Nitride superluminescence expands blue-violet capability

Potential applications for high spatial coherence of superluminescent light-emitting diodes (SLEDs) include optical coherence tomography, fiber-optic gyroscopes and speckle-free displays. Mike Cooke reports.

Two research groups, based in Switzerland and Poland, have recently reported separate studies aimed at developing nitride superluminescent light-emitting diodes (SLEDs). The Swiss group has been extending the wavelength range of its devices, while the Polish group has considered the temperature characteristics with a view to improving performance.

SLEDs are edge-emitting devices, rather like laser diodes (LDs), but with a larger LED-like bandwidth. The resulting emissions have high spatial coherence (with low speckle), but low temporal coherence. Their edge-emitting character gives them good coupling to external optical components and fibers. Possible applications include optical coherence tomography (OCT), fiber-optic gyroscopes (FOGs), testing of fiber-optic equipment, and speckle-free displays. OCT is of interest for biomedical and industrial imaging.

The coherence of emitted light results from stimulated emission that occurs along the waveguide structure of the device, providing amplified spontaneous emission (ASE). The broadband nature of the output occurs due to the suppression of feedback (reflection) and round-trip gain that normally would lead to narrow laser emission modes.

Existing commercial red–infrared (650–1650nm) SLEDs are based on indium phosphide (InP) and gallium arsenide (GaAs) technology.

It is only in the past year that devices using nitride semiconductors have been successfully demonstrated by the Swiss group, which consists of researchers from Ecole Polytechnique Fédérale de Lausanne (EPFL) and EXALOS, a Swiss company that develops and markets red–infrared SLED-based modules and systems [E. Feltin et al, Appl. Phys. Lett., vol95, p081107, 2009]. The nitride SLED produced by them last year was a continuous-wave device emitting violet light at a wavelength of 420nm with a bandwidth of 5nm.

Wavelength extension

EXALOS/EPFL now report extended SLED performance [Marco Rossetti et al, Appl. Phys. Express, vol3, p061002, 2010]. Continuous-wave operation was achieved in the wavelength range 410–445nm. The Swiss nitride semiconductor epitaxy company Novagan was also involved in the latest research.

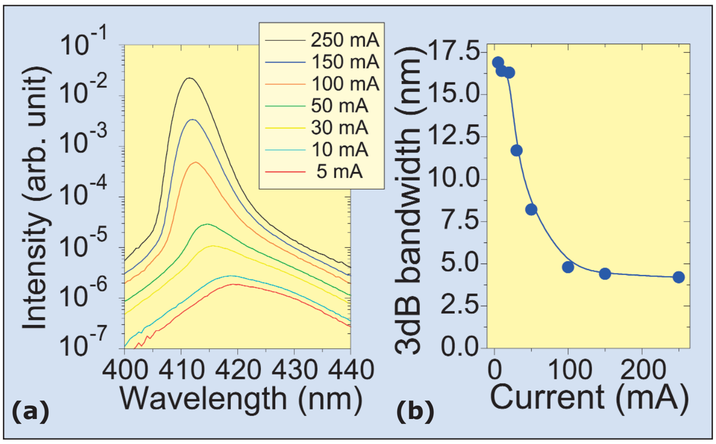

Figure 1. (a) Typical spectra for varying injection current for SLEDs produced by EPFL/EXALOS. (b) Corresponding bandwidth (FWHM) versus current injection (blobs, line is guide for eye).

In the new devices, the SLED layers consisted of indium gallium nitride (InGaN) multi-quantum wells (MQWs) embedded in a p–n waveguide with aluminum gallium nitride (AlGaN) cladding. The layers were deposited using metal-organic chemical vapor deposition (MOCVD) on c-plane free-standing GaN substrates.

Ridges were formed using plasma etching. The output facets were designed to have low reflectivity by tilted cleaving of the ridge and application of anti-reflective (AR) coatings. The temperature of the device during operation for most of the characterizations was controlled at 25ºC, enabled by mounting single chips on copper or diamond heat spreaders.

Along with pulsed and continuous light output power (L) testing, the researchers also studied coupling into single-mode optical fibers. At 150mA the coupling reached an 'excellent' maximum value of 55%. The pulsed operation tests suggest that thermal effects begin to adversely affect the operation of the device for currents greater than 250mA. Increased currents also lead to a narrowing of the spectrum of the SLED (see Figure 1). This is attributed to the selective effects of single-pass amplification.

