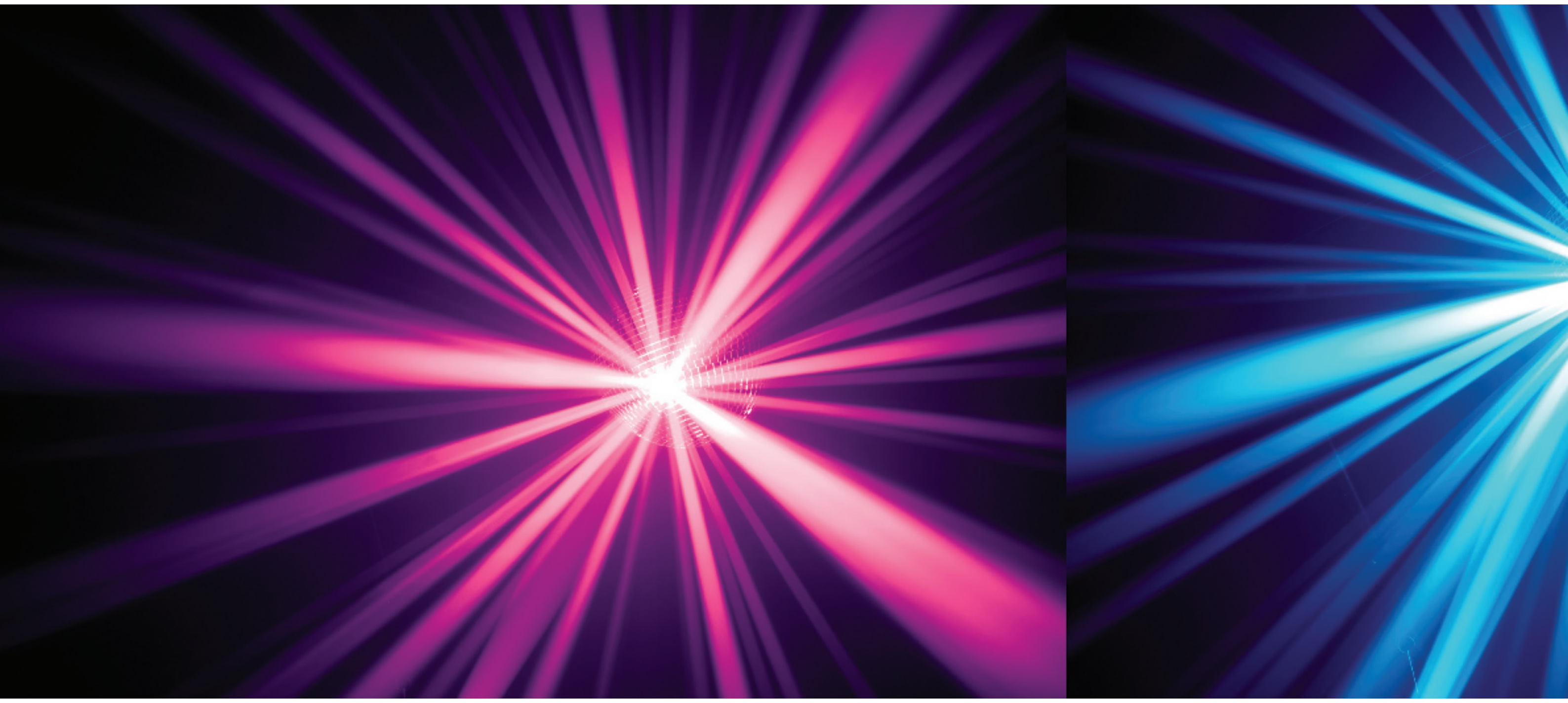

The evolving GaN VCSEL

Building a GaN VCSEL is far harder than making one from GaAs, but progress is being made through the introduction of different types of mirrors, alternative current injection schemes and new crystal orientations.

