Enhancing optical confinement for III-nitride semiconductor laser diodes

Mike Cooke reports on research attempting to improve waveguide and cladding layers for blue 450nm wavelength devices.

The III-nitride semiconductor light-emitting devices that use various combinations of gallium aluminium indium nitride (GaAlInN) have an ever widening range of wavelength applications from the visible to deep ultraviolet. Laser diodes (LDs) have more complex structures, where optical confinement can be as critical as electrical performance, than light emitting diodes (LEDs). However, the properties of laser light are used widely in projector and data storage systems and could even be employed in general lighting in future.

In particular, researchers see potential applications for InGaN LDs in white lighting, since LDs do not suffer from the same efficiency droop problems at high current as LEDs. This is because carrier concentrations in LDs tend to become clamped at the value at the laser threshold, rather than continuing to increase with increased current.

Here, we look at some recent research that has tried to improve optical confinement techniques in blue InGaN LDs.

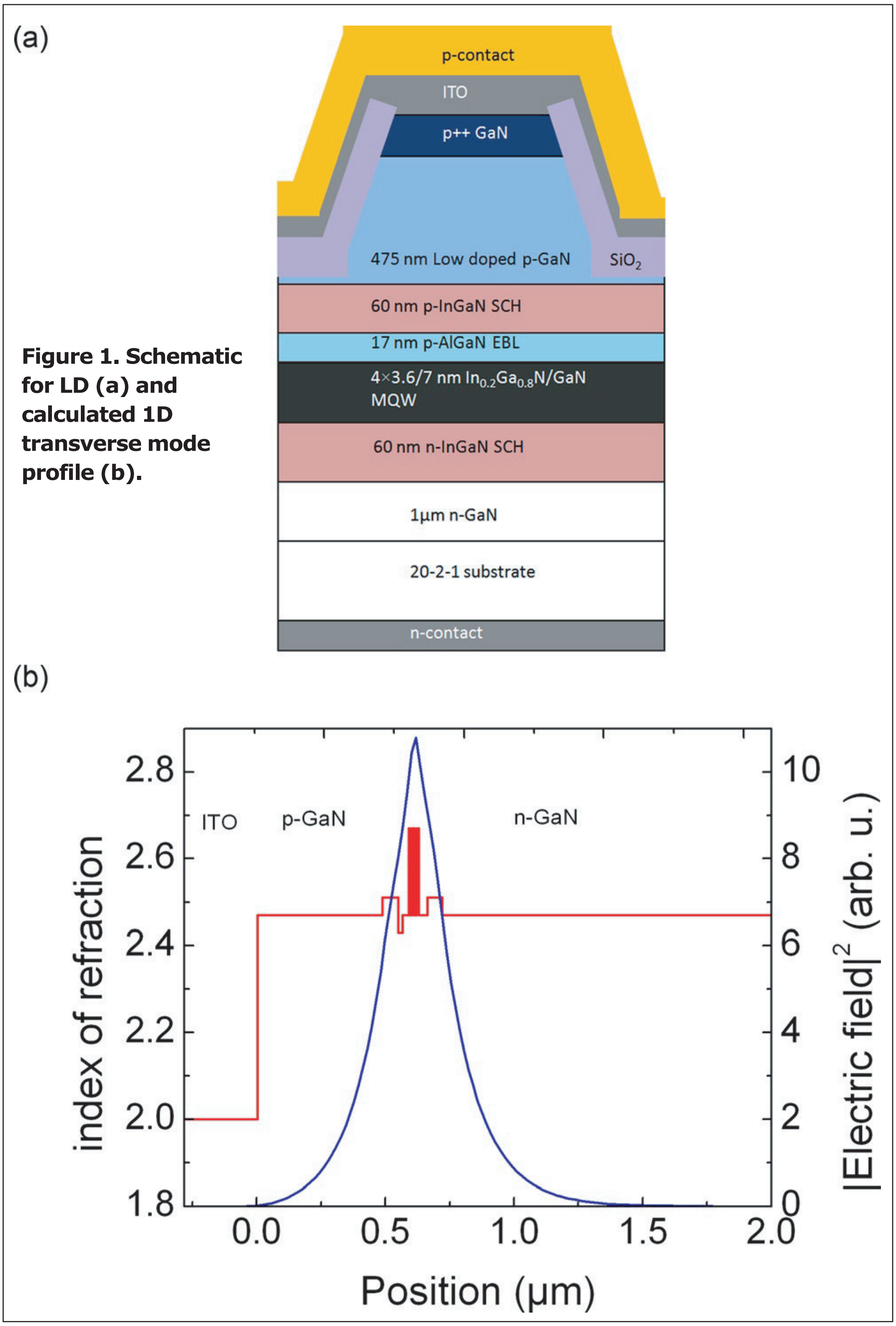

Figure 1. Schematic for LD (a) and calculated 1D transverse mode profile (b).

