Getting a green light from lasers

This year has seen significant steps towards filling the 'green gap' for semiconductor light emission, particularly for lasers. A number of groups have published papers describing various approaches to producing green lasers in the III-nitride material system by using indium gallium nitride (InGaN) based active layers. Mike Cooke reports.

While producing red and blue laser light from semiconductors is relatively simple, producing green lasers has been much harder. Laser diodes (LDs) based on II–VI compound semiconductor materials were demonstrated in the 1990s, but these devices are unreliable under the high currents required to produce lasing.

A green light source is needed to produce full-color RGB projection systems. Green lasers are also used in medical and industrial applications. At present, while compact direct red and blue semiconductor laser diodes are available, green laser light (520–570nm) in commercial laser-diode-based systems, such as overhead projectors, is produced using conversion from sources that emit light at another frequency.

A common technique is to use second-harmonic generation (SHG) from non-linear optics materials to combine photon energies, doubling the light frequency to create a green wavelength. Such conversion techniques naturally waste energy and add bulk to products. Creating a direct green laser diode would enable smaller full-color projectors (e.g. in a mobile phone format) to be produced, hopefully at lower cost.

InGaN layers

With the development of blue–violet–ultraviolet LEDs and laser diodes based on the III-nitride system, starting in the 1990s until the present, it is natural to look to the possibility of extending the wavelength (reducing the frequency) of this material system into the green gap. This involves narrowing the energy bandgap from gallium nitride's bandgap of about 3.4eV (corresponding to the ultraviolet wavelength 365nm) by introducing indium (i.e. $In_xGa_{1-x}N$). However, to get into the green range (520–570nm) requires significant amounts of indium, and growing such layers with the high quality that is needed is extremely difficult. Thermal stability and parasitic chemical reactions have been highlighted as particular problems in growing such layers.

In the past, various techniques have been used to improve material quality, which is particularly important for the active layer, where indium concentrations have to exceed 20% to achieve suitable energy bandgaps to produce green light. One factor that reduces control is the formation of indium-rich clusters.

Further problems arise from the crystal orientation. Normally LDs are grown on GaN, where the surface consists of the c-plane (0001), but then large spontaneous and piezoelectric (i.e. strain-dependent) polarization fields arise from the different effective charges (ionicity) of the group III elements (Ga, Al, In) and nitrogen in the wurtzite lattice. Such large polarization fields shift the energy band levels of the carriers in heterostructures through quantum-confined Stark effects (QCSEs) and also make it difficult to set up the electrical conditions needed for lasing by separating the electron and hole wave-functions, even at high carrier current densities. Wave-function separation reduces the rate at which electrons and holes recombine radiatively, increasing the weight of non-radiative mechanisms.

One approach is to use m-plane $\{10\bar{1}0\}$ GaN, which results in non-polar electronic structures. Violet m-plane GaN LDs were reported in 2007. Among the problems arising from the use of c-plane GaN has been low slope efficiency. Devices using m-plane substrates demonstrate better slope efficiency than those grown on c-plane GaN, meaning that more of the extra power delivered beyond the threshold becomes laser light. It is also desirable for the threshold of turn-on of lasing to be achieved at as low current and voltage as possible. Further orientations with non-polar or semi-polar characteristics include $\{10\bar{1}\bar{1}\}$ and $\{11\bar{2}2\}$ planes.

The different orientations also have an effect on the layers grown above, including the active InGaN layers. For example, thermally induced defects of In diffusion at high concentration are common on c-plane substrates, while on m-plane material stacking faults tend to arise.

GaN substrate

One problem with producing specialist orientation GaN substrates is that the infrastructure is geared around producing c-plane, for example through metal-organic chemical vapor deposition (MOCVD) on sapphire or silicon carbide substrates. For other orientations researchers often have to look to different techniques for GaN growth such as molecular beam

Figure 1. Schematic of hydride vapor phase epitaxy (HVPE) reactor.

epitaxy (MBE) or hydride vapor phase epitaxy (HVPE), which is a fairly old epitaxial process (dating back to the 1960s) with a relatively high growth rate. Nitrides can be grown with a rate of 100–200µm/hour using HVPE. This compares with tens of microns/hour for MOCVD, and 1µm/hour for MBE.

An HVPE machine (Figure 1) consists of a hot-wall reactor (MOCVD uses a cold-wall reactor) and a series of gas supplies: Ga, which is heated and positioned upstream of the substrate; hydrogen chloride (HCl) gas flowing over this precursor will form gallium trichloride ($GaCl_3$); ammonia (NH_3) is used as nitrogen precursor; and hydrogen and nitrogen are used as carrier gases. The same process can be used to deposit AlN buffer layers, with Al replacing Ga.

