High optical power and low-efficiency droop blue light-emitting diodes using compositionally step-graded InGaN barrier

Chih-Chien Pan, Qimin Yan, Houqiang Fu, Yuji Zhao✉, Yuh-Renn Wu, Chris Van de Walle, Shuji Nakamura and Steven P. DenBaars

A compositionally step-graded (CSG) InGaN barrier is designed for the active region of *c*-plane blue light-emitting diodes (LEDs). High external quantum efficiencies of 45, 42, 39 and 36% are achieved at current densities of 100, 200, 300 and 400 A/cm^2, respectively. Compared with GaN barrier devices, LEDs with CSG InGaN barriers showed higher power, lower operating voltage and smaller wavelength blueshift, compared with GaN barrier LEDs. Owing to the low-voltage performance, higher wall-plug efficiency can be achieved for blue LEDs with CSG InGaN barriers.

Introduction: GaN-based light-emitting diodes (LEDs) have attracted considerable attention owing to their wide range of applications including the fields of traffic signals, full-colour displays and general lighting. The efficiency of current *c*-plane GaN LEDs, however, is severely limited by a phenomenon called 'efficiency droop', which refers to the reduction in external quantum efficiency (EQE) of LEDs at high current densities (e.g. $J > 100$ A/cm^2). The physical origin of efficiency droop is still being debated and many theories have been proposed as the possible explanation, including Auger recombination [1, 2], electron leakage [3], carrier injection efficiency [4], polarisation fields [5] and band filling of localised states [6].

On the other hand, several methods have been proposed to mitigate the droop effect and achieve high LED EQE values at high current densities [7–17]. For example, InGaN or linearly graded InGaN barriers with high indium composition (~5–10%) were successfully applied into the LED structures to reduce the polarisation-induced quantum confine stark effect (QCSE) and achieve better carrier injections and more uniform hole distributions in the active region [18]. However, the reduction in the relative potential height between quantum wells (QWs) and quantum barriers (QBs) caused by the high-indium-content InGaN barriers reduces the carrier confinement in the active region [19]. In addition, a lower growth temperature is required for the growth of high-indium-content InGaN QBs, which causes material degradation and defect generation.

In this Letter, we report on a high-efficiency blue LED using a novel compositionally step-graded (CSG) InGaN barrier design. LEDs with CSG InGaN QBs showed higher carrier distribution uniformity and less conduction band offset compared with LEDs with GaN QBs. At low current densities, CSG InGaN barrier LEDs showed comparable performance with conventional GaN barrier LEDs. At high current densities, extremely low droop ratios of 4, 10, 17 and 22% were observed for CSG InGaN barrier LEDs at current densities of 100, 200, 300 and 400 A/cm^2, respectively.

Blue CSG barrier LED structures were grown on a *c*-plane patterned sapphire substrate via the conventional metal-organic chemical vapour deposition system. The device structure consists of a 3 µm-thick undoped GaN layer, a 6 µm-thick n-type GaN with an electron concentration of 7×10^{18} cm^{-3}, followed by 30-pair/GaN (3/3 nm) superlattices. Subsequently, a 9-period InGaN/CSG InGaN MQW active region was grown, consisting of 3.0 nm-thick QWs and 18 nm-thick QBs composed of six 3 nm-thick GaN or InGaN layers with indium compositions of 0, 0.3, 0.6, 0.9, 1.2 and 1.5%, respectively. The indium compositions were estimated by X-ray diffraction (XRD) analysis. On top of the active region was a 3 nm-thick electron blocking layer and a 200 nm-thick p-type GaN capping layer with an Mg concentration of 1×10^{19} cm^{-3}. For comparison, blue GaN barrier LEDs and blue InGaN barrier LEDs with identical structure (except for the active region) were also prepared. Quick test electroluminescence (QT-EL) was performed and the light output powers (LOPs) were measured by a detector underneath the sample. Indium dots were deposited on the p-GaN and n-GaN layers of the samples as p- and n-contacts.