Indium tin oxide

University of California Santa Barbara (UCSB) has used indium tin oxide (ITO) as part of the cladding for semipolar indium gallium nitride (InGaN) laser diodes (LDs) [A. Pourhashemi et al, Appl. Phys. Lett., vol106, p111105, 2015].

The semi-polar ($20\bar{2}\bar{1}$) crystal orientation avoids quantum-confined Stark effects (QCSEs) from the large electric fields in the (0001) c-direction that arise from charge polarization of the III-nitride chemical bond. Devices grown on c-plane material suffer from reduced efficiency because these QCSE fields tend to pull apart electrons and holes, inhibiting recombination into photons.

The ITO cladding was used to reduce the aluminium gallium nitride (AlGaN) content of the device structure. Devices with AlGaN cladding suffer from catastrophic optical mirror damage (COMD) at lower current densities due to the confined optical mode energy density.

Al-free devices grown on gallium arsenide (GaAs) substrates "are less prone to both sudden failure and gradual degradation", according to the researchers. They add: "Although analogous reliability studies still need to be done for III-nitride LDs, these studies suggest that either reducing or eliminating the Al content in the cladding layers could potentially improve the manufacturability and reliability of high power semipolar and nonpolar III-nitride LDs."

Another disadvantage of AlGaN cladding is the low hole carrier density in p-AlGaN due to the poor doping capability of even the best acceptor impurity element — magnesium. Increasing Al-content further reduces hole densities. Low hole density makes for high typical resistivity in p-AlGaN: 4Ω-cm, compared with 1×10^{-4}Ω-cm for ITO. The resistivity in p-GaN is around 1Ω-cm.