Japan's Sumitomo Electric Industries is one of the companies using HVPE to produce non-standard-orientation GaN. In particular, a semi-polar {20$\bar{2}$1} GaN substrate has been used to achieve CW operation of 520nm green InGaN-based LDs [1]. Sumitomo has even produced LDs on semi-polar {20$\bar{2}$1} GaN substrates that achieve 531nm wavelengths in pulsed-mode operation [2].

Sumitomo's {20$\bar{2}$1} GaN material has a threading dislocation (TD) density less than 1×10^6/cm^2. The resulting substrates were n-type with sufficiently low resistivity (0.01Ωcm) for the use of back-side ohmic contacts. Using {20$\bar{2}$1} GaN material increases the homogeneity of the InGaN structures, resulting in narrower spontaneous spectra compared with other attempts at creating green LDs.

CW operation was achieved through improvements in the epitaxial structure enabled by the use of lattice-matched quaternary InAlGaN cladding layers and of a ridge waveguide, compared with the gain guiding used in Sumitomo's previous pulsed laser. The lattice matching improves crystal quality. The cladding was also optimized for optical confinement properties.

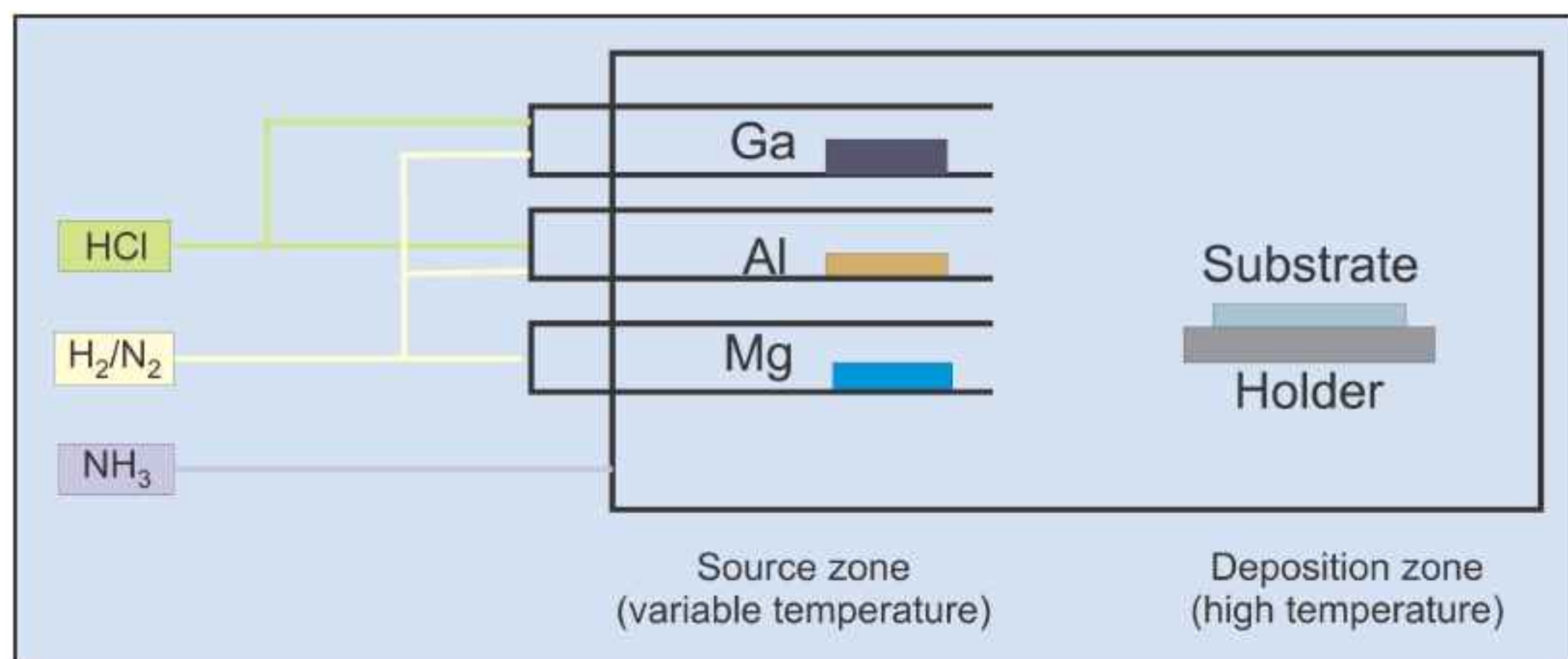The epitaxy was performed using MOCVD of: n-type GaN, an n-type InAlGaN cladding layer, an n-type InGaN waveguide, an InGaN MQW active region, a p-type AlGaN electron-blocking layer, a p-type InGaN waveguide, a p-type InAlGaN cladding layer, and a p-type GaN top contact.

