Performance of high-power III-nitride light emitting diodes

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The performance of III-nitride based high-power light emitting diodes (LEDs) is reviewed. Direct color high-power LEDs with 1 × 1 mm² chip size in commercial Luxeon® Rebel packages are shown to exhibit external quantum efficiencies at a drive current of 350 mA ranging from ~60% at a peak wavelength of ~420 nm to ~27% at ~525 nm. The short wavelength blue LED emits ~615 mW at 350 mA and ~2 W at 1.5 A. The green LED emits ~110 lm at 350 mA and ~270 lm at 1.5 A. Phosphor-conversion white LEDs (1 × 1 mm² chip size) are demonstrated that emit ~126 lm of white light when driven at 350 mA and 381 lm when driven at 1.5 A (Correlated Color Temperature, CCT ~ 4700 K). In a similar LED that employs a double heterostructure (DH) instead of a multi-quantum well (MQW) active region, the luminous flux increases to 435 lm (CCT ~ 5000 K) at 1.5 A drive current. Also discussed are experimental techniques that enable the separation of internal quantum efficiency and extraction efficiency. One technique derives the internal quantum efficiency from temperature and excitation-dependent photoluminescence measurements. A second technique relies on variable-temperature electroluminescence measurements and enables the estimation of the extraction efficiency. Both techniques are shown to yield consistent results and indicate that the internal quantum efficiency of short wavelength blue (λ ~ 420 nm) high-power LEDs is as high as 71% even at a drive current of 350 mA.

1 Introduction

High-power light emitting diodes (high-power LEDs) are now used in a wide range of applications requiring high flux levels (input power typically >0.5 W). Among the most prominent applications are traffic signals, automotive forward and tail/stop lights, and large LCD panel backlights. In addition, high-power LEDs based on the III-nitride material system using phosphor-conversion (PC) to generate white light (blue LED + YAG phosphor) have now reached performance levels that rival and in many cases exceed the capabilities of existing light sources utilized for illumination. For example, cool-white PC-LEDs with luminous efficacy approaching the 100 lm/W regime (350 mA) are now available and have been reported in the literature [1]. As a consequence, solid state lighting for general illumination is becoming a reality as the efficacy of LED light sources surpasses the efficacy of high quality fluorescent lamps (~90 lm/W).

The performance of high-power LEDs is typically reported in terms of the External Quantum Efficiency (EQE), the Power Conversion Efficiency (PCE) [2] or, in the case of visible-spectrum LEDs, the luminous efficacy (\(\eta_L\)). These efficiencies can be related to the fundamental LED performance parameters Internal Quantum Efficiency (IQE), the EXtraction Efficiency (EXE), the peak emission wavelength (\(\lambda_p\)) and the forward voltage (\(V_f\)) via the following equations:

\[
EQE = IQE \times EXE,
\]

\[
PCE = (EQE \times 1240 \text{ V nm})/(V_f \times \lambda_p),
\]

\[
\eta_L = PCE \times V_f,
\]

where \(V_f\) is the wavelength-dependent photo-responsivity of the human eye expressed in lumen per optical Watt (lm/W opt). PCE and \(\eta_L\) can also be linked to the emitted photon flux using the following equations:

\[
PCE = P_{opt}/(V_f \times I_d),
\]

\[
\eta_L = P_{opt}/(V_f \times I_d),
\]
where \( \Phi_{\text{opt}} \) is the radiometric photon flux (light output), \( \Phi_f \) is the photometric photon flux (luminous flux), and \( I_f \) is the forward current.

In general, EQE, PCE, and \( \eta_c \) can be directly measured, while only estimates of IQE can be determined based on, for example, variable-temperature photoluminescence (PL) measurements [3]. EXE is often derived from optical modeling [4].

In this study, we will discuss the performance of state-of-the-art direct color (violet, blue, and green) and phosphor-converted white high-power LEDs. High-power LEDs with multi-quantum well (MQW) and double heterostructure (DH) light emitting regions are considered. Further, we will illustrate measurement techniques that reliably allow the separation of IQE and EXE to accurately represent the current performance status of high-power LEDs.

