Strategies to avoid efficiency drooping in white light-emitting diodes

Mike Cooke reports on attempts to find ways around current and thermal impacts on indium gallium nitride device performance.

Indium gallium nitride (InGaN) light-emitting diodes (LEDs) are at the core of recent solid-state white illumination efforts, targeting high efficiency and long lifetime. High upfront costs and poor color rendering inhibit consumer take up, hampering national and international drives to higher-efficiency lighting.

Costs are increased by effects such as droop, where the output efficiency is reduced as the current and temperature increase beyond some optimum. Avoiding current droop requires a larger number of LEDs to be assembled into a package so the current through single devices is near optimum. Thermal management techniques are required to tackle temperature droop.

Here we look at recent proposals and possible routes to improve efficiency (and color) by applying novel structures.

Blue/cyan wells

Xi'an Jiaotong University and Shaanxi Supernova Lighting Technology Co Ltd in China have reported reduced droop and improved color rendering in white light-emitting diodes that use a multiple quantum well (MQW) structure with 440nm blue and 460nm cyan wells [Yukun Zhao et al, J. Appl. Phys., vol118, p145702, 2015].

The combination of blue and cyan, along with a suitable phosphor, improved the color rendering index (CRI) to 77.0, compared with 66.4 for a pure blue device. The cyan/blue device was therefore much closer to the 80 CRI US Energy Star specification for indoor white light.

The deeper cyan wells are also thought to ameliorate problems associated with low hole carrier concentrations across an MQW structure caused by low mobility compared with electron carriers. Precision measurements of light emission from InGaN MQWs under current

