Droop improvement in high current range on PSS-LEDs

S. Tanaka, Y. Zhao, I. Koslow, C.-C. Pan, H.-T. Chen,
J. Sonoda, S.P. DenBaars and S. Nakamura

The droop property of blue GaN light emitting diodes (LEDs) has been improved by creating a 9 quantum well (QW) LED on a patterned sapphire substrate (PSS). The droop ratio was improved from 45.9 to 7.6%. At a wavelength of 447 nm, and with standard on-header packaging, the 9QW PSS-LED had an output power of 27.6 mW and an EQE of 49.7% at a current of 20 mA. The output power of the 9QW PSS-LED remains linear with increasing drive current, even up to relatively high current density, and the EQE is almost constant.

Introduction: Recently, the light emitting diode (LED) market has been spreading rapidly. Ten years ago, LED devices were only suitable for low brightness and low power applications, such as indicator lamps. At present, LEDs are applicable for high brightness and high power devices (e.g. illumination, car head-lamps) owing to improvements in the external quantum efficiency (EQE). However for commercialisation, LEDs still have a serious problem, known as 'droop'. Droop is a decay of the EQE at high driving current. Almost all InGaN LEDs exhibit a maximum EQE at a very low current density (typically less than $10\ A/cm^2$), unlike other III-V LEDs (e.g. (In,Al,Ga)As and (Al,Ga)InP). As current density is increased beyond $10\ A/cm^2$, a monotonic decay in EQE is observed even under short-pulse, low-duty-factor, constant temperature injection [1–3]. There are different proposed explanations for droop, such as current roll-over [4], carrier injection efficiency [5], polarisation fields [6], Auger recombination [7], junction heating [8], carrier delocalisation from quantum dots [9], exciton dissociation [10], and high plasma carrier temperatures (hot carriers) [11].

Owing to this droop, more LED chips are needed for high power devices, leading to higher prices. Car lamp assembly and illumination manufacturers cannot completely shift to using LED devices because of their high cost. If the droop problem is resolved, these manufacturers can shift to LED devices completely, and the LED market will spread greatly. In this Letter, we report the fabrication and characterisation of InGaN-based LEDs on patterned sapphire substrates (PSS) with improved droop.

Experiment: The PSS-LEDs were grown on n-GaN PSS templates by metal organic chemical vapour deposition (MOCVD). The device structure consisted of a 1 um Si-doped n-type GaN layer, an intermediate layer consisting of a 30 period GaN/InGaN (4 nm/4 nm) superlattice, and an active layer consisting of a six or nine period MQW stack with 20 nm GaN barriers and 4 nm InGaN quantum wells, ending in a 16 nm-thick GaN barrier. This was followed by a 10 nm undoped $Al_{015}Ga_{085}N$ electron blocking layer, and a 200 nm p-type GaN:Mg layer.

Results: A schematic of the device structure is shown in Fig. 1. The typical temperature range was ~1050°C for the n-type GaN layer, with a V/III ratio (the ratio of NH_3 mole fraction to trimethyl-gallium mole fraction) of 3000. The active region was grown at ~800°C with a V/III ratio of 12000. All MOCVD growth was performed at atmospheric pressure (AP).

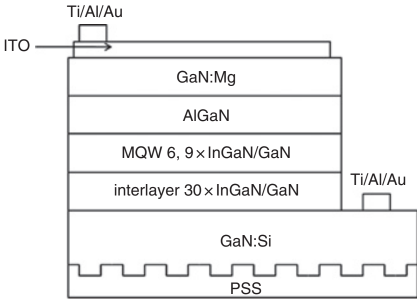

Fig. 1 *Schematic of device structure*

The PSS-LEDs were fabricated by the following process. LEDs with $526 \times 315\ um^2$ mesa sizes were formed by conventional photolithography, followed by chlorine-based inductively coupled plasma (ICP) etching techniques to form the mesa. An indium tin oxide (ITO) transparent p-contact was deposited by electron beam deposition. A Ti/Al/Au-based n-contact and a p-pad were then deposited on the n-GaN layer and the ITO transparent p-contact, respectively. The fabricated devices were packaged on a silver header encapsulated with a silicone dome. All measurements were carried out under pulsed operations at room temperature, and the optical emission power was measured in a calibrated integrating sphere. The device characterisation is limited to 70 mA because of a standard package.

