WHITE EMITTERS

Multi-faced LEDs introduce more color

Color-converting phosphors hamper the efficiencies of commercial white LEDs. But this can be avoided by switching to quantum-well growth on multiple facets, say **Mitsuru Funato** and **Yoichi Kawakami** from Kyoto University.

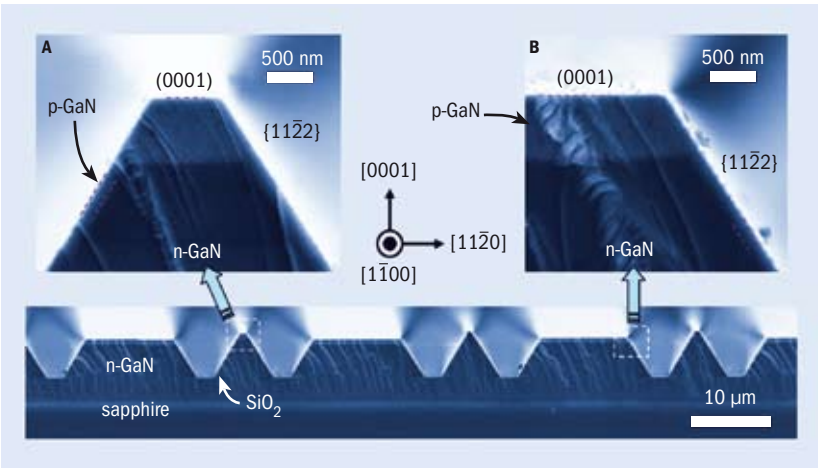

Fig. 1. This corrugated structure features narrow and wide trapezoidal cross-sections (A and B, respectively) produced by GaN growth through SiO_2 masks. The quantum wells on the {11$\bar{2}$2} and (0001) facets emit at different wavelengths. The overall color can be adjusted by current tuning.

Colored LEDs have one significant drawback – a limited color palette. This stems from the light-generating process, which is governed by the bandgap of the active ingredient.

Fortunately, several options already exist for extending LED spectral emission. The most successful method to date is the pairing of a yellow phosphor and blue InGaN chip to produce a white emitter. This device is already a great commercial success thanks to deployment in general lighting, displays, nanobiotechnology and medicine. However, poor color rendering is common due to weak red and green emission, and large variations in the output color often occur across batches of LEDs due to variations in phosphor emission color.

All of these issues can be overcome by employing phosphor-free designs. Mixing the output of red, green and blue LED chips is one option, and this approach can deliver a high degree of control over the overall color. However, device assembly is tricky and carefully designed external optics are needed to ensure good color mixing.

Monolithic designs ought to be a better solution, and researchers from Nichia in Japan and CNRS in France have already made some progress on this front. They have generated white emission from InGaN LEDs featuring several quantum wells (QWs), each with differing colors. However, because the wells are connected in series, the spectral output of this type of device cannot be adjusted by current tuning. Instead, the overall emission is dictated by the individual properties of each QW.

A radical design that connects QWs in parallel could overcome this weakness, which is precisely what we have done at Kyoto University in Japan. This breakthrough was achieved by growing the wells on different crystal facets of GaN. Each crystal plane produces a QW with a particular color, due to the differences in the thickness of the well and its indium composition (figure 1).

Our novel LEDs are made by MOCVD growth on sapphire (0001) at 300 Torr. We can form ridge-shaped structures by using processes allied to those employed for epitaxial lateral overgrowth – the widely used technique for cutting threading dislocation densities in GaN heteroepitaxial layers. A few microns of GaN are deposited, before SiO_2 mask stripes are defined in the [1$\bar{1}$00] direction by plasma-assisted CVD and photolithography. GaN regrowth forms microstructures containing (0001) and {11$\bar{2}$2} facets along the [1$\bar{1}$00] direction. We then deposit InGaN/GaN three-period QWs and p-GaN cap layers onto these microfacets.

The microfacet's shape depends on the SiO_2 mask dimensions. We initially employed mask openings of 5 and 15 µm for our prototype structures. This produced narrow and wide trapezoidal cross-sections, which we refer to as A and B, respectively (figure 1).

Conventional processing

Although our device structure is radically different from that of a conventional LED, this does not prevent us from employing conventional device processing. The photolithography step has been optimized, however, to cater for three-dimensional structures.

Our LEDs are formed by inductive coupled plasma reactive ion etching, which isolates the devices and exposes n-GaN by the removal of a portion of p-GaN and the QWs. Ni/Au and Ti/Al ohmic contacts are deposited on p-GaN and n-GaN, respectively.

Multi-color LEDs result from differences in the indium composition and thickness of the QWs on each of the two facets. The QWs occupy a larger area on the {11$\bar{2}$2} facet than the (0001) facet in A, and vice versa in B (figure 1). Consequently, emission from the {11$\bar{2}$2} facet QWs dominates the output from A, while the (0001) facet dictates the output from B. The overall spectral output can be adjusted by independently varying the drive currents to the two facets because they are connected in parallel.