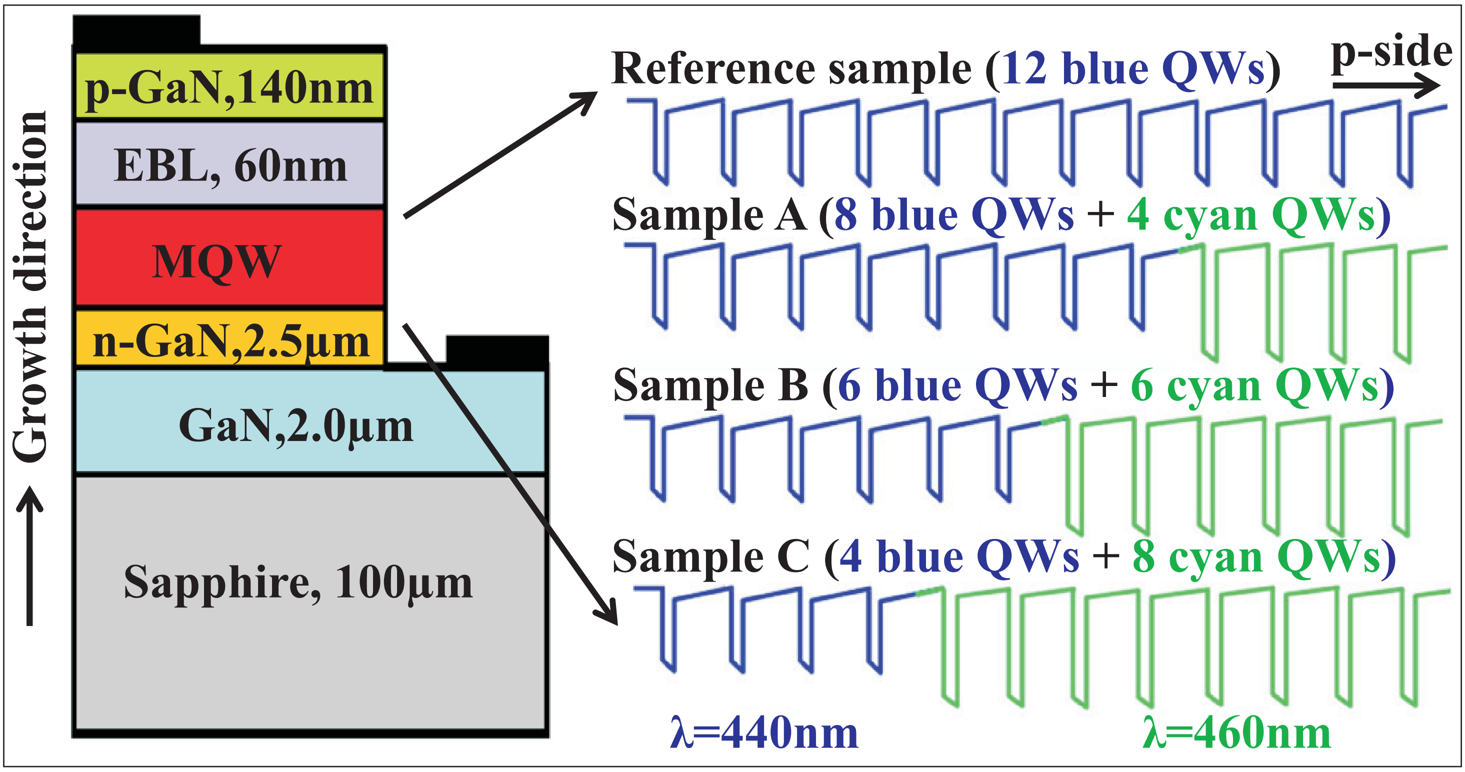

Figure 1. Schematics for LEDs with conventional uniform and dual-wavelength MQW structures.

injection often show that significant levels of radiation come from just the wells next to the p-contact layers.

In the Xi'an Jiaotong/Shaanxi Supernova LEDs, the cyan wells are believed to form a reservoir for holes that can be injected into the blue wells lower down in the device structure (Figure 1). The epitaxial samples were prepared through metal-organic chemical vapor deposition (MOCVD) on sapphire. The active region contained 12x 3nm wells and 12nm GaN barriers. The electron-blocking layer (EBL) consisted of aluminium gallium nitride (AlGaN).

Various combinations of cyan ($In_{0.18}Ga_{0.82}N$) and blue ($In_{0.15}Ga_{0.85}N$) were produced. The higher indium content of the cyan wells was achieved by reducing the growth temperature to encourage greater indium incorporation.

LED chips were fabricated with an indium tin oxide (ITO) current-spreading layer and dimensions of 250μm x580μm. For white light, the chips were encapsulated in oxynitride phosphor (ZYP570N, www.beijingyuji.com/EN-led-Oxynitride-Yellow-Phosphor/239.html).

Simulations suggested that the configuration of 6 cyan and 6 blue wells (Sample B) should have the best combination of increased electron and hole concentrations across the MQW assembly. Further, the reservoir effect of the cyan wells enables stronger injection of holes into the blue region of the MQW. Sample B also had a higher EBL electron barrier, inhibiting overspill of electrons into the p-GaN contact. At the same time, the EBL had a lower barrier to hole injection.

Table 1. Experimental results of IQE and droop ratios at 80A/cm^2.

Peak intensity ratio	IQE (80A/cm^2)	IQE (max)	Q (80A/cm^2)
Reference sample	37.8%	76.0%	50.3%
Sample A	42.2%	75.2%	43.9%
Sample B	48.3%	79.8%	39.5%
Sample C	38.0%	85.5%	55.6%

Although LED sample C had the highest peak internal quantum efficiency (IQE), the highest efficiency at 80A/cm^2 current density was achieved by LED B (Table 1), corresponding to the lowest droop ratio (Q). The poor performance of sample C LEDs at high current was probably due to increased threading dislocation densities, as suggested by x-ray analysis.

Sample B also produced the best CRI in encapsulated devices (Table 2, Figure 2). The correlated color temperature (CCT) was also close to pure white (5500K). The better color performance of sample B devices is attributed to greater intensity of the longer 460nm wavelength giving a CRI enhancement.

III-nitride laser

Weng Chow and Mary Crawford of Sandia National Laboratories in the USA have been theoretically analyzing potential advantages and pitfalls in using lasers rather than LEDs as sources for white-light systems [W. W. Chow and M. H. Crawford, Appl. Phys. Lett., vol107, p141107, 2015].

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Table 2. Color rendering and temperature at 80A/cm^2.