The threshold conditions for the continuous wave (CW) device were: current 95mA, current density 7.9kA/cm^2, and voltage 9.4V. The slope efficiency was 0.1W/A. The wavelength at 110mA is about 520nm and this is maintained up to 2.5mW output power (about 120mA). The researchers see the reduction in threshold voltage from 16V to 9.4V in moving from Sumitomo's earlier pulsed device to the more recent CW operation as being enabled by optimization with an improved doping profile, adjustment of the epitaxial layer structure to the green region, and better crystalline quality of both the InAlGaN cladding and the active layers.

A different angle

Another team that is working on m-plane material is Shuji Nakamura's group at University of California Santa Barbara (UCSB), which has reported on a blue–green laser diode (LD) based on a miscut substrate [3]. Nakamura is responsible for much of the development and commercialization of GaN as a light-emitting material for electronics as part of Nichia Corp in Japan in the late 1980s and all through the 1990s until he became a professor at UCSB in 1999. Also involved in the research is a scientist from Mitsubishi Chemical's Optoelectronics Laboratory, Kenji Fujito, who has worked on HVPE of high-quality non-polar m-plane GaN substrates [4].

Although the UCSB work has only reached 481nm so far, the researchers point to improved performance by using miscut non-polar substrates in terms of lasing threshold currents and slope efficiency, which suggests that moving to longer wavelengths should be 'easy' and a possible route to realizing high-power green laser diodes.

For the UCSB LDs, the m-plane GaN substrate was miscut about 1º in the [000$\bar{1}$] (-c) direction. Miscutting of substrates is commonly used to improve or manipulate material quality on a wide range of substrates. [5]. ►
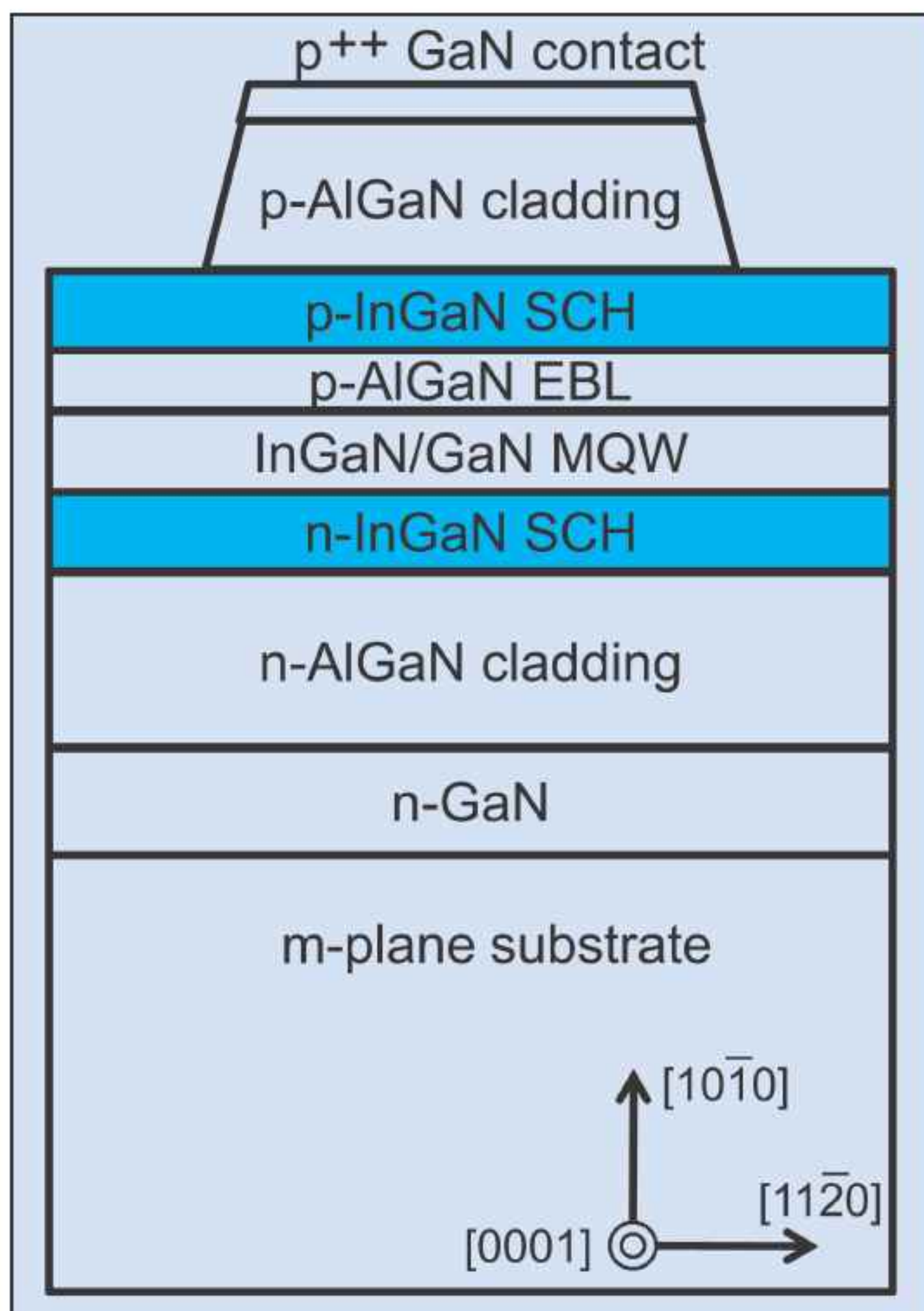
Figure 2. Schematic of laser diode structure used by UCSB. SCH = separate confinement heterostructure. EBL = electron blocking layer.