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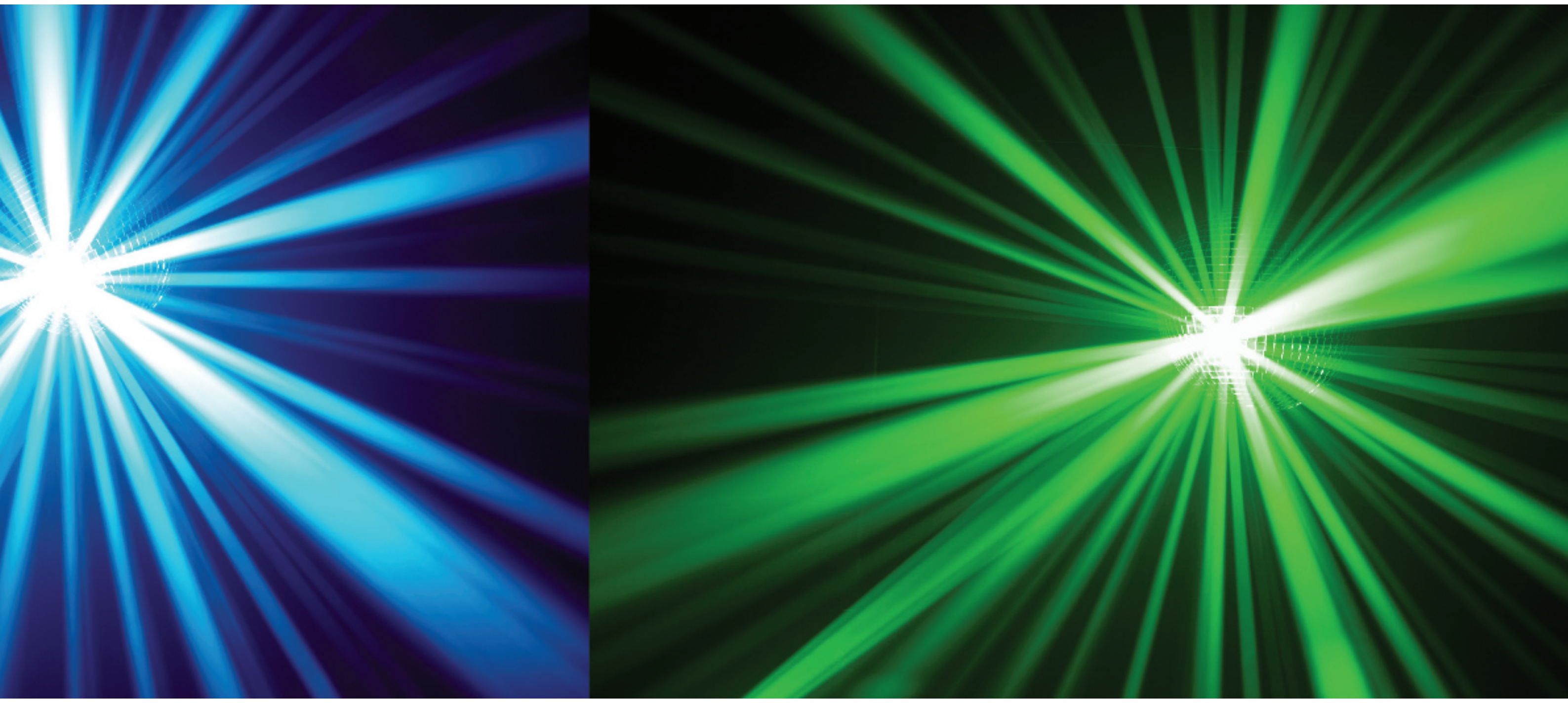
THE VERTICAL-CAVITY SURFACE-EMITTING LASER (VCSEL) has several advantages over its edge-emitting cousin. Superiorities include a lower threshold current, direct modulation at high speeds, a circularly symmetric output beam, wafer-level testing and the option to form densely packed, two-dimensional arrays. Thanks to the geometry of this class of laser, monolithic processing of large batches of devices is possible, and there is no need for cleaving, facet coating and bar handling. Consequently, the VCSEL can combine relatively low manufacturing costs with great performance.

Origins of the device can be traced back to 1977, when Kenichi Iga from Tokyo Institute of Technology first proposed this class of laser. Commercialisation followed in the 1990s, and the VCSEL is now serving a wide range of applications, including fibre optic communication networks, optical interconnects, data storage, sensing and laser printing.

As the VCSEL has evolved, researchers have expanded the range of material systems that can be used to produce this device, cut threshold currents to sub-milliamp levels and increased output powers. They are now in excess of 7 mW for single-lateral-mode devices and beyond watt-level for multi-lateral-mode devices. Error-free serial data rates have also increased significantly, with recent demonstrations exceeding 50 Gbit/s.

