Laser diodes for mid-IR spectroscopy

Mike Cooke reports on developments of devices around the 3μm wavelength carbon-hydrogen bond fingerprint region.

While laser diodes (LDs) are well established for applications in the visible and near-infrared parts of the spectrum, longer-wavelength mid-infrared devices are still in development. In particular, new device structures such as quantum cascade lasers (QCLs) and interband cascade lasers (ICLs) are the subject of much research and companies are keen to drive and commercialize these technologies into new products.

Spectroscopy is an application where laser diodes can be used to create low-cost, compact devices with a wide range of uses such as chemical analysis and medical inspection. Mature laser diode technology in the near infrared (0.75–1.4μm) is already being deployed in this application.

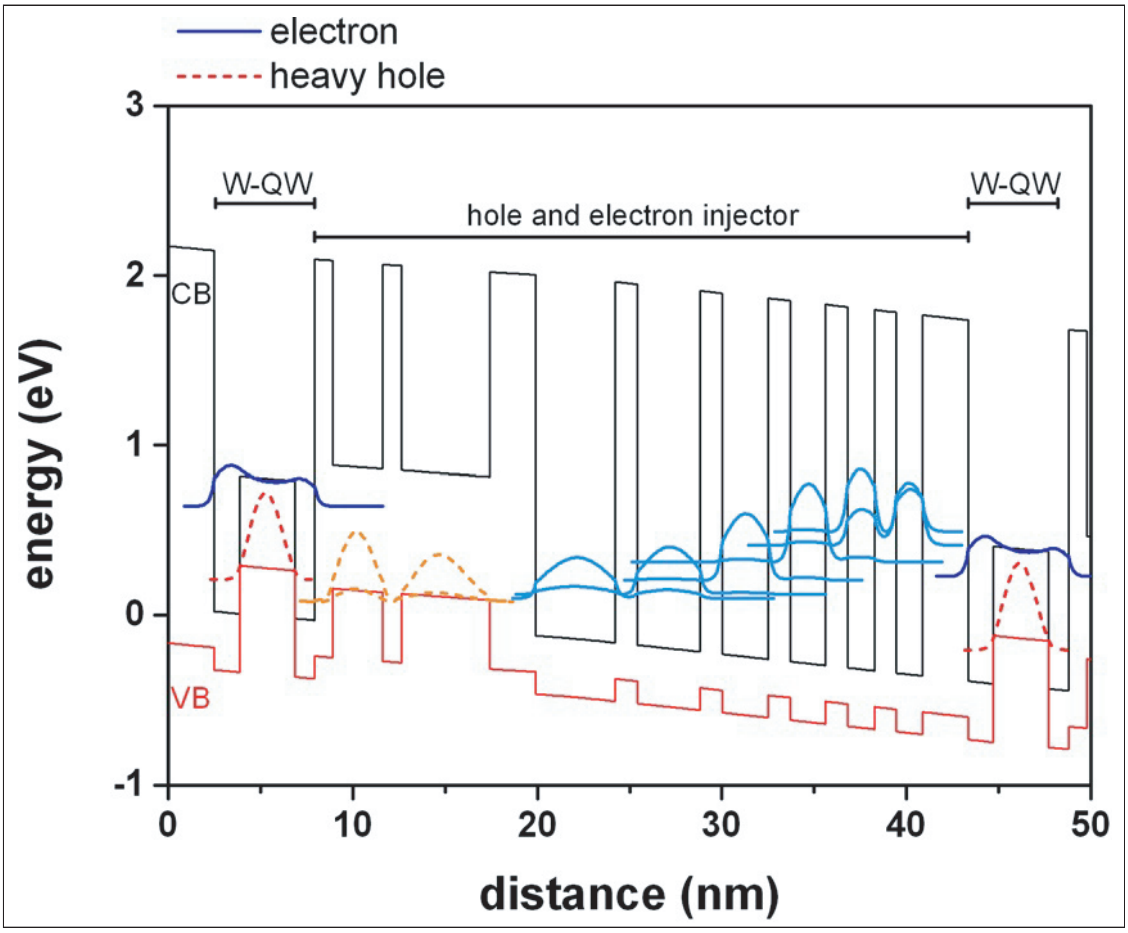

Figure 1. Band structure of conduction and valence bands for one and a half stages, containing two W-QWs and respective hole and electron injectors. Dashed (solid) lines depict absolute moduli square of heavy hole (electron) wave functions at W-QW as well as in injector region.