Figure 3. Dependence of threshold current density on lasing wavelength for various laser diodes produced by UCSB using on-axis and 1° towards [000$\bar{1}$] direction misoriented substrates.

UCSB used MOCVD to grow the laser diode. The active layer was a three-period multi-quantum well (10nm undoped $In_{0.03}Ga_{0.97}N$ barriers, 3nm InGaN wells with ~26% In, estimated through high-resolution x-ray diffraction). Electron-blocking layers (EBLs) and separate-confinement heterostructures (SCHs) were also used (Figure 2).

Ridge lasers pointing in the c-direction were formed using normal photolithography and etch processes. Nomarski and fluorescence optical microscopy of laser diode surfaces grown on nominal on-axis and miscut substrates showed a significantly smoother surface, without 'hillocks', for

Using m-plane substrates from Mitsubishi is Rohm. Scientists at Rohm's Kyoto R&D headquarters extended the wavelength for continuous wave (CW) operation of indium gallium nitride (InGaN) laser diodes... the 499.8nm CW lasing wavelength was the longest reported for such devices at that time
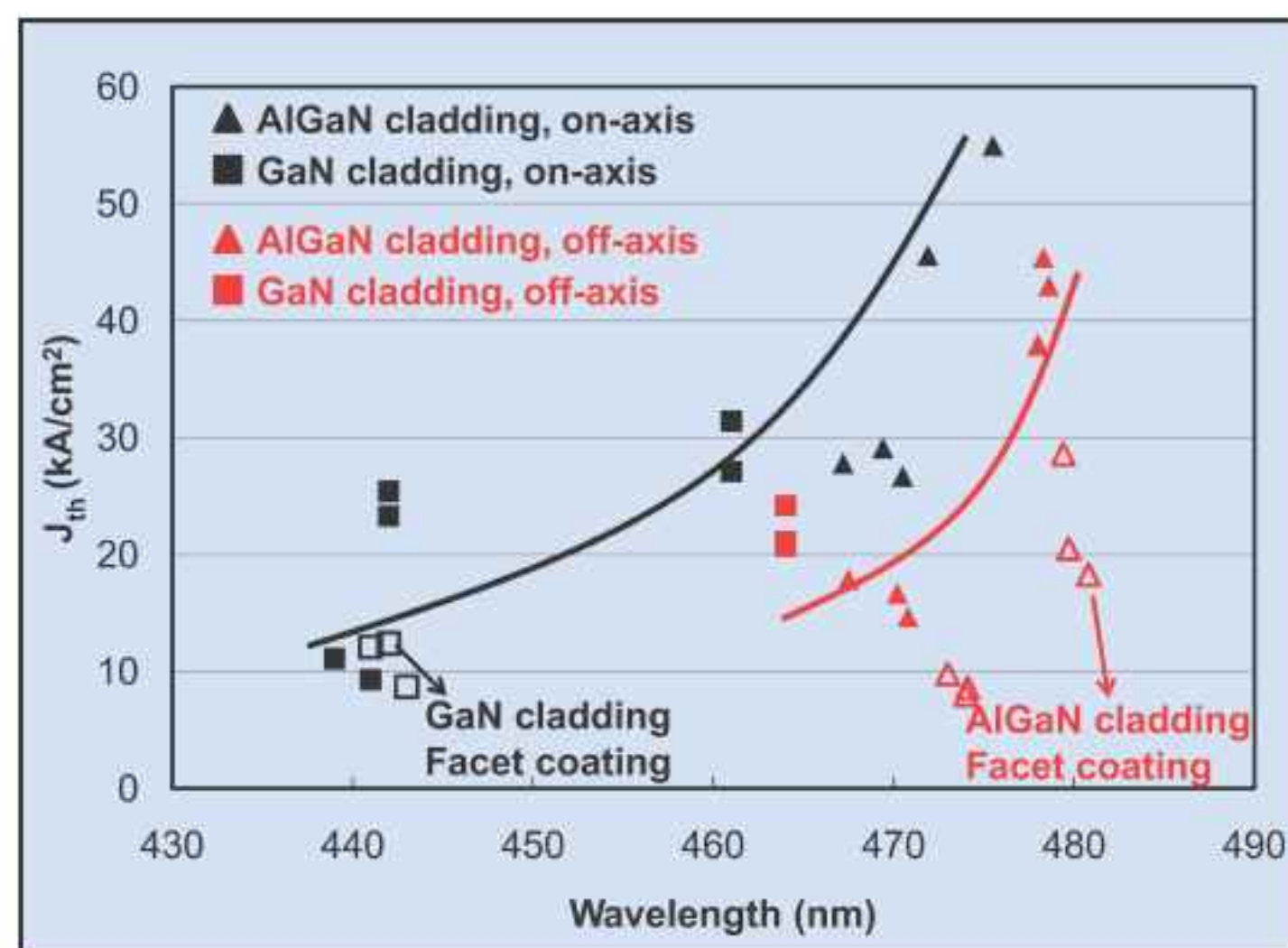
the laser diode grown on the miscut substrate. Also, photoluminescence was much more homogeneous for the miscut substrate device.