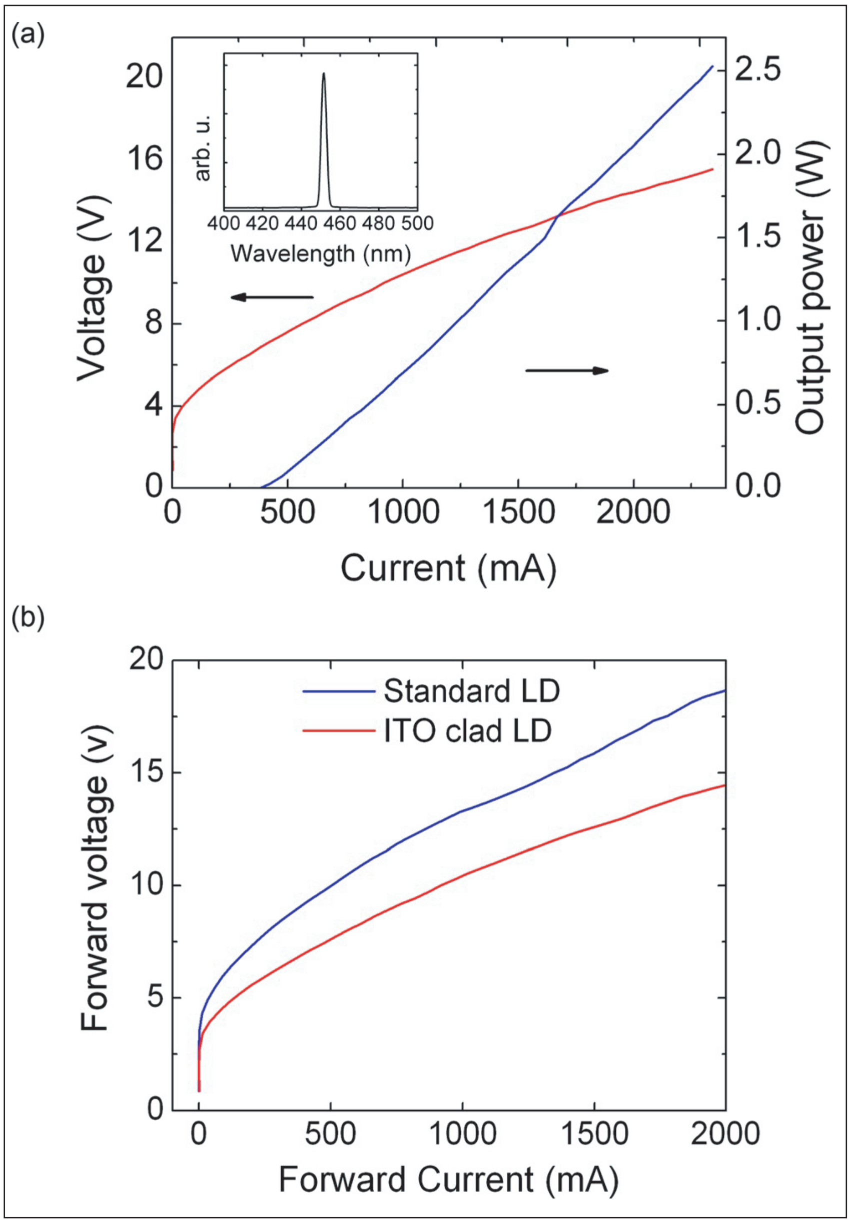

Figure 2. (a) Light output power, current and voltage (L–I–V) characteristics after facet coating for LD. Inset: lasing spectra.

UCSB used metal-organic chemical vapor deposition on semipolar ($20\bar{2}\bar{1}$) GaN substrates to produce the epitaxial material for the LDs (Figure 1). The 60nm upper and lower waveguides consisted of $In_{0.06}Ga_{0.94}N$. The 17nm electron blocking layer (EBL) used magnesium-doped p-$Al_{0.15}Ga_{0.85}N$. The ohmic p^{++}-GaN contact layer was 12nm thick. The magnesium-doping was reduced as much as possible to avoid phonon-assisted absorption by acceptor-bound holes — a mechanism thought to be the single largest contributor to modal loss in III-nitride LDs.

The material was formed into ridge waveguide devices 8μm wide and 1200μm long. The 200nm silicon dioxide current aperture was applied with magnetron sputtering onto the sides of the ridges and the non-ridge areas of the device. The 180nm ITO layer was deposited by electron-beam evaporation at 260ºC in an oxygen-rich atmosphere. The contact metals were titanium/gold on the p-side and aluminium/gold on the n-side.

The devices were separated using a dicing saw. The mirror facets were mechanically polished. The back mirror was coated with an 8-period high reflectivity quarter-wavelength silicon dioxide/tantalum pentoxide structure. The front mirror had a 1-period anti-reflective structure of the same materials.

In pulsed operation at room temperature (Figure 2), the threshold current was 509mA ($5.30kA/cm^2$). The slope efficiency of 1.36W/A represented a differential efficiency of 50%. The researchers comment: "This high slope efficiency corresponded to a maximum output power of 2.52W and an external quantum efficiency of 39% for a drive current (current density) of 2.34A ($24.4kA/cm^2$)."

The team estimates that optical power density at the front mirror with 2.52W operation was 94.43MW/cm^2. The COMD power density for c-plane InGaN LDs of 40–70MW/cm^2 has been reported, versus 30MW/cm^2 for GaAs-based devices under single-pulse excitation.

The researchers point out that the peak output power of their device was not limited by thermal roll-over or COMD, but rather by power-supply limitations to currents less than 2.34A. In terms of current-voltage performance, the reduction in GaN cladding enabled by use of ITO reduced the forward voltage somewhat, but the peak wall-plug efficiency was still low at 7.3%.

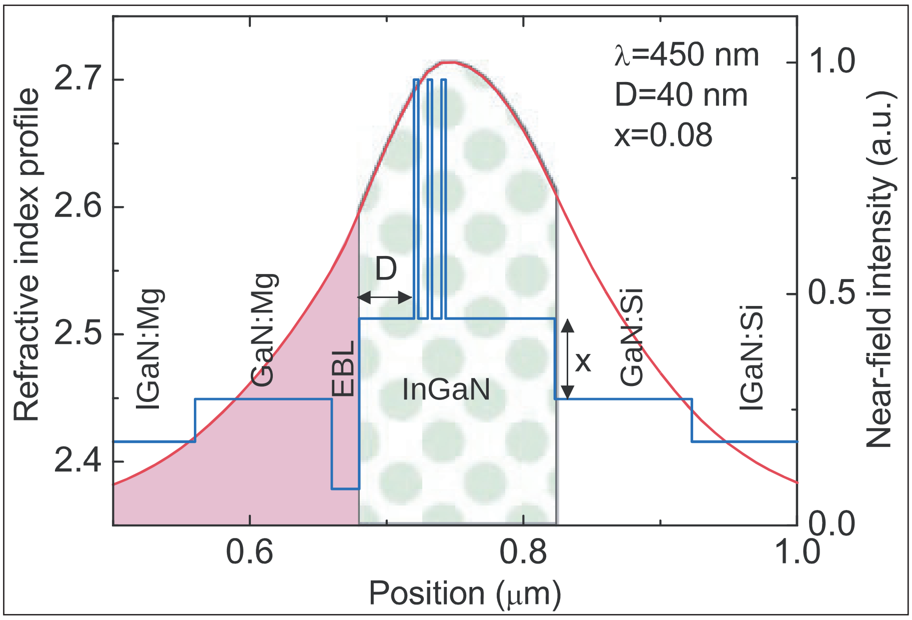

Figure 3. Refractive index profile and corresponding optical mode distribution of blue LD. Solid purple and dotted green regions correspond to optical mode confined within Mg-doped region and InGaN waveguide, respectively.