2 Experimental

2.1 Epitaxial growth All devices described in this article were grown by metal-organic chemical vapor deposition (MOCVD) on sapphire (0001) substrates. The growth method utilized was the conventional 2-step process [5], where a low temperature nucleation layer is deposited directly onto the sapphire wafer followed by high temperature GaN(0001) growth. The resulting threading dislocation density in the GaN ranges from \( 5 \times 10^8 \) cm\(^{-2} \) to \( 3 \times 10^8 \) cm\(^{-2} \). In order to achieve good current spreading, the n-type layers are highly doped with Si. The light emitting region consists either of a traditional InGaN/GaN MQW region where the InGaN layers have ~25–30 Å thick or a single thicker (>90 Å) InGaN layer (DH structure) [6]. The latter structure is designed for high current operation where the thicker InGaN layer distributes the carriers and thus reduces Auger recombination which has been identified as the dominant non-radiative recombination mechanism at high drive current densities [7]. The thicknesses and indium composition of the active regions were determined by X-ray diffraction. The LED wavelength was selected by adjusting the indium content in the InGaN layers. The light emitting region is followed by a Mg-doped AlGaN layer that acts as an electron blocker. The structure was capped by GaN p-type layers. The thickness of the device layers above the light emitting layer was tuned to maximize EXE (see below).

2.2 High-power LED chip design Along with advances in epitaxial growth, chip design improvements in light extraction and power delivery are key to the advances in power and efficiency of high-power III-nitride based LEDs. The features and challenges of different chip designs have been reviewed in detail recently by Krames et al. [8].

The LEDs reported in this study employ a flip chip (FC) design [9], instead of a conventional epi-up design. The high spreading resistance of p-type GaN necessitates large area p-contacts. The FC design enables a reflective p-contact that can be made as thick as necessary for uniform current spreading, without the trade-off in absorption versus current spreading seen in conventional designs employing a semi-transparent p-contact. Bonding both p-contacts and n-contacts to a submount eliminates the obstruction of a wire bond to the chip, with several benefits: no optical obstruction, a lower profile for the lens, and the opportunity to deposit or bond phosphors and optics to the chip. Placing the p-contact down also eliminates the bulk of the nitride layer and the sapphire substrate from the heat conduction path for improved high-power performance. In FC LEDs, EXE is a strong function of the distance between the light emitting region and the p-contact, which acts as a highly reflective mirror. The p-contact mirror forms a half-cavity with respect to the location of light generation that must be tuned appropriately to maximize the number of photons emitted into the extraction cone [4].

The EXE of sapphire-based flip chip LEDs can further be increased by removal of the substrate. When the sapphire is present, a fraction of the generated light is wave-guided in the device layers with low probability of leaving the chip. Thin film flip chip (TFFC) LEDs eliminate this problem [10]. The light extraction surface is now available for roughening which destroys the waveguide and significantly increases EXE. While FC LEDs have EXE in the range of ~60%, TFFC LEDs have EXE of ~80% [8]. All performance data shown in this paper are based on the TFFC design.

The chip layout (Fig. 1) employs an array of n-contact vias fabricated through a continuous p-contact area, with an interlayer dielectric that passivates the mesa walls and sits between overlapping metal layers to enable current distribution [11]. The chip and submount are thermosonically bonded via Au–Au pads to enable a robust, Pb-free interconnect with superior thermal conductivity and reliability. The separation of distribution and contact functions in the n-metallization enables a dramatic reduction in n-contact area, resulting in a significant increase in the light-emitting area (junction area) of the chip over previous generation designs with inter-digitated n-contact fingers [9]. The resulting lower current density leads to higher EQE, due to

Figure 1 (online colour at: www.pss-a.com) Lit high-power LED chip used in state-of-the-art LUXEON K2 or LUXEON Rebel LEDs. Its junction area is about 54% larger than that of previous chips with interdigitated n-contact fingers.

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the increase in EQE with decreasing current density of InGaN devices.

2.3 High-power LED packages The first high-power LED package, LUXEON, provides excellent heat dissipation and mechanical robustness for high-power operation. First released in 1998, LUXEON has become a standard for solid-state lighting and its long-term reliability has been independently benchmarked. Typically operated at 350 mA, LUXEON can also be driven at 700 mA.

The recently released LUXEON Rebel package provides even greater power handling and robustness via materials and component bonding improvements. LUXEON K2 can operate at a dc drive current of up to 1.5 A and allow junction temperatures of 150 °C (PC-white) or 185 °C (direct colors), providing capability for unprecedented levels of light output from a single light-emitter package.