These impressive figures suggest that the VCSEL has no weaknesses. But that's not true. Although this chip delivers very high levels of performance when emitting at the standard wavelengths of 850 nm and 980 nm, it has been very challenging to stretch emission to 1310 nm or 1550 nm, the wavelengths used for long-haul data transmission in optical fibre. Shifting the output to shorter wavelengths has also been tricky, and this has prevented the VCSEL from being used in high-resolution printing, high-density optical data storage, head-up displays, backlighting and chemical/biological sensing (see Figure 1).

Here, we will look at the challenges of fabricating VCSELs that are based on the III-N materials system and span 400 nm to 550 nm. Some impediments to forming this device are very similar to those for



making long-wavelength VCSELs with InP-based materials: a lack of a lattice-matched material system for forming high reflectivity mirrors; the difficulty of realising efficient current spreading layers; and the challenge of producing robust confinement, for both the current and the optical mode. However, the nitrides also presents some additional, substantial complications.

VCSEL challenges

To understand why it is so difficult to make a GaN-based VCSEL, one must first understand how this device operates. It is formed by sandwiching a thin active region between parallel mirrors, and it features a cavity length of a few microns – that's hundreds of times shorter than that of an edge emitter.

The short cavity length enables high-speed direct modulation, thanks to the small photon volume. However, the gain per round-trip pass through the cavity is far less than that for an edge-emitter. To compensate, cavity loss must be very small, and thus the reflectivity of the mirror, which is a distributed Bragg reflector (DBR), must be very high – it has to be of the order of 99 percent.

With a GaAs-based VCSEL, it is relatively easy to form such a high reflectivity. Engineers just have to form a stack of lattice-matched, quarter-wavelength thick alternating layers of GaAs and AlGaAs, which can both be doped, thereby enabling electrical injection into the cavity. Replicating this approach with the III-Ns has proved impossible, so far, because there are no straightforward methods to form lattice-matched, highly reflective conducting mirrors. This had led several groups to introduce new types of device structures, which either combine an epitaxial DBR with a dielectric one, or employ dielectrics for both mirrors (see Figure 2).

Another consequence of the VCSEL's short cavity length is the complex standing-wave profile of the electric field intensity. To optimise laser performance, it is essential to position the active region at the peak of this standing wave, while aligning lossy layers, such as heavily doped layers, at a standing wave null. Very precise control of the cavity length is needed to realise this. This is readily achievable in all-epitaxial structures, but more challenging in devices that feature double dielectric DBRs and are formed with substrate lift-off or thinning.

A lack of conductivity in the mirrors used in a GaN VCSEL makes it harder to deliver uniform current injection into the active region, and ultimately to realise high modal gain. Carriers are introduced into the active region with sophisticated current injection schemes, such as single or double intra-cavity contacts. With these approaches, a highly conductive layer spreads the current laterally, prior to injection into the active region. III-nitrides are unsuitable for current-spreading, due to their very low conductivity. Better is the semi-transparent material indium tin oxide (ITO), but even its conductivity is insufficient to prevent current spreading issues for device apertures greater than 10 μm in diameter. ITO also has significant optical loss in the visible, making the placement of this layer critical to device performance.

A further challenge for the GaN-based VCSEL is current confinement. It is tricky to do this with selective oxidation, a process that is repeatable and reliable for manufacturing GaAs VCSELs. So researchers have turned to current confinement schemes that include patterning apertures in SiO_2 or Si_3N_4 and selective-area surface passivation via reactive ion etching of *p*-GaN.

Challenges unique to GaN

On top of the challenges just highlighted, III-nitrides have their own materials issues. Devices grown on the most common GaN plane, the *c*-plane, are hampered by polarization-related electric fields within the active region that impair material gain and increase threshold currents. Device progress is also held back by the high-cost and limited availability of high-quality native substrates, which are needed to realise epilayers with acceptable defect densities. But even if this native foundation is used, high-quality epilayer growth is tricky, due to the lack of lattice

Figure 1: Applications for GaN-based VCSELs include high-density optical data storage, displays, high-resolution printing, and chemical/biological sensing

and thermal matching between most III-Ns (there is an exception: GaN and one composition of AlInN). This places restrictions on epitaxy, and tends to lead to material that is plagued with cracks or extended defects. These imperfections cut mirror reflectivity, increase scattering loss and result in current leakage paths.