However, wavelengths longer than 2.4μm (short-infrared) and up into the mid-infrared (3–5μm) provide more detailed information about many molecules. For example, the 3μm region of the mid-infrared spectrum can be used to study stretch vibrations in carbon-hydrogen bonds. Most organic materials have such bonds and the different spectroscopic responses can be used to "fingerprint" particular molecules. For such fingerprinting, one seeks strong absorption cross-sections and high spectral selectivity.

In addition to QCLs (3–10μm) and ICLs (2.7–5.5μm), some more traditional and mature quantum well laser technologies reach out to these wavelengths. Here, we look at some recent research seeking to provide laser diode technology for ~3μm spectroscopy.

Reducing interband cascade wavelengths

Researchers based in Germany and UK claim record short 2.8μm wavelength performance for interband cascade lasers [Julian Scheuermann et al, Appl. Phys. Lett., vol106, p161103, 2015].

The team from nanoplus Nanosystems and Technologies GmbH and Universität Würzburg in Germany and University of St Andrews in the UK are interested in tunable laser absorption spectroscopy (TLAS) or other spectroscopic analysis.

nanoplus provides ICL laser diodes with 3–6µm wavelength with a view to spectroscopy. Their devices have recently been used in an optical feedback cavity-enhanced absorption spectroscopy (OF-CEAS) experiment where the minimum detectable absorption coefficient for a methane (CH_4) wavelength at 3.24µm, corresponded to 3 parts per billion sensitivity at atmospheric pressure [K. M. Manfred et al, Appl. Phys. Lett., vol106, p221106, 2015].

ICLs are seen as a sort of hybrid of traditional diode and quantum cascade laser technology. The "sweet spot" for emissions is in the range 3.6–3.8µm. Advantages of ICLs over QCLs are lower threshold currents and power consumption. However, ICLs generally have lower output power.