Sample	Reference	A	B	C
CIE (x, y)	0.3289,0.3395	0.3239,0.3482	0.3269,0.3498	0.3273,0.3726
CCT (K)	5660	5868	5737	5698
CRI	66.4	75.6	77.0	74.7

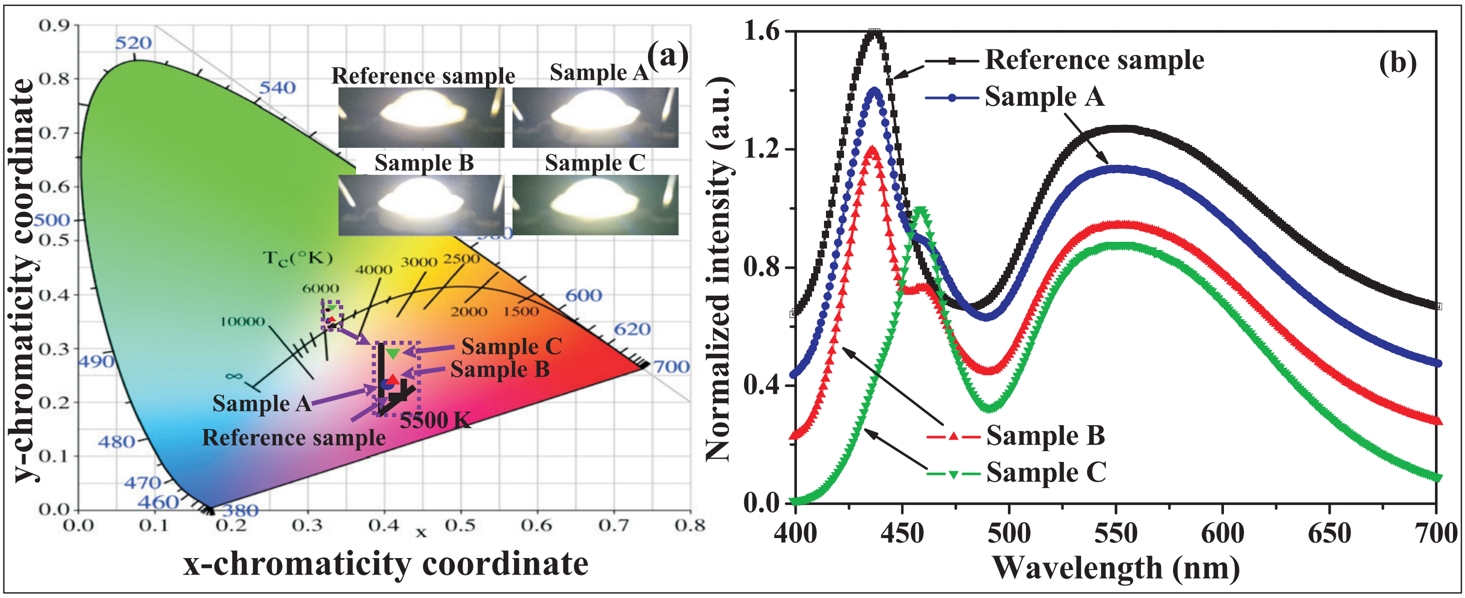

Figure 2. (a) CIE 1931 chromaticity diagram and (b) normalized experimental electroluminescence spectra of four encapsulated LED samples with phosphors at 80A/cm^2. Insets: four LED samples radiating on probe platform.