The latest LUXEON Rebel package also improves upon the power handling of the benchmark LUXEON, but focuses on reducing size and cost. LUXEON Rebel has a footprint of only 14 mm². A magnified image of a LUXEON Rebel high-power LED is shown in Fig. 2. Also shown in Fig. 2 is the actual size of a LUXEON Rebel LED. In high total flux applications, the smaller size allows proportionately greater packing of emitters into a given area. In color mixing applications, the reduced emitter spacing reduces the path length for full color mixing to less than half that of competing power packages. In general, the design of optical systems can be simpler and more efficient with a smaller emitter size. Also, updated bonding technology in the chip and package make both LUXEON Rebel and LUXEON K2 completely Pb-free devices.

2.4 Determination of IQE and EXE While EQE, PCE, and \( \eta_1 \) can be directly measured (e.g., in an integrating sphere with calibrated detector), IQE (and, therefore, EXE) can only be estimated. The uncertainty of the estimate can significantly be reduced when multiple independent experimental techniques are employed and the experimental data are compared to results from ray-trace modeling of EXE [8]. We have used two experimental approaches to determine IQE and EXE. One is based on variable-excitation and variable-temperature photo-luminescence (PL) [3]. A 405 nm CW laser with maximum power of 175 mW was used to selectively excite the InGaN light emitting layer(s) in the LED structure. The laser power was varied to measure PL efficiency as a function of excitation density. The maximum excitation power density was estimated to be 10 kW/cm² on the sample surface. The sample was mounted on a cold finger in a cryostat chamber to vary the temperature between 4 K and 300 K. The luminescence spectrum from the LED was collected by a monochromator and a CCD detector. As the sample temperature is decreased, the non-radiative lifetime increases and the peak IQE can be considered close to 100% at 4 K. At each temperature step, the PL response was measured as a function of excitation density. By normalizing the PL efficiency measured at room-temperature to the maximum PL efficiency measured at 4 K, IQE as a function of excitation density can be estimated. As a key performance parameter, the peak IQE value is recorded.

A second approach employs variable-temperature electroluminescence (EL). A packaged LED lamp is mounted on a cold finger in the cryostat-chamber and the EL response is recorded by a Si photo detector as a function of \( I_L \) and at multiple temperatures. The photo-detector response was calibrated resulting in a family of EQE (\( I_L \)) curves. As the temperature decreases, EQE increases due to the increase of IQE. Below a certain temperature EQE will no longer increase (EQE\textsuperscript{max}) and IQE can be considered close to 100% in these cases enabling the determination of at least a lower bound of EXE.

Results from both approaches were compared and generally found to be in good agreement. All LED performance parameters were measured under quasi-CW conditions (pulse length = 20 ms) without active cooling in integrating spheres with NIST-traceable calibration.

3 Results and discussion

3.1 Direct-color high-power LEDs The performance of state-of-the-art direct color, high-power LEDs is summarized in Fig. 3. EQE measured at \( I_L = 350 \) mA is shown as a function of peak wavelength. Results are shown for LEDs based on III-nitrides (InGaN light emitting region) and III-phosphides (InGaAlP light emitting layers). High-power III-P based LEDs complement III-N devices to span the entire visible spectral range [12] and are included in Fig. 3 for completeness. The EQE of III-N based high-power LEDs peaks in the wavelength range between 410 and 430 nm. At shorter and longer wavelength, EQE decreases. For near UV LEDs (365 nm to ~410 nm) the origin of the efficiency decrease has been identified as insufficient confinement of carriers in the shallow InGaN QWs and insufficient screening of carriers from non-radiative processes.
Figure 3 (online colour at: www.pss-a.com) External quantum efficiency vs. peak wavelength for high-power LEDs based on the III-nitride (InGaN light emitting layer) and III-phosphide (InGaNP light emitting layer) material systems. All data shown in Fig. 3 are based on high-power LEDs produced by Philips Lumileds except the data point at 365 nm, which is reported in Ref. [14].