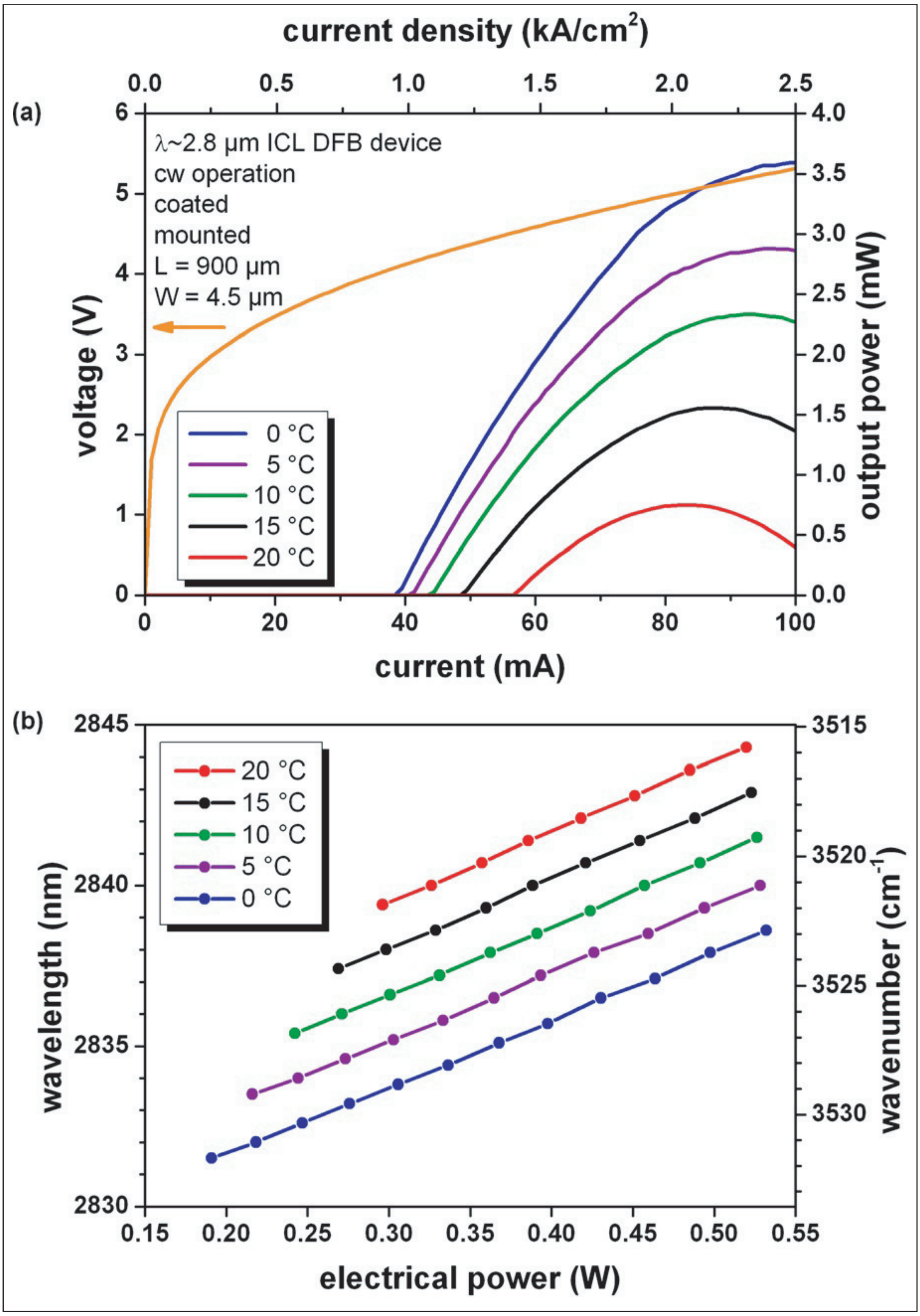

Figure 2. (a) Light output, current and voltage characteristics of ICL DFB device at temperatures ranging from 0°C to 20°C in cw operation. (b) Respective tuning diagram, showing range of single-mode operation.

A 5-stage structure was grown on tellurium-doped gallium antimonide (GaSb) using solid-source molecular beam epitaxy. The stages (Figure 1) included a W-type quantum well with 2.5nm AlSb/1.4nm InAs/3.0nm $Ga_{0.65}In_{0.35}Sb$/1.1nm InAs/1.0nm AlSb. The electron injector region consisted of six InAs/AlSb pairs with the five nearest to the W-QW highly silicon doped to encourage carrier rebalancing. Although the paper does not report the structure of the hole injector, it seems likely to consist of GaSb/AlSb layers.

The ICL region was sandwiched in a waveguide with 200nm GaSb confinement on each side and 1.5µm/2.5µm upper/lower cladding with InAs/AlSb superlattice layers. The confinement and cladding were separated by transition layers that smoothed the conduction-band discontinuity.