Finally, the internal quantum efficiency of an InGaN emitter diminishes at higher drive currents and longer wavelengths – well-known issues that are referred to as droop and the green gap, respectively. Droop is a non-radiative process, so it ideally clamps in diode lasers above threshold, but it still increases the threshold current. Meanwhile, the green gap makes it very difficult to fabricate VCSELs emitting at 500 nm and beyond.

First breakthrough

In April 2008, more than a decade after Shuji Nakamura reported the first electrically injected, GaN-based edge emitting laser, researchers at the National Chiao Tung University (NCTU) in Taiwan announced the first electrically injected GaN-based VCSEL. This 462.8 nm laser featured a 10 μm-diameter aperture, produced a continuous output at 77K, exhibited a clear transition from spontaneous to stimulated emission, and had a threshold current and threshold current density of 1.4 mA and 1.8 kA cm^{-2}. The authors did not report the output power of this chip, but revealed a divergence angle of about 11.7°, a polarization ratio of 80 percent, and a non-uniform emission profile across the aperture above threshold, with several apparent bright spots.

Development of the bottom epitaxial DBR, which showed a reflectivity of 99.4 percent and was crack free, played a crucial role in the first demonstration of an electrically injected, GaN-based VCSEL. On this mirror – a 29 period epitaxial AlN/GaN bottom DBR – the researchers formed a ten-period $In_{0.2}Ga_{0.8}N$ (2.5 nm)/GaN (7.5 nm) quantum well/barrier stack and an eight period dielectric Ta_2O_5/SiO_2 top DBR. Inserting five-and-a-half pairs of AlN/GaN superlattices with an optical length totalling $\lambda/2$ cut biaxial strain in the DBR. Carriers entered the active region via a lateral double-intra-cavity current injection scheme employing a SiN_x current aperture. ITO with a thickness of 240 nm, equating to λ, covered this and improved current spreading.

Limitations of this design were probably: the relatively thick ITO layer, which introduced significant optical loss to the cavity; current crowding in the intra-cavity contact; and poor thermal conductivity of the sapphire substrate. It is also possible that the absence of an electron-blocking layer impaired carrier confinement.

Efforts by NCTU were followed by a flurry of results showing device improvements (see Figure 3 for details). In 2008 Nichia Corporation reported the first electrically injected lasing at room temperature, using a device based on a flip-chip geometry. By employing a vertical contact configuration and mounting a chip that features double-dielectric DBRs on a highly thermally conductive silicon substrate, the researchers addressed three issues: current crowding, low thermal conductivity of sapphire, and the challenges associated with III-nitride DBR growth. Thanks to these refinements, the VCSEL did not suffer from a hike in operating voltage that can occur with severe current crowding and lead to greater heat generation. Optical losses were minimal in the device, thanks to the high reflectivity of the DBR.

To form this chip, the researchers began by forming an epiwafer on *c*-plane sapphire with an active region comprising a two-period stack of interleaving 9 nm-thick quantum wells and 13 nm-thick barriers. Current injection occurred through an 8 μm diameter, SiO_2 aperture covered with 50 nm of ITO, plus metal electrodes that formed the *p*-side contact. Measurements revealed that the ITO had an optical loss of 0.5 percent near the lasing wavelength, so to minimize this, the team added an Nb_2O_5 layer with a thickness of $\lambda/8$. This positioned the centre of the ITO at a standing-wave null.

Final fabrication steps included deposition of an 11.5 period SiO_2/Nb_2O_5 bottom DBR over a portion of the current injection area, the addition of a bonding metal to the top of the planarized structure, and flip-chip bonding to a silicon substrate, followed by sapphire removal via laser lift-off. Chemical-mechanical polishing thinned the *n*-side of the bonded epitaxial layers to 1.1 μm, before the team added an *n*-contact and a seven period SiO_2/Nb_2O_5 top DBR.

The 414.4 nm VCSEL that resulted was capable of delivering continuous-wave emission at room temperature, had a threshold current of 7.0 mA and threshold current density of 13.9 kA cm^{-2}, and produced a peak output of 0.14 mW. Threshold voltage for the device was a relatively low 4.1 V – about half that of the VCSEL from NCTU – due, most likely, to vertical current injection.