PCE is more relevant than EQE as a performance metric in LED applications, since it represents the efficiency of converting electrical power into optical power (Eq. (4)). Recent performance in PCE and \( \eta_L \) versus drive current is shown in Fig. 4 for violet, blue and green LUXEON Rebel high-power LEDs using TFFC. In Fig. 4a, PCE is shown as a function of peak wavelength. The violet (\( \lambda_p \sim 420 \) nm) device peaks at PCE = 61% and reaches 50% at 350 mA. PCE of the blue (\( \lambda_p \sim 447 \) nm) device peaks at PCE = 58% and reaches 44% at 350 mA, and PCE of the green (\( \lambda_p \sim 522 \) nm) device peaks at PCE = 37% and reaches 21% at 350 mA. The optical power output (\( P_{\text{opt}} \)) of these devices was measured to be 614 mW, 480 mW, and 221 mW at 350 mA, respectively, and 2044 mW, 1524 mW, and 597 mW at 1.5 A, respectively.

Figure 4b shows the performance of the same green LED in photometric units, \( \eta_L \) and \( \Phi_L \), as a function of drive current. Again, \( \eta_L \) represents the conversion efficiency of electrical power into perceived light flux by the human eye (Eq. (5)). \( \eta_L \) of the green (\( \lambda_p \sim 522 \) nm) device peaks at 212 lm/W and reaches 106 lm/W at 350 mA. At 350 mA and 1.5 A, \( \Phi_L \) is 110 lm and 271 lm, respectively.

3.2 DH high-power LEDs While ubiquitous to III-nitride LEDs, the peak and then drop in efficiency with increasing drive current is not necessarily an inherent property of III-nitride LEDs but rather a consequence of the specific MQW light emitting layer design. It has been shown [7] that the Auger recombination coefficient in InGaN is sufficiently high so that this mechanism dominates non-radiative recombination at the carrier densities present in MQW active regions at high drive currents. As a consequence, the efficiency reduces as drive currents >100 mA in 1 \times 1 \text{mm}^2 InGaN MQW high-power LEDs (Fig. 4). A straightforward way to reduce the impact of Auger recombination is to lower the carrier density which can be accomplished by thicker light emitting layers. High-power LEDs employing a DH epitaxial design have decreased the slope of efficiency versus drive current, while maintaining high-performance on an absolute scale [6].
Figure 5 summarizes performance of high-power LEDs with MQW and DH light emitting region. The specific data shown in Fig. 5 are for laboratory devices that employ additional light extraction technology and increase EXE of a LUXEON Rebel LED (with TFFC) by ~5%.

As illustrated in Fig. 5, the blue (λ_p ~ 442 nm) DH device surpasses the blue (λ_p ~ 447 nm) MQW device for drive currents greater than 350 mA, retaining PCE = 38% at 1 A (MQW: 35%) and 27% at 2.5 A (MQW: 23%). The emitted photon flux is 1.36 W at 1 A (MQW: 1.20 W) and 2.64 W at 2.5 A (MQW: 2.19 W).

3.3 PC-white high-power LEDs While there are multiple ways to generate white light from III-nitride based high-power LEDs (see for example Ref. [15]) combining a blue LED with a yellow (cool white, Correlated Color Temperature, CCT ~ 5000 K) or yellow and red (warm white, CCT ~ 3000 K) phosphor provides for a relatively high efficacy path to white light generation. Performance data for 1 × 1 mm² size PC-white high-power LEDs are shown in Fig. 6.

Figure 6 includes luminous efficacy and luminous flux data for two high-power LEDs. One LED contains a DH and the other LED contains a MQW light-emitting layer. The DH phosphor-converted white (CCT ~ 5100 K) device operates at 90 lm/W at 1 A and 62 lm/W at 2.5 A. The corresponding fluxes are 318 lm and 608 lm, respectively. When operated at 2 A (7.6 W electrical input power), this device produces 531 lm of light exceeding the flux delivered by a 40 W incandescent bulb.

The luminous efficacy of the MQW LED (CCT ~ 4700 K) peaks at 154 lm/W and reaches 116 lm/W at 350 mA emitting a flux of 126 lm. At 1 A this device produces 290 lm with a luminous efficacy of 85 lm/W.