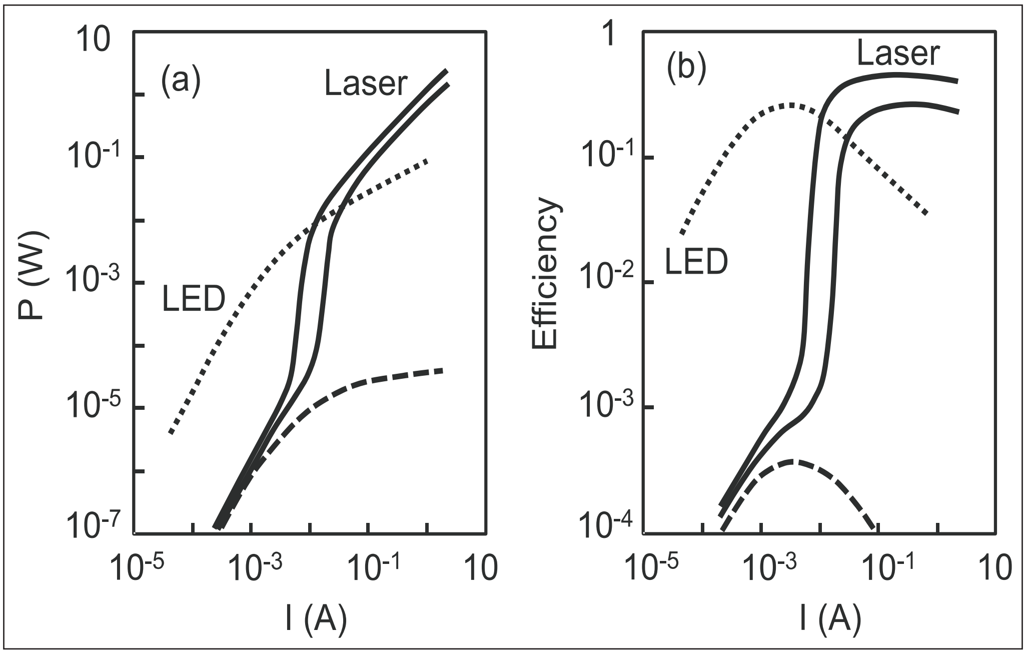

Figure 3. (a) Simulated output power and (b) efficiency versus injection current for LED (dotted curve) and array of 9 VCSELs. Solid curves show cases where lasing threshold is reachable because of sufficiently low cavity loss (1/ps and 2/ps). The dashed curve is for high cavity loss of 4/ps, where lasing is not possible. Spontaneous emission factor is 0.01.

The current droop effect is associated with high carrier populations in the active light-emitting regions of such devices.

Recently, it has been suggested that InGaN laser diodes could avoid the efficiency problem above threshold where the carrier population is clamped to a relatively low level [see, e.g., Semiconductor Today, p76, July–August 2015; Mike Cooke, Semiconductor Today, p70, November 2013].

Chow and Crawford comment: "The extent to which efficiency droop can be solved by lasers depends on a complicated interplay involving non-radiative losses, stimulated emission, spontaneous emission, and intracavity absorption. An accurate quantitative evaluation should be performed before committing substantial resources towards laser-based lighting development."

First, the researchers compared models for an LED with a vertical-cavity surface-emitting laser (VCSEL), using a fully quantized approach for the behavior of electrons, holes and photons. The active region consisted of a 2nm single quantum well of $In_{0.37}Ga_{0.63}N$ in GaN barriers. The area of the LED was 100μm x 100μm. The VCSEL was a 3x3 array with cells of area 5.6μm x 5.6μm — a 3% fill factor compared with the LED area. The VCSELs used distributed Bragg reflectors (DBRs) as confinement. The VCSEL array properties were designed to give 1W power at 1A current.

The simulations show that, with low absorption cavities, one can expect improved power and efficiency above threshold over LED performance (Figure 3). However, the low efficiency below threshold could "limit the use of lasers in general lighting applications, e.g. where dimmable lights are advantageous for energy savings," according to Chow and Crawford.

The researchers therefore suggest that nanolasers could be an alternative without the low efficiency at low current. Such devices use nano-scale resonant structures to channel spontaneous emission into lasing modes, giving more light below threshold. In 2012, there were reports of such devices operating at room temperature with optical pumping.

Chow and Crawford's nanolaser simulation was for a 12x12 array with 560nm x 560nm cells — a 0.5% fill factor compared with the VCSEL array. The nanolaser structure was based on a VCSEL with photonic lattice on the surface. The laser mode was from a defect site in the photonic lattice. Again, the aim was for 1W power at 1A current. The model gives similar performance to the LED below threshold and to the laser above threshold (Figure 4).

Thermoelectric pumping enhancement

Massachusetts Institute of Technology (MIT) and University of California Santa Barbara (UCSB) in the USA have been investigating the possibility of taking advantage of high temperature and thermoelectric pumping to improve the light output power (LOP) from InGaN LEDs, avoiding the need for external cooling [Jin Xue et al, Appl. Phys. Lett., vol107, p121109, 2015].

The researchers write: "The LED is shown to work in a mode similar to a thermodynamic heat engine operating with charged carriers pumped into the active region by a combination of electrical work and Peltier heat (phonons) drawn from the lattice."

The team says that their results suggest the possibility of removing bulky heat-sinks in commercial high-power LEDs, bringing a considerable reduction in cost.

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While current-induced droop has received wide attention from scientists and engineers, the temperature-induced effect has not been comprehensively studied, says the MIT/UCSB team.

The MIT/UCSB researchers developed a device with an optimal operating region at 615K that increased the LOP four-fold over room temperature (295K) with virtually no reduction in wall-plug efficiency (WPE).

The researchers comment: "This low-bias optimal regime of high LOP and high WPE at elevated temperature does not universally exist for common GaN-based LEDs. The demonstration of the sample studied is attributed to the low current droop and low thermal droop for the EQE in this device."