Fig. 1 demonstrates the QT-EL power against various currents for LEDs with GaN barriers, CSG InGaN barriers and InGaN barriers. The QT-EL power on the CSG InGaN barrier samples is slightly lower but very close to that of the conventional GaN barrier LEDs, which is much higher than that of the LEDs with high-indium-content InGaN barriers. The performance improvement in CSG InGaN barrier LEDs over the InGaN barrier LEDs is possibly due to the increased barrier growth temperature (~850°C), which resulted in a better crystal quality in the active region. This is also consistent with the photoluminescence (PL) measurement results (data not shown here), in which the CSG InGaN barrier LEDs showed a much higher PL intensity with InGaN barrier LEDs. Furthermore, the performance of InGaN barrier LEDs may also suffer from insufficient carrier confinement due to reduced QB height.

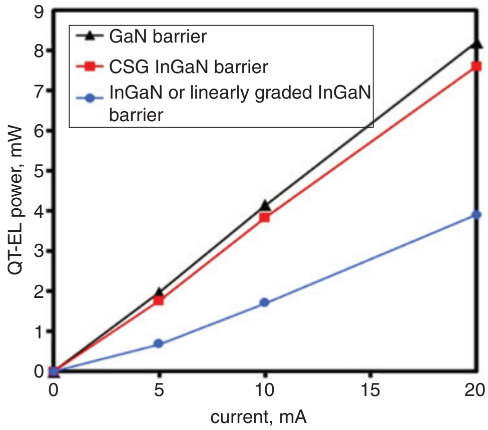

Fig. 1 *QT-EL power for LED with GaN, InGaN and CSG InGaN barriers*

The LED fabrication process is described in our previous work [16]. Fig. 2*a* shows the schematic views of the CSG barrier LED structures, where the changes in conduction band (Ec) is also schematically illustrated. Fig. 2*b* shows a scanning transmission electron microscope (STEM) image of the CSG barrier LED sample taken along the projection of the *c*-axis, indicating a high crystal quality of the devices. GaN barriers LEDs with the same structures were also fabricated and characterised as reference samples. For the characterisation of LEDs, encapsulated devices were measured under DC and pulsed conditions at room temperature.

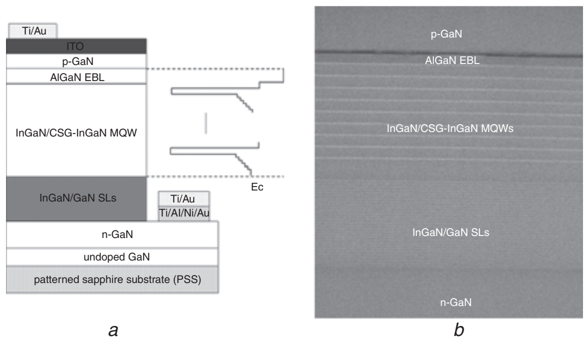

Fig. 2 *Structure of grown devices*

a Schematic structure of LED with CSG InGaN barrier
b STEM image of LED with CSG InGaN barrier

Fig. 3*a* shows the pulsed LOPs and EQEs of GaN barrier LEDs and CSG InGaN barrier LEDs at various current densities. At current densities of 100, 200, 300 and 400 A/cm^2, the CSG InGaN LEDs showed LOPs of 127, 240, 332 and 416 mW and EQEs of 45, 42, 39 and 36%, respectively, which are higher than those of the conventional GaN barriers LEDs at the same current densities. Furthermore, the CSG InGaN LEDs also showed lower-efficiency droop ratios of only 4, 10, 17 and 22% at current densities of 100, 200, 300 and 400 A/cm^2, respectively, which are smaller than those of GaN barrier LEDs (9, 16, 24 and 29%) at the same current densities. Fig. 3*b* shows the current–voltage (*I–V*) characteristics and wall-plug efficiency (WPE) of GaN barrier LEDs and CSG InGaN barrier LEDs under DC measurements. Again, the CSG InGaN LEDs showed lower forward voltages and, more importantly, higher WPEs (30 and 25%) at a current density of 100 and 200 A/cm^2, respectively, which are higher than the WPE (25 and 20.0%) of GaN barrier LEDs.