The SLED output wavelength can be shifted by varying the indium content of the wells (see Figure 2). Three devices achieved similar output powers at high injection current, centered at 412nm, 424nm and 432nm with full-width at half-maximum (FWHM) in the range 4–5nm. The fourth device (D in Figure 2) had a lower-power spectrum centered at 445nm, and a wider FWHM of ~8nm. The poorer performance of this last device is blamed on non-optimized growth conditions leading to degradation of the active region. The longer wavelength of D requires higher concentrations of indium, which is a factor that commonly reduces material quality and creates inhomogeneities that can affect the gain performance of MQW systems.

The thermal performance of the SLEDs was also tested by varying the heat-sink temperature in the range 20–100ºC in pulsed operation. A characteristic temperature (T_0) was defined from an exponential fit of the currents required to achieve 10mW output. The 140K value obtained is comparable to the characteristic temperature for threshold current of blue–violet LDs, indicating good thermal stability of the SLEDs.

Funding for the research came from the Swiss Innovation Promotion Agency and National Centers of Competence in Research (NCCR).

Thermal performance

The Institute of High Pressure Physics of the Polish Academy of Sciences and TopGaN have been studying the temperature dependence of such violet devices emitting at about 405nm in the temperature range 263–295K [Katarzyna Holc, J. Appl. Phys., vol108, p013110, 2010].

The Polish devices were fabricated using epitaxial wafers that were constructed in the same way as for laser diodes. Free-standing gallium nitride substrates were produced using hydride vapor phase epitaxy (HVPE). To improve the quality of the subsequent epitaxial layers, the surface was mechanically polished to introduce an intentional misorientation of the surface by 0.5º with respect to the c-plane of the GaN crystal structure.

The researchers comment: "The mis-cut is critical to obtain the particular step-flow growth mode and desired indium incorporation during the epitaxial structure build-up".

The wafer was then subjected to a mechano-chemical polish and a high electron carrier density layer of GaN was deposited in a high-pressure reactor. The electron density in the layer is 5x10^{19}cm^3 compared with ~10^{18}/cm for the HVPE-GaN. The electron density arises from oxygen donors that are a feature of the deposition process that is used. Such an electron-rich layer "constitutes an excellent bottom cladding layer in the laser epi-structure, preventing the optical mode from leaking into the substrate entirely".

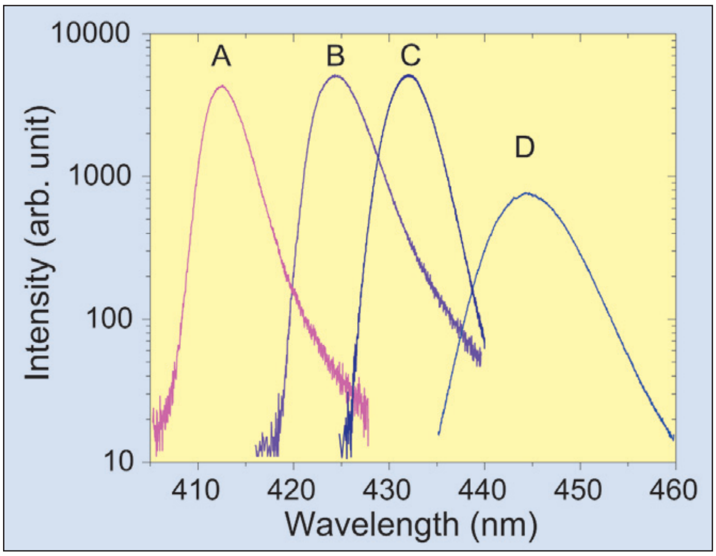

Figure 2. High-injection spectra of EPFL/EXALOS SLEDs with varying amount of indium in the active region.

Having prepared the substrate, the researchers then used MOCVD to finish the epitaxial structure: 600nm n-$Al_{0.08}Ga_{0.92}N$ bottom cladding, 50nm n-GaN lower waveguide, 50nm $In_{0.02}Ga_{0.98}N$ injection layer, three pairs of $In_{0.1}Ga_{0.9}N$/n-$In_{0.02}Ga_{0.98}N$ (3.5/8nm) quantum wells and barriers, 20nm p^+-$Al_{0.2}Ga_{0.8}N$ electron-blocking layer (EBL), 80nm GaN waveguide, 330nm p-$Al_{0.08}Ga_{0.92}N$ upper cladding and a 30nm p^+-GaN subcontact. The n-type doping was silicon and the p-type doping was magnesium.