The low thermal droop was achieved by using low-defect-density substrates, reducing the amount of Shockley–Read–Hall non-radiative recombination. The low-bias operation avoided Auger recombination effects and current droop.

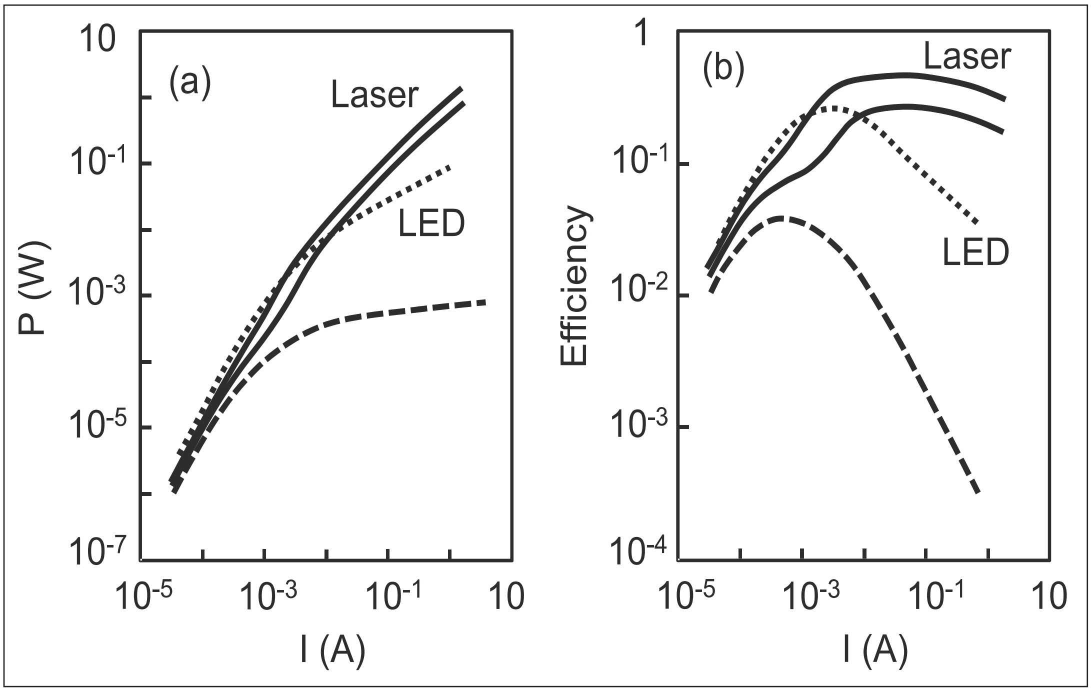

Figure 4. (a) Output power and (b) efficiency versus injection current for LED (dotted curve) and array of 144 nanolasers with spontaneous emission factor 1. Solid curves show cases where lasing threshold is reachable because of sufficiently low cavity loss (1/ps and 2/ps). The dashed curve is for 4/ps cavity loss.

The researchers produced 450nm-emitting material on semi-polar [20$\bar{2}\bar{1}$] free-standing GaN substrate (Figure 5). The design targeted high power output and low current-induced droop. Encapsulated devices with zinc oxide vertical-stand packaging and back-side roughening to increase light extraction achieved an external quantum efficiency of 50.1% and 140mW light output power at 100A/cm^2 current density.

Temperature-dependent experiments were carried out without encapsulation or packaging, reducing EQE and WPE. The LED die was placed on the flat surface of a hemispherical sapphire lens with anti-reflective coating. The lens-chip assembly was put in an opening in a copper arm that was used for heating. The light output from the lens was collected by a parabolic reflector and guided into a calibrated silicon photodetector.

The device was tested in pulse-mode, presumably to avoid self-heating affecting the temperature-dependent measurements (Table 3). The LED showed a small EQE