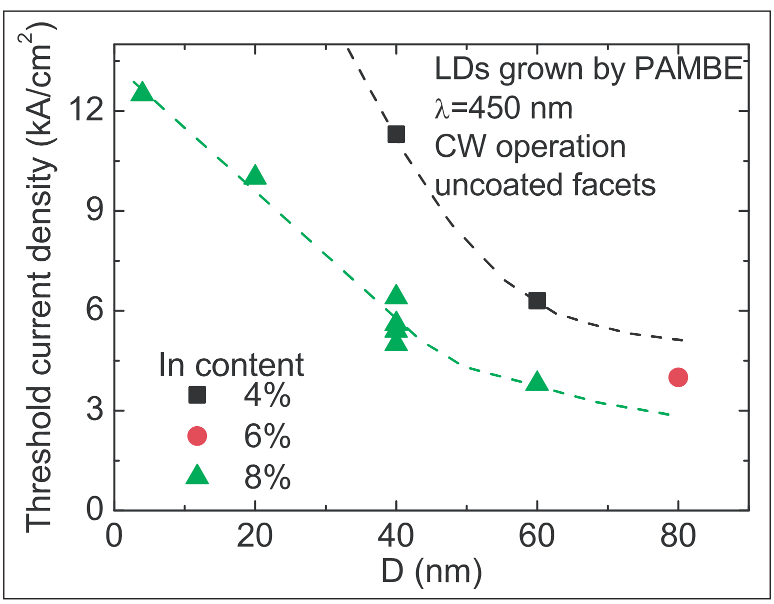

Figure 4. Threshold current density of LDs as function of distance D between MQW and magnesium-doped EBL. Dashed lines are guides to the eye.

Waveguide confinement

Researchers in Poland have been using InGaN waveguides to enhance optical confinement in 450nm wavelength blue LDs, reducing threshold currents [Grzegorz Muziol et al, Appl. Phys. Express vol8, p032103, 2015]. The team from Institute of High Pressure Physics and TopGaN Ltd employed low temperature plasma-assisted molecular beam epitaxy (PAMBE) in order to achieve high material quality with indium contents up to relatively high values of 8%.

The epitaxial material for the laser diodes (Figure 3) was grown on c-plane bulk ammono-GaN substrates with dislocation density of around 10^4/cm^2. The layers up to and including the multiple quantum well (MQW) were constant in thickness with 80nm $In_xGa_{1-x}N$ bottom waveguide, and three 2.6nm $In_{0.17}Ga_{0.83}N$ quantum wells separated by 8nm $In_xGa_{1-x}N$ barriers.

The emission wavelength of all devices was within 2nm of 450nm. The structure also included 700nm silicon-doped aluminium gallium nitride ($Al_{0.065}Ga_{0.935}N$) bottom cladding, designed to compensate for the tendency to bow caused by strain from the different lattice constants of GaN and InGaN. With the AlGaN bottom cladding the radius of curvature of the 1″ substrate was in the range 40–60m.

The thickness D of the upper $In_xGa_{1-x}N$ waveguide layer was varied up to 80nm. Increasing the indium content x up to 8%, and D to 80nm, reduced the laser threshold current (Figure 4). With D at 5nm and x at 8%, the threshold current was 12.5kA/cm^2 — increasing D to 80nm reduced this to 3.6kA/cm^2. Changing x from 4% to 8% reduced the threshold by 50%. Despite the increased distance between the electron blocking layer (EBL) and MQW structure, the researchers found no decrease in injection efficiency.

The researchers believe that the effect of increasing D is to reduce the overlap of the optical mode with the magnesium-doped layers of the device, which have larger optical absorption than undoped regions. However, increased x also increases optical absorption because the band-edge is closer to that of the quantum wells and also as a result of indium fluctuations in higher content material. At the same time, the refraction index contrast of high-x InGaN with the surrounding layers reduces optical leakage, enhances optical confinement and increases differential gain of the light amplification. ■

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