➤

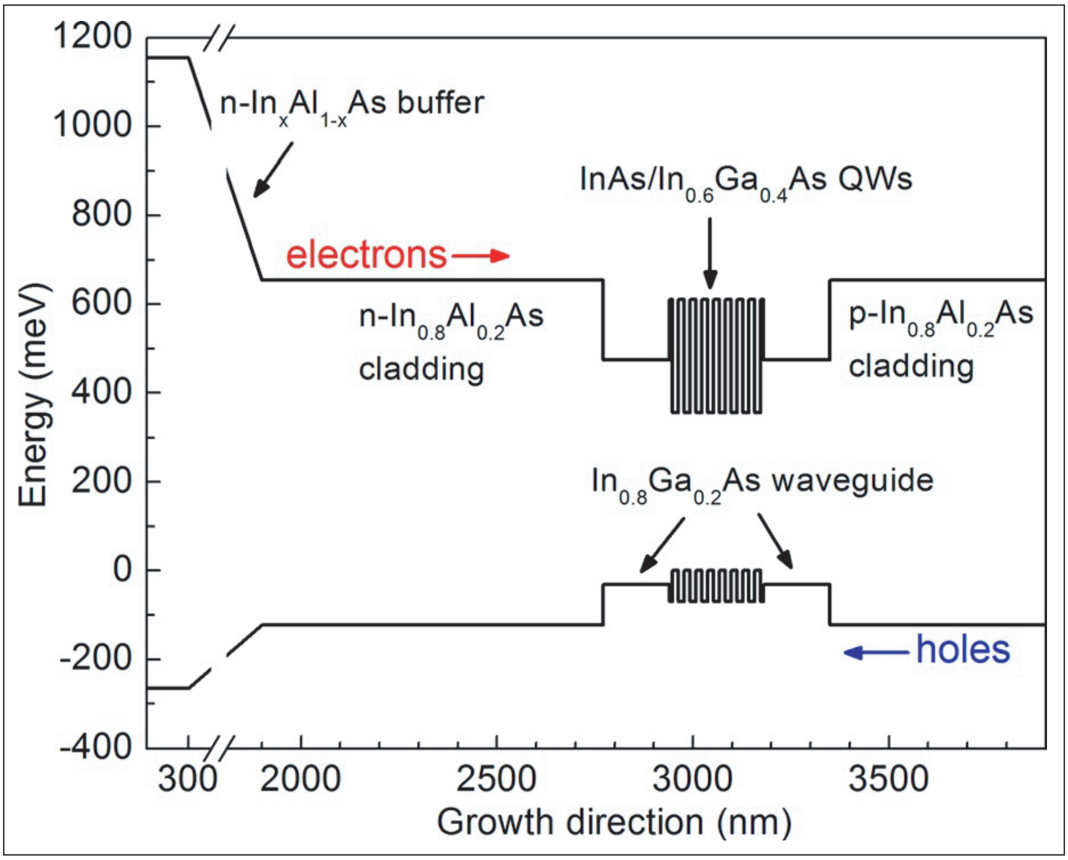

Figure 3. Energy-band structure of InP-based metamorphic type-I QW laser. Injection directions of electrons and holes are indicated.

➤ Broad-area, ridge-waveguide (RWG) and distributed feedback (DFB) devices were produced from the epitaxial material. The RWG and DFB laser diodes were passivated with silicon nitride and silicon dioxide.

For the DFB laser diodes, metal gratings on the sides of the ridges were used for longitudinal mode selection. The top contact metals were sputtered. Electrochemical deposition of 10μm of gold provided thermal management. The substrate was thinned to 150μm before deposition of the bottom contact.

The structures were cleaved into bars with 900μm cavities. The devices were further passivated with aluminium oxide on the front facet. The back facet was coated with a highly reflective metal mirror.

The DFB devices were mounted on aluminium nitride heat spreaders and soldered into TO packaging with thermoelectric cooling. The packaging was hermetically sealed. The windows were anti-reflective.

The broad-area laser diodes had a threshold current density of 383A/cm^2 at 20ºC under pulsed operation. According to the researchers, the threshold is only slightly higher than for devices with wavelengths longer than 3μm.

Cascaded type-I QW devices have been reported with thresholds as low as 100A/cm^2 for quinary diode lasers and around 300 A/cm^2 for a superlattice design. QCL thresholds tend to be greater than 2kA/cm^2, depending on materials.

The characteristic temperature for the threshold (T_0) of the broad-area ICL was 67K, claimed as a record for ICL material by the researchers. The emission wavelength peaked around 2.84μm.

Narrow-RWG laser diodes with 3mm long, 7.8μm-wide cavity had continuous wave (cw) output power of more than 11mW at 20ºC. These diodes emitted laser light up to 50ºC. Previous reports of ICLs with emission wavelengths shorter than 3μm have been for broad-area devices in pulsed operation.

The DFB output up to a few milliwatts (less than 4mW) in cw operation at room temperature. The threshold was at 1.4kA/cm^2. The threshold power was 6.2kW/cm^2 — much lower than the best indium phosphide QCLs reported so far.

