Improvements in III-nitride technology continue apace in both opto- and microelectronic device performance as well as in lifetimes and stability, with 2005 being no exception. Similar improvements are occurring in parallel in their related fields of application, while the work of Shuji Nakamura and colleagues at UCSB on non-polar and semi-polar GaN facets merits separate coverage and could allow LEDs to leap ahead in efficiency into new markets.

Dr Alan Mills

Expanding horizons for nitride devices & materials

At the end of 2005, Cree reported an optical output of 100 lumens per Watt for a small white-LED chip. This is noteworthy because, for the first time, the optical output for these LEDs has achieved about 50% of the theoretical maximum. This rate of progress is ahead of most light-output roadmaps and was attained in a shorter time than for red, orange and green coloured LEDs. It is also indicative of the huge worldwide effort in place to develop economic replacements for most white light sources, which now may be a few years closer, because of this output milestone and because of contributions from improved output stability and longer lifetimes. Even with little penetration of the general lighting market, high-brightness LED sales for 2005 will be $4-5bn, with 15–20% growth anticipated for 2006. The market is expected to be $7-8bn by 2008, then up to $11bn by 2010 — mainly a result of the complete superiority of LEDs for most coloured lighting requirements and the success of white LED backlighting for mobile devices. However, if either Cree's high lumen values or UCSB's non-polar growth technology can be turned into marketable products within a couple of years, this 2010 sales value could be surpassed, while the number of growth markets continues to increase.

Optoelectronics

In optoelectronics, III-nitride lasers are penetrating many (and creating new) markets to support an ever-growing range of consumer products. The advent of the Blue-Ray® and competing solid-state blue laser technologies is a good example, since they provide the consumer with the basis for the very high-density optical storage DVDs that are now available (10–30 GB capacity discs, with 50 GB and higher to come). Most of these lasers are made by MOCVD processes on various low-defect-level substrates. However, research into MBE-grown GaN lasers continues at Sharp Laboratories Europe in Oxford, where Heffernan *et al* had previously reported the first MBE-grown lasers with threshold current densities of 30 kA/cm² and voltages of 34 V. Such values were typical for early GaN lasers grown by MOCVD processes. Their recent work includes MBE laser diode growth on low-defect-level free-standing (FS) GaN wafers from both Lumilog and Sumitomo Chemical Industries. On these substrates, the threshold currents have been reduced to about 120 mA, with voltages in the 7–10 V range, reducing the threshold power densities to 4.8 kA/cm² — comparable to MOCVD-grown laser diodes. Although not competitive with MOCVD lasers at this time, they have passed an early milestone, with MBE-grown GaN laser lifetimes in excess of 3 minutes.

For the first time, the optical output for these [white] LEDs has achieved about 50% of the theoretical maximum

The potential high performance and efficiency of micro-LEDs, particularly in arrays, has been reported previously by academic laboratories such as the universities of Strathclyde, Hong Kong and Kansas State. Now, Choi *et al* from the University of Hong Kong have expanded this performance window with the development of hexagonally packed blue LED micro-arrays (a hexLED) with sides of 25 μm and 5 μm spacings that can easily be defined by photolithography. The hexLED's tight packing provides a fill factor in excess of 80%, compared to about 60% for previous packing arrangements. For 470 nm blue hexLED arrays at 20 mA drive currents, the optical power output versus current is more than double that of broad-area LEDs, although the superiority does decline gradually to about 30% higher power as the input current increases to 100 mA (see Figure 1). Where these micro-arrays can be used, they provide the potential for improved power efficiencies, better heat management and light output, and very efficient addressable micro-displays.

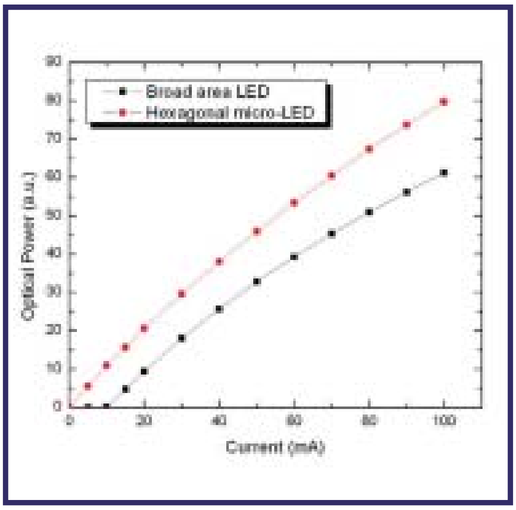

Figure 1. Optical power performance of hexLED. (Courtesy of H. W. Choi, University of Hong Kong, and S.J. Chua, National University of Singapore.)