A comparison of 2x500μm laser diodes with uncoated facets in pulsed operation (1% duty cycle) shows a lower threshold current (153mA, compared with 413mA for nominal on-axis device) for the miscut substrate. Further, less blue shift was seen in moving from spontaneous emission to laser emission (~483nm spontaneous wavelength for both miscut and nominal, 471nm for miscut lasing, 461nm for on-axis lasing). These properties are attributed to larger indium fluctuations in the on-axis samples. A clarification of the mechanisms is promised in a future publication from the group.

The threshold current density tends to increase with wavelength (Figure 3), but with the miscut devices generally reporting a lower value. The longest lasing wavelength found was 481nm (10nm away from the spontaneous photoluminescence wavelength at 491nm) from a coated facet device in pulsed operation (1% duty cycle).

Non-polar route

Also using m-plane substrates from Mitsubishi is Rohm. Scientists at Rohm's Kyoto R&D headquarters extended the wavelength for continuous wave (CW) operation of indium gallium nitride (InGaN) laser diodes (LDs) [6]. The Rohm researchers claimed in February that the 499.8nm CW lasing wavelength was the longest reported for such devices at that time.

The Rohm team grew the LDs on freestanding m-plane wurtzite GaN substrates using low-pressure MOCVD. By growing in the m-plane direction, rather than the more usual c-plane, the devices avoid large polarization electric fields.
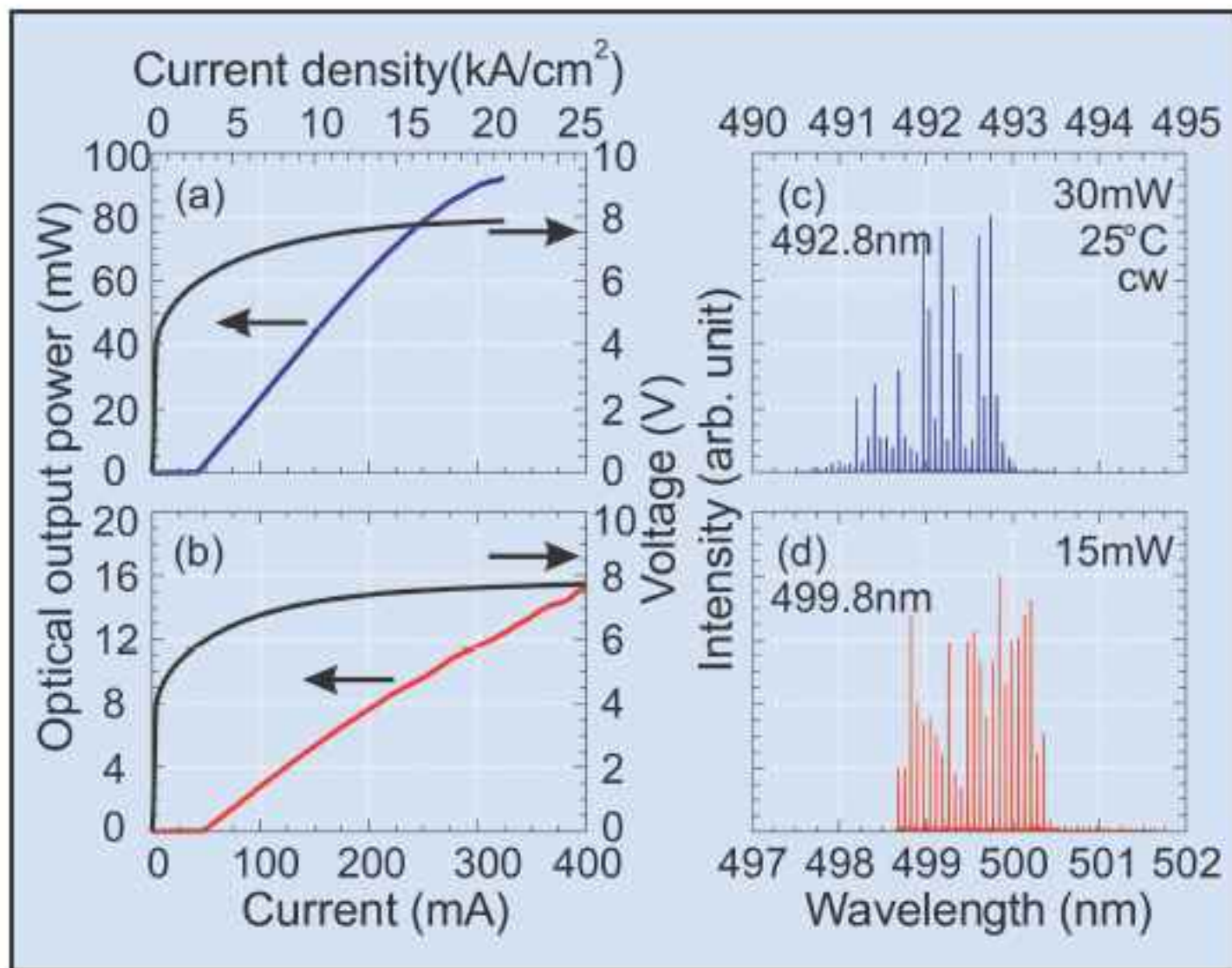
Figure 4. Output power (L–I, left scale) and voltage (V-I, right) performance with respect to current for the two Rohm InGaN devices — 70% reflective front mirror LD70 (a) and 97% reflective LD97 (b) — with respective spectra (c and d).