Although the emission from this laser was linearly polarized, its orientation with respect to the crystal axes was unclear and probably random. That's not surprising, given the cylindrical symmetry of the VCSEL cavity and relatively isotropic gain in the quantum well plane. Developers of this device also noted non-uniformity in the lasing spot across the current aperture. This might be due to inhomogeneities in cavity length, surface morphology, or active region quality.

By turning to dielectrics for both the mirrors, the researchers circumvented challenges associated with the growth of high-reflectivity, crack-free DBRs, and they also benefited from superior heat dissipation and current injection. But they paid a penalty for all of this: greater process complexity. Fabrication of a double-dielectric VCSEL involves bonding, laser lift-off and well-controlled thinning. Cavity-length control is also tough, because it is difficult to polish a large-area substrate in a uniform manner to a sub-micron thickness.

Better foundations

Following in the footsteps of developers of GaN-based edge-emitting lasers, Nichia's researchers switched to free-standing GaN substrates. That move increased the room temperature, continuous-wave output power of their VCSELs by almost a factor of five to 0.62 mW. Improvement stemmed from slashing the defect density in the epitaxial layers by three orders of magnitude to several million per square centimetre.

The team attributed the higher output power of its VCSEL – which employed the same fabrication and device structure as its predecessor, with the exception of the substrate removal process – to a more uniform and complete filling of

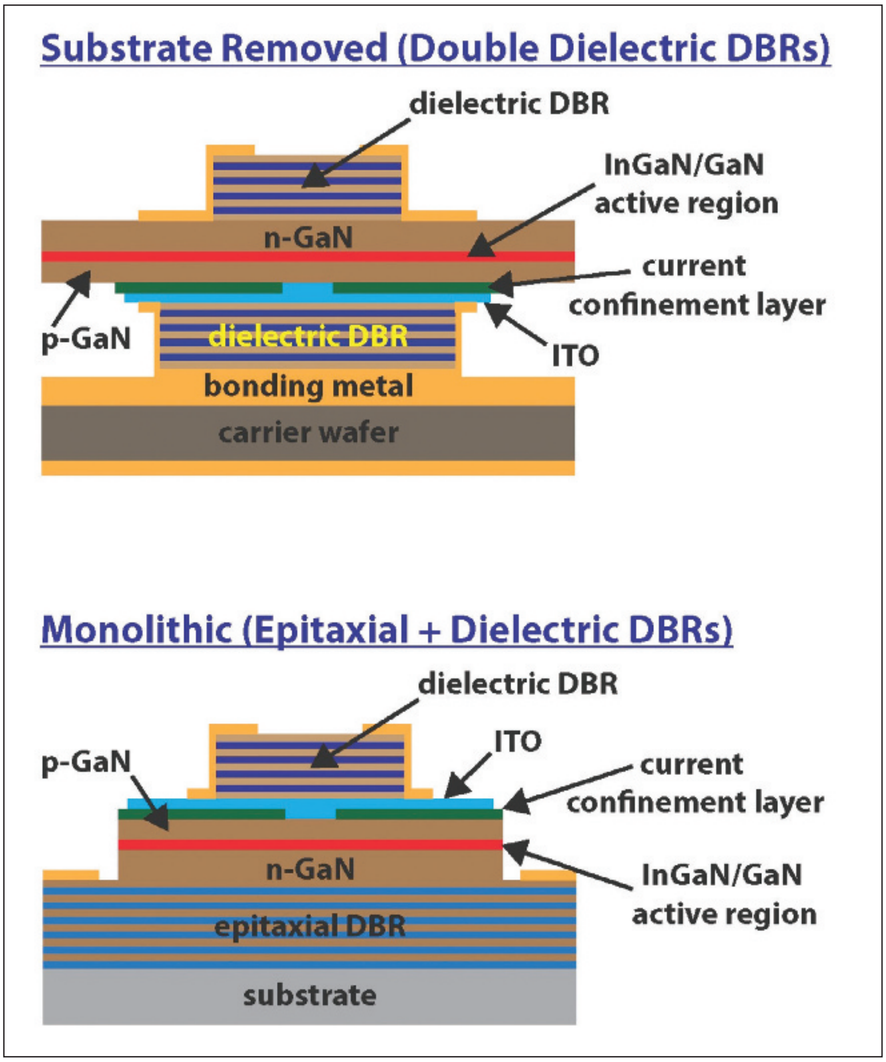


Figure 2: GaN VCSEL structures that have been demonstrated. The top structure requires wafer bonding and removal of the substrate from the cavity using thinning or etching. The bottom structure utilizes a lattice-matched epitaxial bottom DBR and a dielectric top DBR

the lasing aperture. Longitudinal mode spacing indicates a 4 μm cavity length, which is sufficient to support a number of longitudinal modes. Multiple modes might account for the higher threshold currents in these devices.