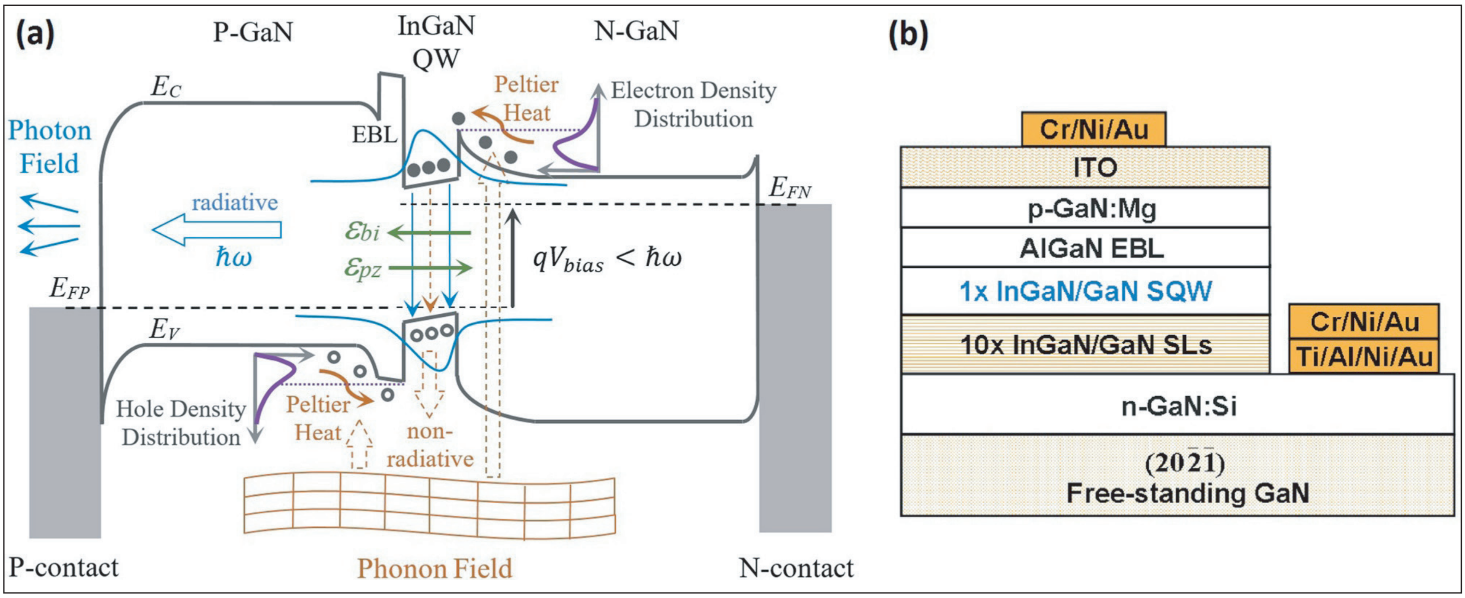

Figure 5. (a) Band diagram of InGaN single-quantum-well (SQW) LED, and thermoelectric pumping mechanism. (b) Epitaxial structure of device.