The Rohm LD structures consisted of layers, in sequence, of n-type GaN, n-type AlGaN (cladding), n-type InGaN (waveguide), a two-period InGaN multi-quantum well (active), p-type AlGaN (electron blocking), p-type InGaN (waveguide), p-type AlGaN (cladding), and p-type GaN (contact). Ridged stripes were etched out to form the laser structures (bottom width 2.5µm). A ZrO_2 insulator was used. The cavities were 600µm in length. Cleaving along the c-plane was used to form the mirror facets. Sputtered dielectric was used to create front and back mirrors. The back mirror was 99% reflective, but two different reflectivities were used for the front mirror (70% and 97%) to investigate the role of self-heating in LD performance.

For comparison, devices with similar threshold currents were chosen for detailed testing (Figure 4). The device with a 70% front mirror (LD70) had a threshold current of 42mA (density 2.8kA/cm²), threshold voltage of 5.9V and slope efficiency for producing laser emission of 0.4W/A. The figures for LD97 were 46mA (3.1kA/cm², 5.9V, and 0.05W/A, respectively. The maximum output powers for LD70 and LD97 were 92mW and 15mW. These come in well above the typical 5mW output of c-plane blue-green LDs. Spectral measurements showed the peak wavelengths of LD70 (operated at 30mW) and LD97 (15mW) to be 492.8nm and 499.8nm, respectively. Many sharp peaks are seen in the spectra.