We have produced a range of multi-color LEDs with various growth conditions and stripe patterns, which have different emission spectra (figure 2). According to microscopic luminescence measurements, blue emission is produced from the {11$\bar{2}$2} facet. Yellow

About the authors
Mitsuru Funato is an associate professor in the department of electronic science and engineering at Kyoto University. He is interested in crystal growth and optical/structural properties in wide-bandgap III-nitride semiconductors.
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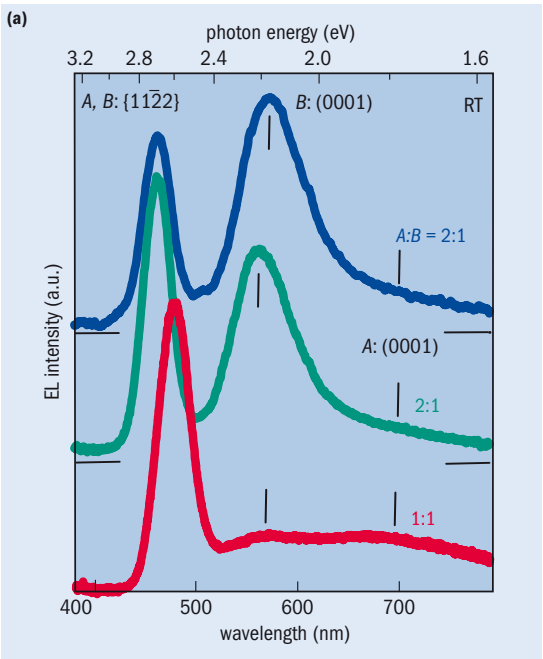
emission comes from the (0001) facets in B, while red results from the (0001) facets in A.

Color mixing of the red, yellow and blue emission creates a white output without the need for any external optics. This has a chromaticity close to that of a "blackbody". Color temperatures of 4000, 6000 and 15,000 K were produced by varying the A:B ratio and the growth conditions. These color temperatures overlap those of fluorescent lamps (3000–6500 K) and conventional white LEDs (5500 K). Our LED design is also capable of producing pastel colors, such as bluish and greenish white, through careful control of the mask patterns and the growth conditions.

Simulations have revealed that our LEDs have high extraction efficiencies, which result from the three-dimensional structures. This means that additional process steps are not required to boost extraction. It also suggests that the current fabrication process is suitable for high-volume manufacture. However, improvements are needed to our device's red and green quantum efficiencies before it can take on today's commercial white LEDs.

We are addressing this goal with a new structure, and results will be presented in the near future. Our devices have the potential to deliver high efficacies, thanks to the absence of phosphors and the incorporation of three-dimensional structures, and we are optimistic that our multifacet LED will be a key device in next-generation solid-state lighting.



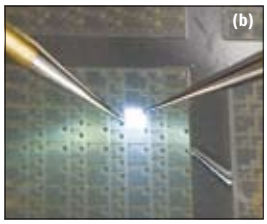


Fig. 2. (a) Variations in the SiO_2 mask pattern produce different white-light color temperatures. **(b)** A color temperature of 5000 K can be produced when A:B is 1.

Further reading

M Ueda *et al.* 2007 *Appl. Phys. Lett.* **90** 171907.
Y Kumagai *et al.* 2008 *Appl. Phys. Exp.* **1** 045003.
M Yamada *et al.* 2002 *Jpn. J. Appl. Phys.* **41** L246.

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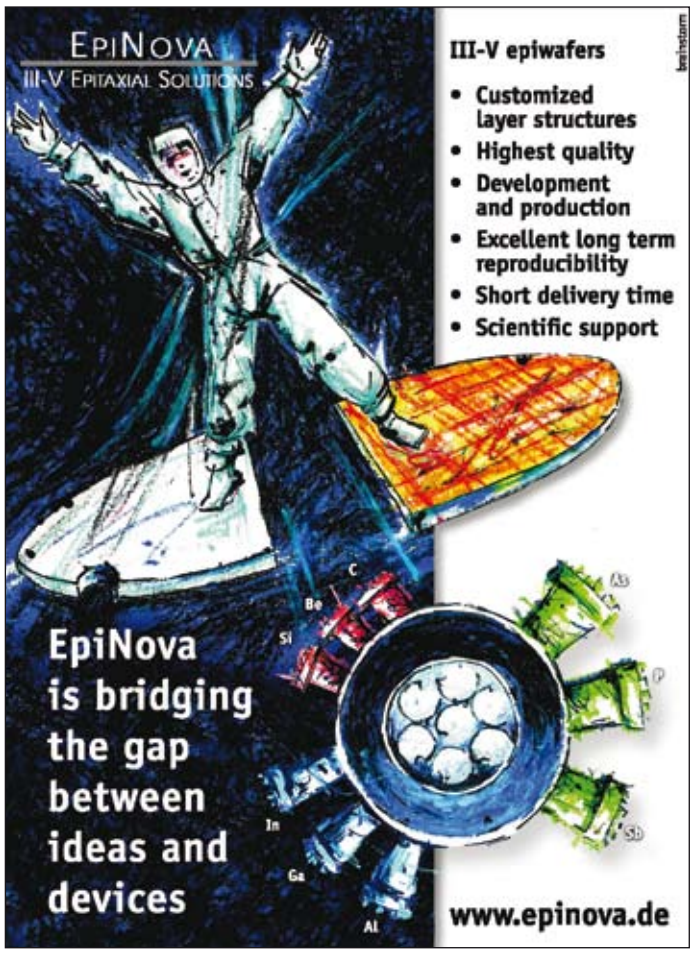
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