The droop ratio was calculated by (1):

$$\text{Droop ratio} = (\text{Max EQE-EQE at } 60\,\text{mA})/\text{Max EQE} \times 100(\%) \tag{1}$$

Figs. 2 and 3 illustrate the emission power and EQE at increasing drive currents. Fig. 2 shows the results of the 6QW device, and Fig. 3 shows those of the 9QW device. At a current of 20 mA, forward voltage of 4.03 V and a wavelength of 447 nm, the 6QW PSS-LED has an output power of 28.1 mW and an EQE of 50.7%. However, the EQE of the 6QW device is greatly decreased by increasing drive currents. In contrast, the 9QW PSS-LED has an output power of 27.6 mW and an EQE of 49.7% at a current of 20 mA, forward voltage of 5.34 V and a wavelength of 447 nm. The output power of the 9QW PSS-LED remains linear with increasing drive current, even up to relatively high current density, and the EQE is almost constant, as can be seen in Fig. 3. This is a very promising result.

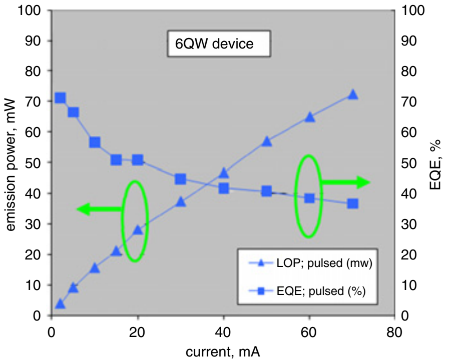

Fig. 2 *Emission power and EQE characteristics of 6QW device at pulsed drive currents from 2 to 70 mA*

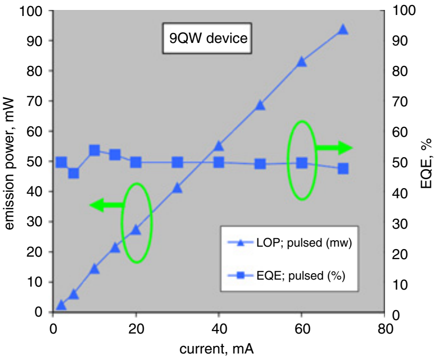

Fig. 3 *Emission power and EQE characteristics of 9QW device at pulsed drive currents from 2 to 70 mA*

We believe that this improvement is owing to reduced carrier density in the device with a higher number of QWs. A lower carrier concentration would lead to reduced Auger recombination and lower carrier overflow from localised states and the QWs. As a result, the EQE remains constant with increasing drive current. The droop characteristics of the 6QW and 9QW devices are shown in Table 1. The droop ratio of the 6QW device is 45.9%. In contrast, that of the 9QW device is only 7.6%, which is suitable for a commercially available product.

Increasing the number of QWs should be an effective method for improving droop. In the future, we will try to examine active regions with higher numbers of QWs, or increased well thickness, which will result in lower carrier density in the active region, thus improving the droop. In this Letter, we believe the main reasons for droop is Auger recombination, and carrier overflow. However, lower carrier concentration could improve droop for several reasons, such as dislocations [12], Auger recombination [13], carrier injection, transport, and leakage processes [14, 15].

Table 1: Droop characteristic of 6QW and 9QW device

	EQE (%)			Vf (V)	
Device	Max	20 mA	60 mA	20 mA	Droop ratio (%)
6QW	71.1	50.7	38.4	4.03	45.9
9QW	53.6	49.7	49.5	5.34	7.6

Conclusion: We have improved the droop property of blue GaN LEDs by creating a 9QW PSS-LED. The droop ratio was improved from 45.9 to 7.6% by increasing the number of QWs from 6 to 9. At a wavelength of 447 nm, the 9QW PSS-LED had an output power of 27.6 mW and EQE of 49.7% at a current of 20 mA, with standard on-header packaging. In the 9QW PSS-LED, the output power remains linear with increasing drive current, even up to relatively high current density, and the EQE is almost constant.