By comparing the wavelength shift from CW and pulsed operation, the researchers determined that self-heating effects lead to a red-shift of the emission. Band-filling effects — when, with increasing numbers of carriers in the active region, the electrons and holes become more separated in energy — would lead to higher-energy photons, and hence to a blue-shift in the spectrum.
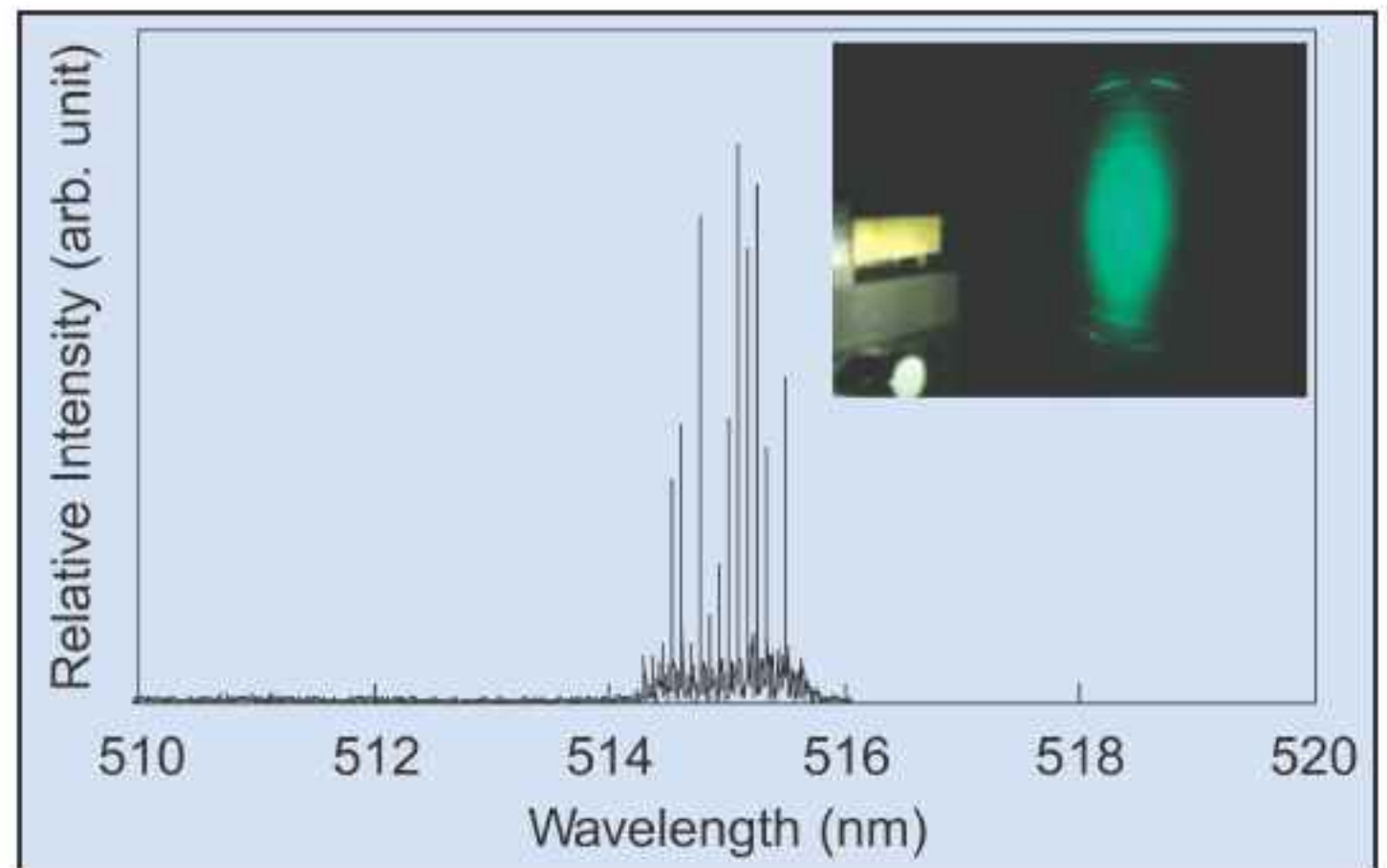

Figure 5. Lasing spectra of the 515nm LD with an output power of 5mW under CW operation at 25ºC.

Consortium

Another group that is using HVPE as a route to non-polar GaN substrates is a consortium of German/Swiss universities that aims to close the 'green gap' with light emitters, including lasers, under a project funded by Deutsche Forschungsgemeinschaft (DFG, German research foundation) and Switzerland's National Science Foundation (SNF). The title of the collaboration is 'Polarization Field Control in Nitride Light Emitters' (PolarCoN), which was established in 2008. The research is due to complete its €2m first phase in 2011. The universities that are involved are Ulm, Regensberg, Otto-von-Guericke Universität Magdeburg, Technische Universität Braunschweig, Stuttgart, Technische Universität Berlin, and the Swiss Federal Institute of Technology Zurich (ETH).

The research ranges from the growth of non-polar GaN quasi substrates by HVPE, through to the physics and technology of nitride-based non-polar green laser diode structures. The consortium says that various MOCVD, simulation and characterization activities will be carried out, with the main emphasis being on creating structures on HVPE substrates with surfaces in either non-polar or semi-polar directions, and overcoming the resulting material and structural problems. Another possible approach being considered is the minimization of polarization-induced fields on c-plane surfaces by carefully matching material combinations such as AlInN–GaInN.

The University of Ulm is leading the work on HVPE, with a view to growing non-polar full 2" wafers. The substrates that are being worked on include: r-plane sapphire, giving a-plane GaN; m-plane SiC, leading to m-plane GaN; and m-plane sapphire, resulting in m-plane/semi-polar GaN non-polar GaN bulk substrates. GaN grown with a c-plane is used as a reference. Ulm has also recently explored alternative structuring techniques to provide non-polar surfaces on c-plane GaN in inverted pyramid structures or stripes in a silicon dioxide mask.