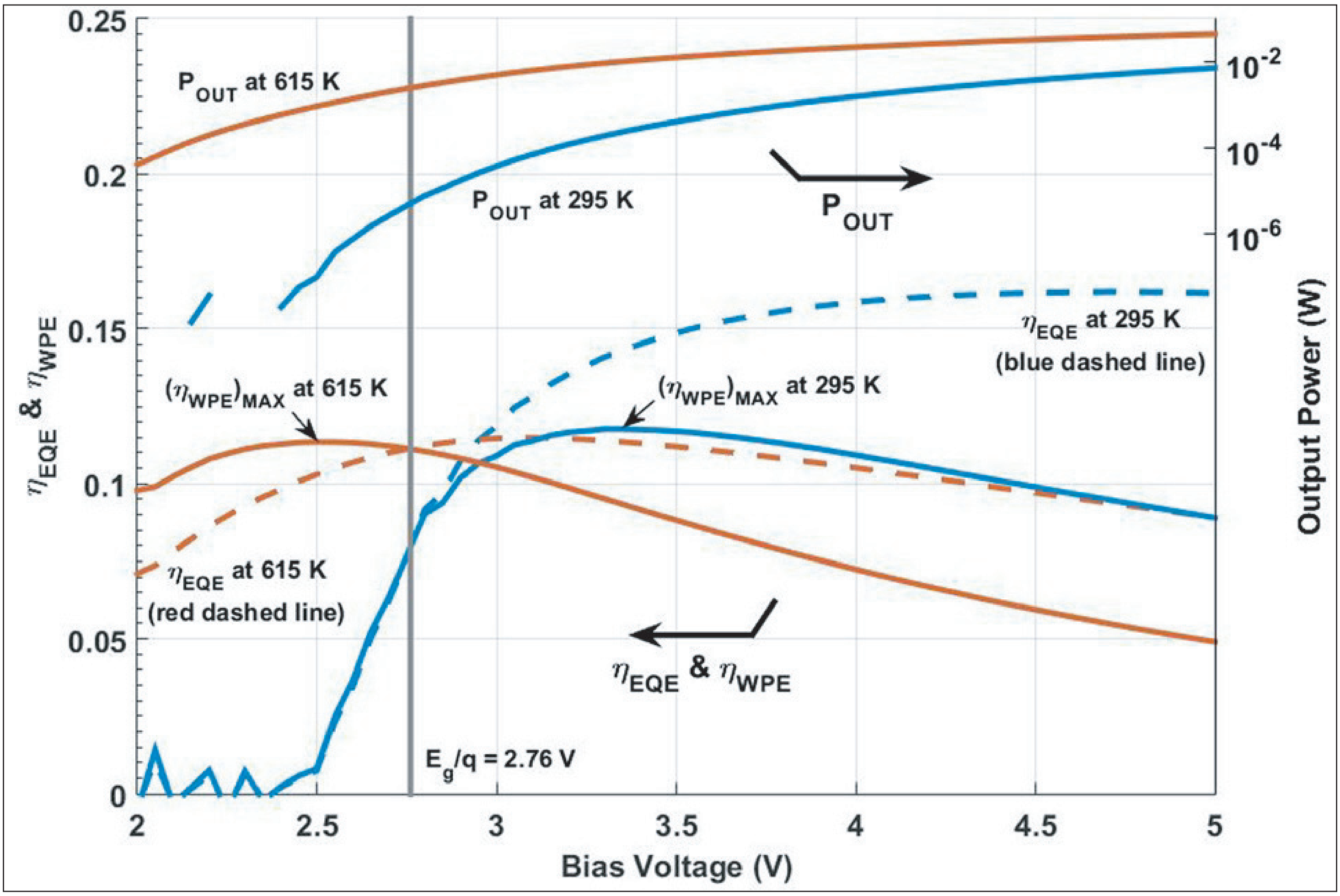

Figure 6. EQE (dashed lines) and WPE (solid lines) versus LED bias voltage at two extreme temperatures cases. Blue lines correspond to 295K (room temperature) and red lines correspond to 615K high temperature. Bias voltage of 2.76V corresponds to 450nm-wavelength photon.

Table 3. Conditions of peak WPE at different temperatures.

T	V	J	P_{OUT} at max WPE	η_{EQE}	$\eta_{WP\ MAX}$	$Q_{Peltier}$
295K	3.35V	0.61A/cm^2	2.40W/cm^2	14.31%	11.77%	3.46x10^{-1}W/cm^2
375K	3.10V	1.00A/cm^2	3.61W/cm^2	13.07%	11.61%	3.12x10^{-1}W/cm^2
455K	2.95V	2.11A/cm^2	7.01W/cm^2	12.06%	11.26%	3.43x10^{-1}W/cm^2
535K	2.75V	2.94A/cm^2	9.06W/cm^2	11.19%	11.21%	−9.83x10^{-2}W/cm^2
615K	2.50V	3.26A/cm^2	9.24W/cm^2	10.30%	11.35%	−9.02x10^{-1}W/cm^2

droop at higher currents (~10A/cm^2). The WPE was more peaked at a particular current that increased with temperature. While the EQE peak reduced at higher temperature, the WPE was more constant. The researchers comment: "In fact, since the collection efficiency of the experimental setup is optimized at room temperature, thermal expansion of the heating stage relative to the photodetector is likely responsible for the small roll-off in the measured WPE at higher temperatures."

At the same time as the WPE peak shifts to higher currents at higher temperature, the required bias decreases — from 3.35V at 295K to 2.5V at 615K — giving reduced power consumption (Figure 6). The light output power increased by around 4x with the temperature increase for a small WPE drop of 0.42% measured on equipment calibrated at 295K and not corrected for thermal expansion effects.

The WPE exceeded the EQE above 535K, indicating the effects of thermo-electric pumping. The researchers comment: "The injection current density in the case of 615K (3.26A/cm^2) is already close to the value of 5A/cm^2, which is the operating point of common high-power GaN-based LEDs."

The researchers used an empirical equation to derive a characteristic temperature for the thermal droop, which for their devices was 869K, compared with less than 200K for typical GaN LEDs grown on c-plane sapphire. The high characteristic temperature indicates very low thermal droop. ■

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