suns exposures in Table 1. The efficiency increases from 1.5% to 3.4% when the concentration ratio increases from 1 to 200 suns. The efficiency is increased by a factor of 2.3, whereas V_{OC} is increased by a factor of 1.3. The higher rate of increase of the ratio in η than that in V_{OC} is due to the increase in J_{SC} with increasing concentration ratio. That is, the nitride-based solar cells operate effectively even at 200 suns. The conversion efficiency of 3.4% is the highest ever reported value for nitride solar cells.

5 Summary In conclusion, we investigated the nitride-based solar cells under concentrator conditions. V_{OC}, J_{SC}, and η monotonically increased from 1 to 200 suns, while FF decreased slightly. J_{SC}, V_{OC}, FF, and η were 510 mA/cm^2, 1.9 V, 70%, and 3.4%, respectively, at AM 1.5G and 200 suns at RT.

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