Switching from sapphire to a native substrate increased operating lifetime significantly. However, even with this superior foundation, the threshold current still increased after only 10 minutes of operation. Meanwhile, variations in cavity length are higher than those for the VCSEL formed on sapphire, because lapping and polishing is required to remove native GaN.

Researchers at Nichia and NCTU have continued to refine their GaN VCSELs over the last few years, and other groups have also contributed to the development of this device. Advances at NCTU led to the report of room-temperature, continuous-wave lasing in summer 2010, using a hybrid DBR design on a sapphire substrate. Improvements in performance resulted from: a trimming of ITO thickness to 30 nm to reduce optical loss; the addition of an AlGaN electron-blocking layer to quash carrier overflow; and an improved *p*-side contact, thanks to the introduction of a 2-nm-thick p^+-InGaN layer between *p*-GaN and ITO.

Using a similar fabrication process, device geometry and epitaxial bottom DBR as before, but moving to a ten-period InGaN (2.5 nm)/GaN (12.5 nm) quantum well/barrier stack and increasing the pairs of Ta_2O_5 and SiO_2 layers from eight to ten, helped improve device performance. Emitting at 410 nm, the second-generation VCSEL had a reduced threshold voltage of 6 V and

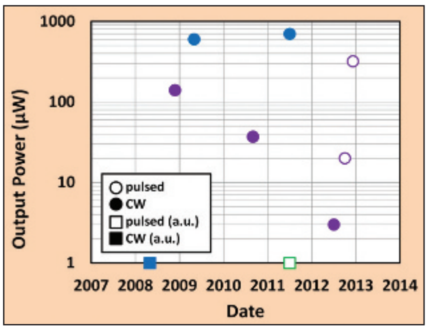


Figure 3: Electrically injected GaN-based VCSEL output power vs. time. Closed circles are CW, open circles are pulsed, and squares represent output powers originally reported in arbitrary units (a.u.). Data points are color-coded to the emission wavelength

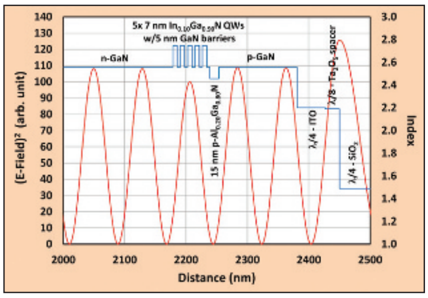


Figure 4: Standing-wave profile in the cavity region of a typical GaN-based VCSEL, illustrating the alignment of the gain region with a standing wave peak and the lossy ITO with a standing wave null

produced an output power of 37 μW. Threshold current and threshold current density were 9.7 mA and 12.4 kA cm^{-2}, and the polarization ratio at this shorter wavelength was only 55 percent.

Researchers at Nichia have also made recent advances, using their fabrication process for violet VCSELs to make blue and green cousins. The blue emitter produced a continuous-wave output of 0.7 mW, while the green equivalent delivered a pulsed output (power not revealed). According to this team, the homogeneity of the lasing spot within the injection aperture is critical to obtaining higher performance. This underscores the importance of effective, lateral-current-spreading layers.

Further contributions to VCSEL development have come from Panasonic Corporation, which has produced violet VCSELs capable of continuous-wave operation using a fabrication process similar to that developed by Nichia. This team, which is currently developing GaN-based VCSEL arrays, has turned to relatively long cavity lengths of typically 6 μm to permit multiple longitudinal modes within the gain spectrum. Merits of this approach include reduced thermal sensitivity and increased uniformity of the elements in the arrays.

Non-polar structures

Another option for improving VCSEL performance is to turn to non-polar structures, which increase optical gain and lower threshold current density through the elimination of the quantum confined Stark effect (QCSE). A team from the University of California, Santa Barbara, which included myself, pursued this approach. We were the first to demonstrate a GaN-based VCSEL on a nonpolar (*m*-plane) substrate.