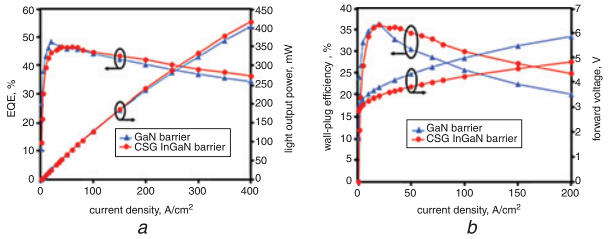

Fig. 3 *Experimental results of EQE and WPE*

a Pulsed LOP and EQE
b DC forward voltage and WPE against current density for LEDs with GaN and CSG InGaN barriers

Fig. 4*a* shows the pulsed peak wavelength and full width at half maximum (FWHM) against various current densities for GaN barrier LEDs and CSG InGaN barrier LEDs. With increasing current density from 1 to 400 A/cm^2, the CSG InGaN barrier LEDs showed a smaller wavelength shift of 19.5 nm compared with that of the GaN barrier LEDs (24.5 nm). The smaller blueshift of the CSG InGaN barrier samples could be attributed to the reduction in the piezoelectric-polarisation-related electric field and QCSE in the InGaN QW with the CSG InGaN QB structure. On the other hand, the CSG InGaN barrier LEDs also showed a smaller FWHM than that of GaN barrier LEDs, indicating an improved crystal quality in the active region of the CSG InGaN barrier LEDs.

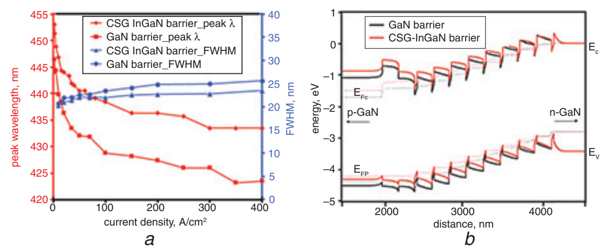

Fig. 4 *Experimental results on spectrum and simulation results on energy band diagram*

a Peak wavelength and FWHM for LEDs with GaN and CSG InGaN barriers at different current densities
b Simulated band diagram for LEDs with GaN and CSG InGaN barriers

To investigate the electronic properties of LEDs with different QBs, band diagram simulations were performed using a semi-empirical simulation software based on a drift-diffusion model considering the strain, spontaneous and piezoelectric polarization fields, doping and carrier mobility. Shockley-Read-Hall, radiative and Auger recombination coefficients of 4×10^7 s^{-1}, 2×10^{-11} cm^3/s and 4×10^{-31} cm^6/s were used in the simulations. Fig. 4*b* shows the energy band diagram of the GaN barrier LED and the CSG InGaN barrier LED at a current density of 100 A/cm^2. It is clear that the conduction band offsets for the CSG InGaN barrier LED is much smaller than those of the GaN barrier LED. This smaller offset can minimise the driving force for the leakage of electrons out of the active region, resulting in reduction in efficiency droop at high current densities. Furthermore, a more uniform carrier distribution and reduced carrier concentration were also observed during the simulation (data not shown here) possibly due to the reduced QCSE, which may also contribute to the improved device performance (i.e. low droop and small wavelength shift) for CSG InGaN barrier LEDs.

Conclusion: By applying CSG InGaN barriers in our multiple QW LED devices, high EQEs of 45% (WPE = 30%) and 42% (WPE = 25%) with low-efficiency droop ratios of only 3.9 and 9.5% can be achieved at current densities of 100 and 200 A/cm^2, respectively. The high-efficiency performance can be attributed to the mitigated electron overflows and Auger recombination at high current densities by reducing the conduction band offset and carrier concentrations in the QWs. Moreover, a small blue shift and FWHM were observed in CSG InGaN barrier LEDs due to less QCSE and better crystal quality in the active region compared with conventional GaN barrier LEDs.

Acknowledgments: The authors acknowledge the Solid-State Lighting and Energy Center (SSLEC) at UCSB.

Submitted: *12 May 2015* E-first: *9 July 2015*
doi: 10.1049/el.2015.1647
One or more of the Figures in this Letter are available in colour online.

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