Edging towards the green

Not all groups have abandoned the c-plane; for example, Nichia researchers have used a free-standing c-plane GaN substrate to grow their devices, managing to coax continuous 515nm 'green' laser light out of an InGaN structure [7]. The active layer consists of InGaN multi-quantum wells (MQWs). As with most commercial laser diodes, lower-refractive-index separate-confinement hetero-structures (SCHs) are used to confine the emitted light in the lasing cavity.

The dimensions of the resulting laser diode ridge were 2x600μm. CW characterization of the devices was carried out at 25ºC (Figure 5). Below 500nm, the devices had a threshold current density of 1–2kA/cm^2; this begins to increase as the amount of indium increases to the level needed to achieve a wavelength of 515nm (4.4kA/cm^2, corresponding to 53mA for the particular device). The 515nm device had an output power of 5mW at 88mA (and voltage 5.5V).

The paper also shows improved uniformity of photo-luminescence compared with previous laser diodes produced by the team that operated at wavelengths longer than 470nm. The Nichia group explains this as being due to their improved growth of the layers, particularly of the active MQW structure. The previous structures suffered from non-radiating regions with poor crystal quality. These non-radiating regions were not found in the newer structures.

Temperature variation and lifetime characteristics were also determined. Devices rated at 510–513nm wavelength were operated at 25ºC, with automatic power control for 500 hours giving an estimate of the lifetime at more than 5000 hours — the point when the operating current has increased 30% over the initial current.

Nichia's team describes their achievement as being 'green' LDs, presumably on the basis that in terms of spectral colors (violet, blue, green, yellow, orange red) 'green' is allotted the 495–570nm space. However, green is better perceived when in the range 520–570nm, while blue comes from 440–490nm. The range 490–520nm is better described as 'blue–green'.

Defect reductions

Also working on the c-plane is optoelectronics device manufacturer Osram Opto Semiconductors, which has created a 515nm laser with an output power of 50mW with greater temperature stability, easier control and higher modulation capability at several 100MHz [8]. It defines 'true green' by the spectral range 515–535nm.

In pulsed mode at room temperature the laboratory prototype achieved an optical output of 50mW and a wavelength of 515.9nm; the threshold current density was about 9kA/cm^2 and the voltage was 7.1V. The slope efficiency was about 130mW/A. A previous Osram Opto laser diode grown on c-plane GaN crossed the 500nm boundary [9] and had a threshold current of 8.2kA/cm^2 and a slope efficiency of 650mW/A.

The device was based on improved epitaxy and design of the active region, giving a 10-fold reduction in defect levels. An 11μm broad-area gain-guided laser structure was used in a pulsed mode (500ns pulse length, 1% duty cycle) to minimize thermal effects and for accurate measurement of thermal characteristics.

Osram Opto is also involved in the project MOLAS, which is funded by the German government's Ministry for Education and Research until March 2011 (FKZ 13N9373). Targeted at technologies for ultra-compact and mobile laser projection systems, among its aims is the projection of consistently sharp, true-color, high-contrast images — irrespective of the projection distance or surface — even in cell phone or camera formats. ■

The author Mike Cooke is a freelance technology journalist.

References

1. Yoshizumi et al, Applied Physics Express, vol2, p092101, 2009
2. Enya et al, Applied Physics Express, vol2, p082101, 2009
3. Lin et al, Applied Physics Express, vol2, p082102, 2009
4. Fujito et al, physica status solidi (a), vol205, p.1056, 2007
5. See, e.g., Cooke, Semiconductor Today, p.64, September 2009; www.semiconductor-today.com/news_items/2009/JULY/INP_140709.htm
6. Okamoto et al, App. Phys. Lett., vol.94, p.071105, 2009
7. Miyoshi et al, Applied Physics Express, vol2, p062201, 2009
8. Avramescu et al, Appl. Phys. Lett., vol95, p071103, 2009
9. Queren et al, Appl. Phys. Lett., vol94, p081119, 2009

Table 1. Comparison of some achievements towards green laser diodes in 2009.

	Date online	Reference	Wavelength nm	Threshold mA	kA/cm^2	V	Slope W/A	Operation mode
Sumitomo	21/8/09	[1]	520	95	7.9	9.4	0.10	cw
Osram Opto	17/7/09	[8]	515.9		9	7.1	0.13	pulsed
Sumitomo	17/7/09	[2]	531	924	15.4			pulsed
Sumitomo	17/7/09	[2]	520	491	8.2	17.7	0.04	pulsed
UCSB	24/6/09	[3]	481	380	18		0.05*	pulsed
Nichia	22/5/09	[7]	515	53	4.4	5.2	0.14**	cw
Osram Opto	27/2/09	[9]	500		8.2		0.65	
Rohm	18/2/09	[6]	499.8	46	3.1	5.9	0.05	cw
Rohm	18/2/09	[6]	492.8	42	2.8	5.9	0.40	cw

* Slope estimated from graph in paper. ** Slope calculated from data in paper.