Also competing in the small LED category are the InGaN/GaN LED multiple quantum disks (MQDs) grown on nanorods at Sophia University in Tokyo. The nanorods, grown by Kikuchi *et al*, support LEDs with a wide range of visible emission wavelengths, and for the first time they have observed multiple colour emission from a nanocolumn LED (see Figure 2) for typical emission spectra. These nanorods are self-organised single crystals, 20–200 nm in diameter with a density of ~10^{10} cm^{-2} and grown by RF-plasma-assisted MBE on n-type (111) silicon. These are potential candidates for the manufacturing of high-performance LEDs, because of the very high current injection efficiencies aided by the low dislocation densities in the rods. The LED structure has a growth sequence of 500 nm of n-doped GaN (the column), followed by undoped GaN[10 nm], between two and eight pairs of InGaN[2 nm]/GaN[3 nm] wells for the multi-quantum wells (MQWs), then undoped GaN[10 nm] and magnesium-doped GaN[500 nm]. Finally, 500 µm-diameter Ni/Au transparent electrodes were deposited on the as-grown surface. By changing the growth conditions of the active layers, a range of emissions, from violet to red, can be obtained. A photo image of a 500 nm-diameter MQD LED array is shown in Figure 3, from which it can be seen that the colours from each disk are quite uniform for first-generation devices.

Shorter-wavelength solid-state UV LEDs and lasers using AlN, GaN and BN materials are in demand for a wide range of applications, such as chemical sensing, phosphor excitation, and water and air purification, as well as a great potential for biosensors (many with important security implications). Labs around the world are working towards this goal. AlN (with a bandgap of 5.7 eV) would have the shortest-wavelength potential for a UV emitter. However, due to difficulties in processing AlN, only values for AlGaN LEDs and lasers have been demonstrated. Here, the shortest room-temperature UV wavelength possible is expected to be ~210 nm. To date, the shortest achieved for AlGaN have been reported by Kawanishi *et al*: 250 nm for LEDs and 350 nm for lasing by current injection and 241.5 nm for lasing by optical pumping.

The shortest room-temperature UV wavelength possible [for AlGaN] is expected to be ~210 nm

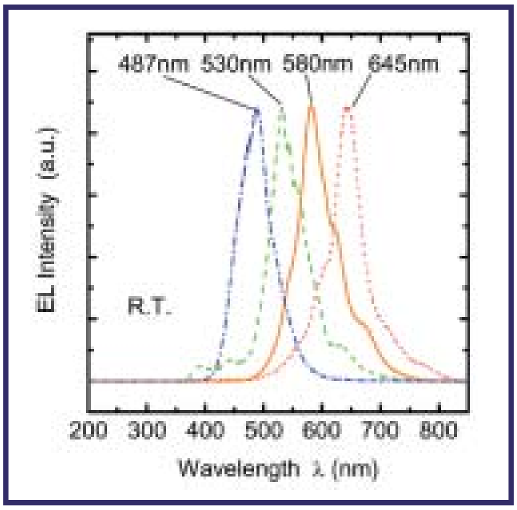

Figure 2. Electroluminescence spectra of InGaN MQD nanocolumn LEDs at room temperature. (Courtesy of Akihiko Kikuchi et al, Sophia University, Japan.)

These devices are MOCVD grown on silicon carbide using AlN/GaN multi-layer buffers and conform to the diagram in Figure 4. In their latest work, Kawanishi and colleagues have moved closer to their 210 nm UV goal by modifying the MOCVD epitaxial process to an 'alternate source feeding epitaxy' (ASFE) process, which is similar to atomic-layer or pulsed-precursor processes. ASFE enables them to reduce threading dislocation defect levels in their AlGaN MQW layer structure to $6x10^8$ cm^{-2}. With the new process, in which they postulate reduced precursor pre-reaction, both a 50% lower optical pumping threshold and a first-time value of 228.9 nm for lasing at 24K were achieved (Figure 5). The lasing frequency appears to be quite stable, with the temperature coefficient of lasing for the 229 nm laser determined to be 0.0025 nm/K over the 20–140K range.

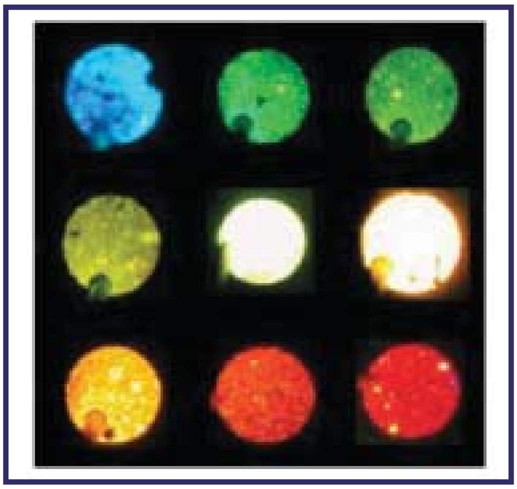

Figure 3. Microscope images of InGaN MQD nanocolumn LEDs emitting at room temperature. The emission colours in each electrode are almost uniform. The diameter of electrodes is about 500 µm. (Courtesy of Akihiko Kikuchi et al Sophia University, Japan.)