The processing of this epitaxial material into SLEDs was similar to that used for ridge-waveguide, oxide-isolated LDs. Mesa structures measuring 3µm wide and 300nm high were created through a reactive ion etch. To prevent standing waves/optical feedback between the cleaved facets outputting the light, the ridge was tilted 5º with respect to the cleavage plane. Standing waves would create laser action, not superluminescence. Laser diodes were created side-by-side with the SLEDs to allow for comparisons. The researchers did not use any dielectric coatings for their SLEDs or LDs.

The chips resulting from this process were soldered p-side down on diamond heat spreaders and mounted in custom packages. The devices were tested under constant current conditions. A thermoelectric cooler was used for temperature control. A constant-flow dry nitrogen atmosphere was used to avoid water condensation.

Comparison of SLED and LD light output versus current shows an exponential increase for the SLED as opposed to the threshold behavior for LDs at 250mA. The output is more than an order of magnitude smaller for the SLED — an effect that the researchers attribute to overheating in the active region. SLEDs are therefore very temperature sensitive.

The FWHM for the SLED emission spectrum, under pulsed operation, is 8.14nm at 160mA, reducing to 5.23nm at 400mA. A blue-shift in the emission is also seen under higher current injection, reflecting the shift in gain characteristics. ➤

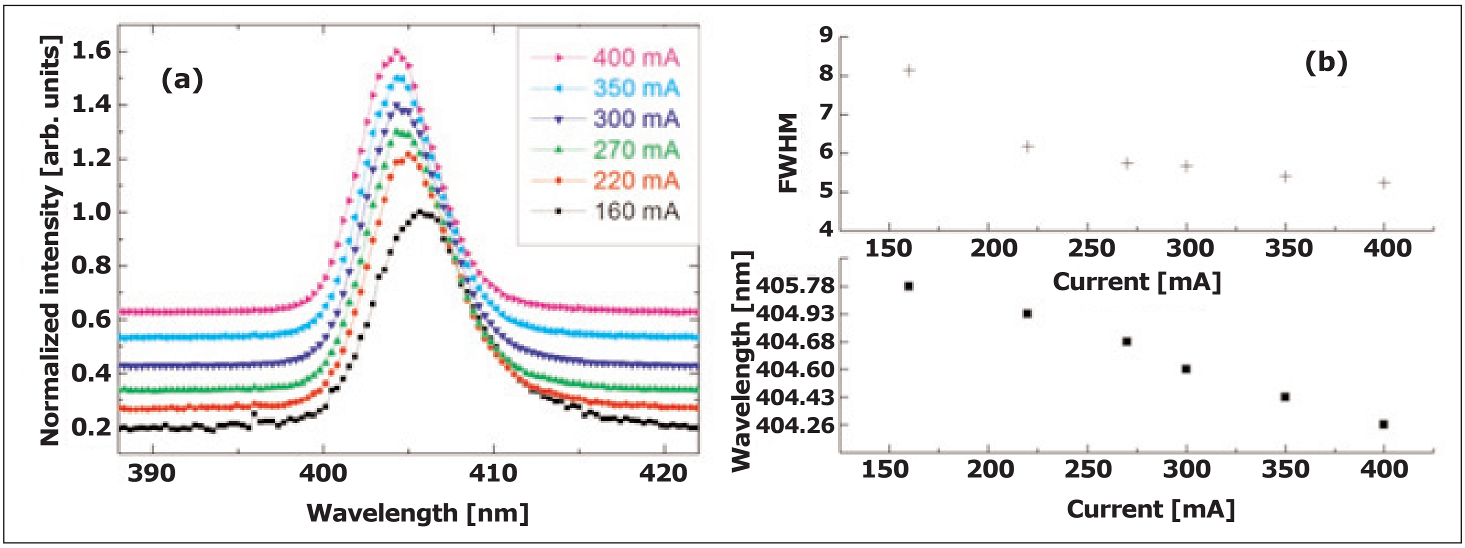

Figure 3. (a) Polish Academy of Sciences/TopGaN SLED spectra measured at different current densities and (b) central wavelength at different currents and corresponding FWHM values.