3.4 IQE and EXE analysis Figure 7 summarizes results from the PL-based IQE determination. Shown are measured PL efficiency as a function of excitation laser power at 4 K and 300 K for a blue InGaN/GaN MQW LED with λ_p = 450 nm. The temperature dependency of the PL efficiency at maximum excitation is shown in the inset of Fig. 7.
At 300 K, the PL efficiency increases as the excitation density increases due to the increase of the radiative recombination rate relative to the Shockley–Read–Hall (SRH) non-radiative recombination rate. It reaches close to a maximum efficiency at maximum excitation in the example shown in Fig. 7. The efficiency typically drops as the excitation is further increased (not shown in Fig. 7). As discussed earlier, Auger non-radiative recombination is believed to be the dominant cause of the efficiency reduction [7]. As the temperature decreases, the PL efficiency peaks at lower excitation density than at 300 K because the SRH non-radiative recombination is suppressed at low temperature. The efficiency decreases even at 4 K at high excitation likely due to the combined effect of Auger non-radiative recombination and sample heating due to the CW excitation. By assuming the peak efficiency to be 100% at 4 K, IQE at 300 K can be estimated. For the example shown in Fig. 7, peak IQE at 300 K is estimated to be 63%. In this analysis, the photon recycling effect was assumed to be negligible.

In order to verify the IQE value estimated from the PL measurement described above, LUXEON Rebel with TFFC LEDs were fabricated from this wafer and characterized by variable-temperature EL measurements. At room-temperature, EQE was measured to be 57.4% at 35 mA (peak EQE) and 49.4% at 350 mA. As the temperature decreased, EQE increased and reached a maximum of ~85% at 15 K. Because IQE at this temperature can be considered to be close to 100%, EXE is equal or higher than EQE. Therefore, we estimated EXE of the LUXEON Rebel with TFFC LED to be ~85%. This value is slightly higher than but very close to what was determined from optical modeling for similar devices (EXE ~ 80%) [8].

Employing EXE as determined from the variable-temperature EL analysis (EXE = 85%) we arrive at values for peak and 350 mA IQE of 67% and 58%, respectively. The peak IQE is close to the value that was estimated from variable-temperature PL (~63%) illustrating that these analysis techniques yield consistent results. Similar analyses were performed for multiple LEDs across the available color range and EXE ranging from 80 to 85% is typically determined. For a green LUXEON Rebel LED with TFFC ($\lambda_p = 530$ nm), IQE was estimated to be 51% at the efficiency peak and 32% at 350 mA.

**4 Conclusion** The performance of high-power direct color and PC-white LEDs has significantly increased over the last several years. The performance improvement is based on advances in epitaxy producing higher quality device layers and leading to increases in the IQE. IQE of typical blue high-power LEDs used to pump yellow phosphor now reaches ~60% (at 350 mA). An alternative active region design, such as a single thick InGaN layer (DH LED), is showing a clear path to significant improvements in high drive current (>1 A for a 1 × 1 mm$^2$) efficiency. Chip design has also advanced with consequent increases in the EXE. Here, state-of-the-art devices feature TFFC technology and EXE is reaching 80 to 85%. Finally, high power-LED packages are now in production that enable extremely high current operation (such as LUXEON K2) or allow for close packaging of multiple LEDs because of their small footprint (such as LUXEON Rebel). The tight packaging either enables high light density or color mixing in small spaces when blue, green, and red LUXEON Rebel LEDs are closely assembled. Table 1 provides a summary of performance data demonstrated for 1 × 1 mm$^2$ high-power LEDs.

Based on the demonstrated performance, high power III-N based LEDs clearly have the potential to replace incandescent and fluorescent light sources for general illumination. Further performance improvements combined with advances in LED manufacturing will reduce the cost of high-power LEDs in illumination applications in the foreseeable future. In the meantime, a host of applications will benefit from many of the other advantages that LEDs provide, such as long life, ruggedness, and their small size.

### Table 1 Performance data of direct color and PC white high-power LEDs with 1 × 1 mm$^2$ chip size for a range of peak wavelength.

<table>
<thead>
<tr>
<th>$\lambda_p$ (nm)/CCT (K)</th>
<th>EQE (%)</th>
<th>PCE (%)</th>
<th>$P_{opt}$ (mW)</th>
<th>$P_{opt}$ at 1.5 A (mW)</th>
<th>$\eta_L$ (lm/W)</th>
<th>$\Phi_L$ (lm)</th>
<th>$\Phi_L$ at 1.5 A (lm)</th>
<th>IQE* (%)</th>
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* Calculated with EXE = 90%.

References

[2] The power conversion efficiency is often referred to as wallplug efficiency.