24 November 2010
doi: 10.1049/el.2010.3306
One or more of the Figures in this Letter are available in colour online.

S. Tanaka, I. Koslow, C.-C. Pan, H.-T. Chen, J. Sonoda, S.P. DenBaars and S. Nakamura (*Materials department, University of California, Santa Barbara CA 93106, USA*)

E-mail: shinichi_tanaka@engineering.ucsb.edu

Y. Zhao (*Electrical and Computer Engineering Department, University of California, Santa Barbara, CA 93106, USA*)

S.P. DenBaars and S. Nakamura: Also with the Electrical and Computer Engineering Department, University of California, Santa Barbara, USA

References

1 Krames, M.R., Shchekin, O.B., Mueller-Mach, R., Mueller, G.O., Zhou, L., Harbers, G., and Craford, M.G.: ‘High-brightness AlGaInN light-emitting diodes’, *Proc. SPIE*, 2000, **3938**, pp. 2–12
2 Kim, A.Y., Goetz, W., Steigerwald, D.A., Wierer, J.J., Gardner, N.F., Sun, J., Stockman, S.A., Martin, P.S., Krames, M.R., Kern, R.S., and Steranka, F.M.: ‘Performance of high-power AlInGaN light emitting diodes’, *Phys. Status Solidi A*, 2001, **188**, pp. 15–21
3 Nakamura, S., and Fosol, G.: ‘The blue laser diodes’ (Springer, Berlin, 1998)
4 Monemar, B., and Sernelius, B.E.: ‘Defect related issues in the “current roll-off” in InGaN based light emitting diodes’, *Appl. Phys. Lett.*, 2007, **91**, p. 181103
5 Rozhansky, I.V., and Zakheim, D.A.: ‘Analysis of the causes of the decrease in the electroluminescence efficiency of AlGaInN light-emitting-diode heterostructures at high pumping density’, *Semiconductors*, 2006, **40**, pp. 839–845
6 Kim, M.H., Schubert, M.F., Dai, Q., Kim, J.K., Schubert, E.F., Piprek, J., and Park, Y.: ‘Origin of efficiency droop in GaN-based light-emitting diodes’, *Appl. Phys. Lett.*, 2007, **91**, p. 183507
7 Shen, Y.C., Mueller, G.O., Watanabe, S., Gardner, N.F., Munkholm, A., and Krames, M.R.: ‘Auger recombination in InGaN measured by photoluminescence’, *Appl. Phys. Lett.*, 2007, **91**, p. 141101
8 Efremov, A.A., Bochkareva, N.I., Gorbunov, R.I., Larinovich, D.A., Rebane, Yu.T., Tarkhin, D.V., and Shreter, Yu.G.: ‘Effect of the joule heating on the quantum efficiency and choice of thermal conditions for high-power blue InGaN/GaN LEDs’, *Semiconductors*, 2006, **40**, pp. 605–610
9 Okamoto, K., Kaneta, A., Kawakami, Y., Fujita, S., Choi, J., Terazima, M., and Mukai, T.: ‘Confocal microphotoluminescence of InGaN-based light emitting diodes’, *J. Appl. Phys.*, 2005, **98**, p. 064503
10 Chichibu, S.F., Sota, T., Wada, K., and Nakamura, S.: ‘Exciton localization in InGaN quantum well devices’, *J. Vac. Sci. Technol. B*, 1998, **16**, pp. 2204–2215
11 Vasconcellos, A.R., Luzzi, R., Rodrigues, C.G., and Freire, V.N.: ‘Hot-phonon bottleneck in the photoinjected plasma in GaN’, *Appl. Phys. Lett.*, 2003, **82**, p. 2455
12 Schubert, M.F., Chajed, S., Kim, J.K., Schubert, E.F., Koleske, D.D., Crawford, M.H., Lee, S.R., Fischer, A.J., Thaler, G., and Nanas, M.A.: ‘Effect of dislocation density on efficiency droop in GaInN/GaN light-emitting diodes’, *Appl.Phys. Lett.*, 2007, **91**, p. 231114
13 Shen, Y.C., Mueller, G.O., Watanabe, S., Gardner, N.F., Munkholm, A., and Krames, M.R.: ‘Auger recombination in InGaN measured by photoluminescence’, *Appl. Phys. Lett.*, 2007, **91**, p. 141101
14 Beattie, A.R., and Landsberg, P.T.: ‘Auger effect in semiconductors’, *Proc. R. Soc. Lond. A*, 1958, **249**, p. 16
15 Hader, J., Moloney, J.V., Pasenow, B., Koch, S.W., Sabathil, M., Linder, N., and Lutgen, S.: ‘On the importance of radiative and Auger losses in GaN-based quantum wells’, *Appl. Phys. Lett.*, 2008, **92**, p. 261103