By comparing experimental data from pulsed operation and temperature control with a simple model (Figure 4), the researchers have come to believe that the problems shown by the temperature dependence of the devices arise primarily from the spontaneous emission. Temperature variation of the gain that is provided by stimulated emission has only secondary importance in the behavior.

The researchers conclude: "The results strongly indicate the need for reducing nonradiative recombination in SLED devices and tight temperature control of all the elements within those structures."

The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.

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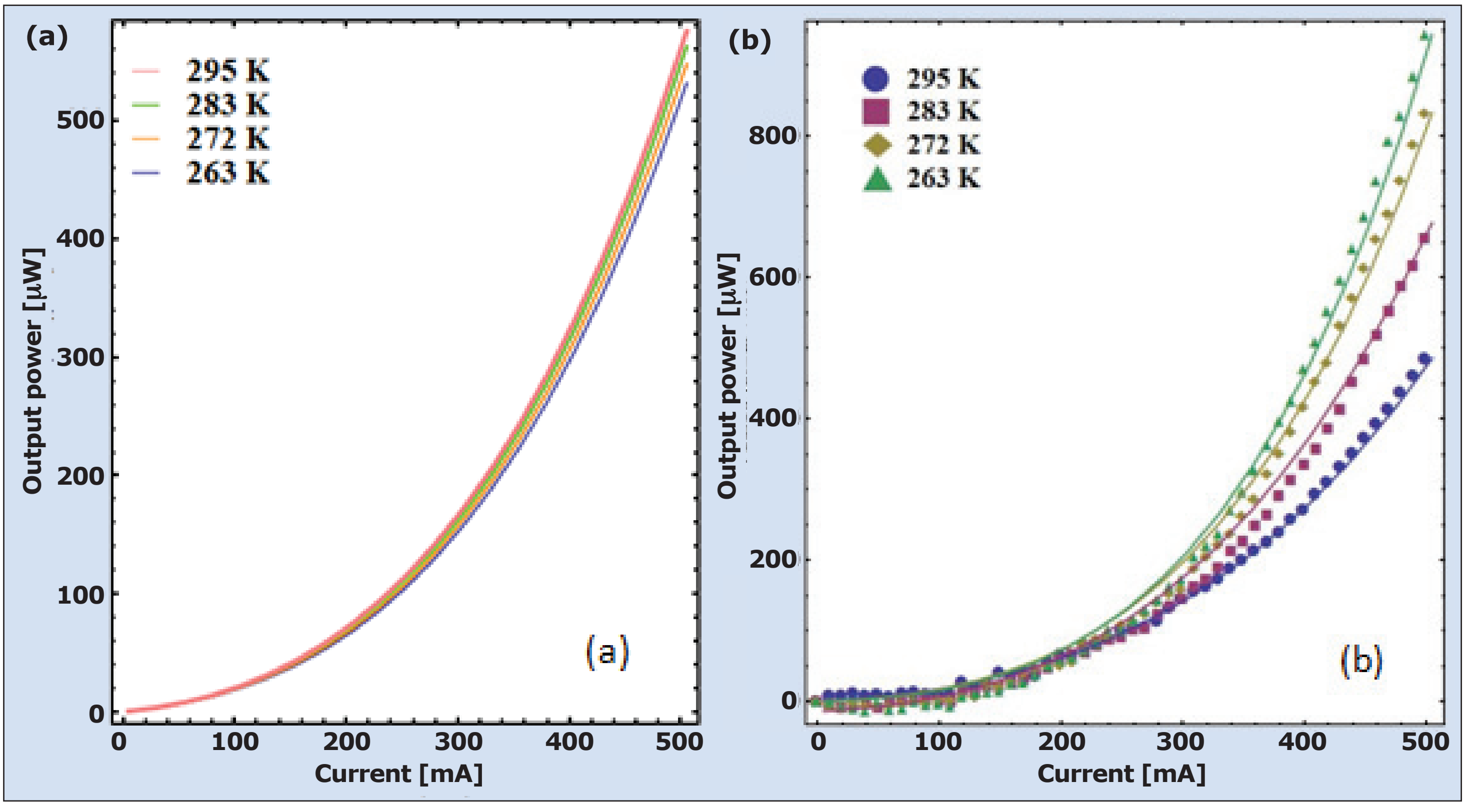

Figure 4. (a) Calculated power output vs current including only gain at different temperatures; (b) measured SLED output power (symbols) and calculated signal (solid line) taking into account spontaneous emission.