Current based tuning (Figure 2) gave a 7nm wavelength range (21nm/W, 0.13nm/mA). Combining current and temperature (0.29nm/K) tuning extended this to 12nm. The researchers say that this is more than sufficient for TLAS. By varying the DFB gratings, wavelengths between 2777.5nm and 2928.8nm, a range of more than 150nm, could be produced.

Antimony-free QW

China's Shanghai Institute of Microsystem and Information Technology has developed a long-wavelength indium arsenide (InAs) QW laser diode grown on indium phosphide (InP) substrate [Y. Gu et al, Appl. Phys. Lett., vol106, p121102, 2015]. The researchers claim the longest wavelength achieved, 2.9μm, as a record for antimony-free (Sb) structures.

Antimony-based semiconductor lasers can achieve 3μm cw operation at room temperature, using gallium antimonide substrates. However, GaSb is more expensive than InP and presently is of lower quality. Further, GaSb-based devices suffer thermal management problems due to its low thermal conductivity.

Gas-source molecular beam epitaxy (GS-MBE) was used to grow the laser structure (Figure 3) on sulfur-doped (001) n-InP. An indium aluminium arsenide template/cladding layer of 0.87μm metamorphic n-$In_{0.8}Al_{0.2}As$ (485ºC) was grown on 1.6μm compositionally graded InAlAs buffer (495–455ºC) on top of

$In_{0.52}Al_{0.48}As$, lattice-matched with the underlying InP substrate. The indium-content grading went from 52% to 84%, overshooting the 80% of the metamorphic template layer. The overshoot was designed to ensure full relaxation of the template layer. The n- and p-type doping for InAlAs layers were provided by silicon and beryllium, respectively.

The active region featured a multiple QW structure with eight 15nm InAs wells in 15nm $In_{0.6}Ga_{0.4}As$ barriers, grown at 435ºC. The QW material composition and thicknesses were designed to provide strain compensation with respect to the template. The use of eight wells compensated for the impact on radiative recombination from the relatively large density of threading dislocations (10^6–10^7/cm^2) in the template layer.

$In_{0.8}Al_{0.2}As$ was chosen for the waveguide material, which has been found to have better performance than $In_{0.8}Al_{0.2}As$ or $In_{0.8}Al_yGa_{1-y}As$ alternatives. The upper p-InAlAs cladding was 1.8µm, followed by 300nm p-$In_{0.8}Al_{0.2}As$ for the contact. The waveguide, cladding and contact were grown at 465ºC.

Ridge waveguide laser diodes were produced with 8µm wide ridges. Isolation was provided by 300nm silicon nitride. Finished devices were mounted epi-side up on copper heat sinks. The measurements were made with the devices in a liquid nitrogen cryostat.

A laser diode with a 0.8mm-long cavity lased around 2.80µm at 160K under 200ns 100kHz pulsed operation at 1.2x the threshold current. The wavelength red-shifted to 2.91µm at 230K, “by far the longest wavelength of InP-based type-I QW lasers,” according to the research team.

Continuous wave operation was limited to less than 180K due to self-heating effects. The 150K cw output power was 1.2mW/facet at 400mA injection. The cw lasing operation voltage was ~1V at 150K and ~1.2V at 180K.

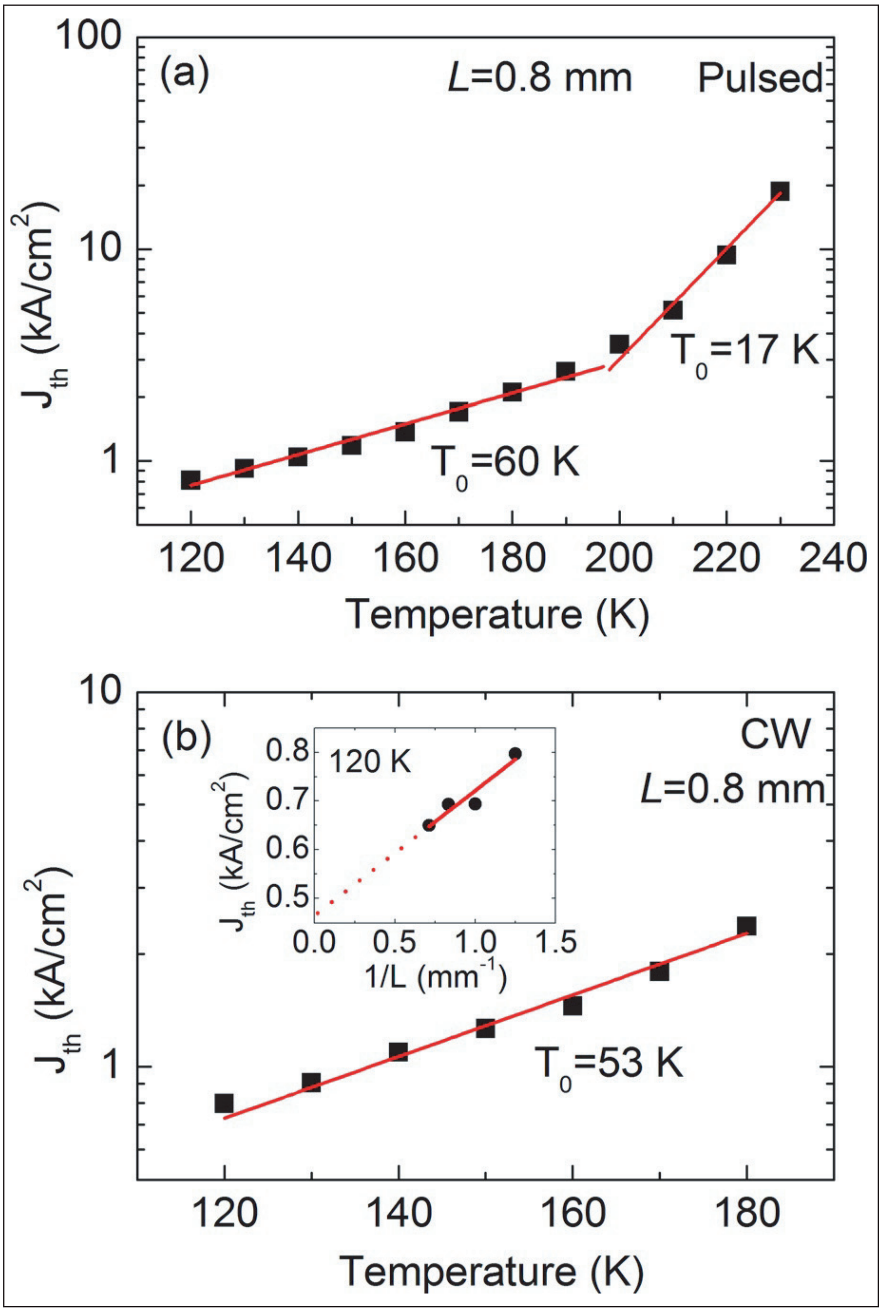

Figure 4. Temperature dependence of threshold current density of laser with 0.8mm cavity length under (a) pulsed and (b) cw operation. Inset of figure (b) cw threshold current density (J_{th}) as a function of reciprocal cavity length (1/L) at 120K. Solid and dotted lines are fits to experimental data and extrapolation, respectively.

The pulsed and cw current density thresholds at 120K were 812A/cm^2 and 797A/cm^2, respectively (Figure 4). The increase in threshold for pulsed operation had a characteristic temperature (T_0) of around 60K between 120K and 200K. The corresponding figure for cw injection was 53K. Above 200K, T_0 for pulsed operation decreased to 17K. This drop is attributed to increased carrier loss.

Extrapolating the cw threshold current at 120K to infinite cavity length gave a value of 465A/cm^2. The 1.4mm cavity threshold was 650A/cm^2.

The researchers say that they need to improve carrier confinement to increase operation temperatures. Electron and hole leakage could be reduced with blocking layers on the n- and p-sides of the device. The researchers describe their work as being at an early stage. ■

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