By switching to non-polar or semi-polar quantum wells, in addition to avoiding or reducing the QCSE, we can ensure that the polarization direction of the lasing mode is always aligned along a given crystal direction. This is not the case for conventional VCSELs, which typically exhibit a random polarization direction.

We formed our VCSEL on a free-standing, *m*-plane GaN substrate. Fabrication involved a band-gap-selective, photo-electrochemical (PEC) undercut etching of an intra-cavity embedded sacrificial layer of InGaN. This enabled bonding and removal of the epitaxial layers from the substrate. Thanks to this approach, we could realise precise cavity length control while employing top and bottom dielectric DBRs and recycling expensive, free-standing GaN substrates. To improve current spreading, we used a λ/4-layer of ITO that was positioned at a standing-wave null of the cavity to minimise optical loss (see Figure 4).

Violet VCSELs produced in this manner emitted 19 μW and had a threshold current of 70 mA. This high threshold may be due to ITO absorption loss or cracking during the bonding process. Polarization of the lasing mode was observed to be along the *a*-direction for all devices tested.

The polarization ratio for these devices is close to one (see Figure 5 for an illustration of polarization alignment). Thanks to polarization locking in these non-polar VCSELs, they could someday be used to fabricate large arrays of devices with the same polarization direction. Such emitters may find use in various applications.

Alternative mirrors

Further progress of the electrically injected, GaN-based VCSEL was reported in 2012 by a team from EPFL. They formed monolithic devices using highly reflective, defect-free $Al_{0.18}In_{0.82}N$ DBRs that are lattice matched to GaN. A free-standing *c*-plane GaN substrate provided the foundation for this emitter, which featured a bottom epitaxial DBR and a top dielectric DBR. Such a structure avoids the tricky fabrication steps of the other approaches, which require the removal of the cavity from the substrate or substrate thinning. The price to pay for this is a more challenging epitaxial structure. However, with well-developed epitaxial DBR technology, this monolithic structure presents a viable path toward high-volume manufacture of GaN-based VCSELs.

The EPFL team has also pioneered a simple method for forming a current aperture – passivating portions of the *p*-GaN with reactive-ion-etching, plasma treatment. With ITO acting as the current spreading layer, uniform light emission is possible throughout the aperture. Devices lased at 420 nm, produced a pulsed output of more than 300 μW and had a 70 mA threshold current. Researchers blamed the high threshold current on ITO absorption loss and insufficient reflectivity in the top DBR. Options for cutting current are to trim the thickness of the ITO and tune its position.

Which way forward?

Over the last few years, progress of the GaN VCSEL has been significant, but key challenges must be overcome before this device can enjoy commercial success. Researchers must pursue either new DBR technologies, or develop methods to generate stand-alone cavities that have well-controlled lengths and can be attached to dielectric DBRs. If air-gap bottom DBRs could be created by selective removal of every other λ/4-layer using band-gap-selective PEC etching, only several periods would be needed to produce extremely high reflectivities. However, fabrication of such structures is very tough. So it may be that further optimisation of the AlInN DBR scheme developed at EPFL leads to the first manufacturable GaN-based VCSEL.

What is clear is that if approaches involving substrate removal via backside wafer thinning are to become commercially viable, they will require more precise control of cavity length. This might be possible with a combination of thinning and band-gap-selective PEC etching, which could planarize the cavity with an embedded stop-etch layer placed at the desired cavity thickness. Full substrate removal using PEC etching also presents challenges. However, this approach does provide cavity length control and it enables the recycling of expensive, free-standing GaN substrates.

Another area requiring improvement is that of the current spreading layers. Addressing this is essential for the realisation of larger-area devices that will deliver higher output powers. The ITO technology that is widely used today has been pushed to its performance limits, so further progress will hinge on the introduction of novel injection schemes and materials. This could involve the introduction of reliable, low-resistance tunnel junctions in GaN. Armed with this refinement, engineers would not have to concern themselves with the current spreading issue, because *p*-GaN could be replaced with higher conductivity *n*-GaN. Alternatively, developers of GaN VCSELs could increase current spreading by employing novel, two-dimensional materials with high transparency and high lateral conductivity.

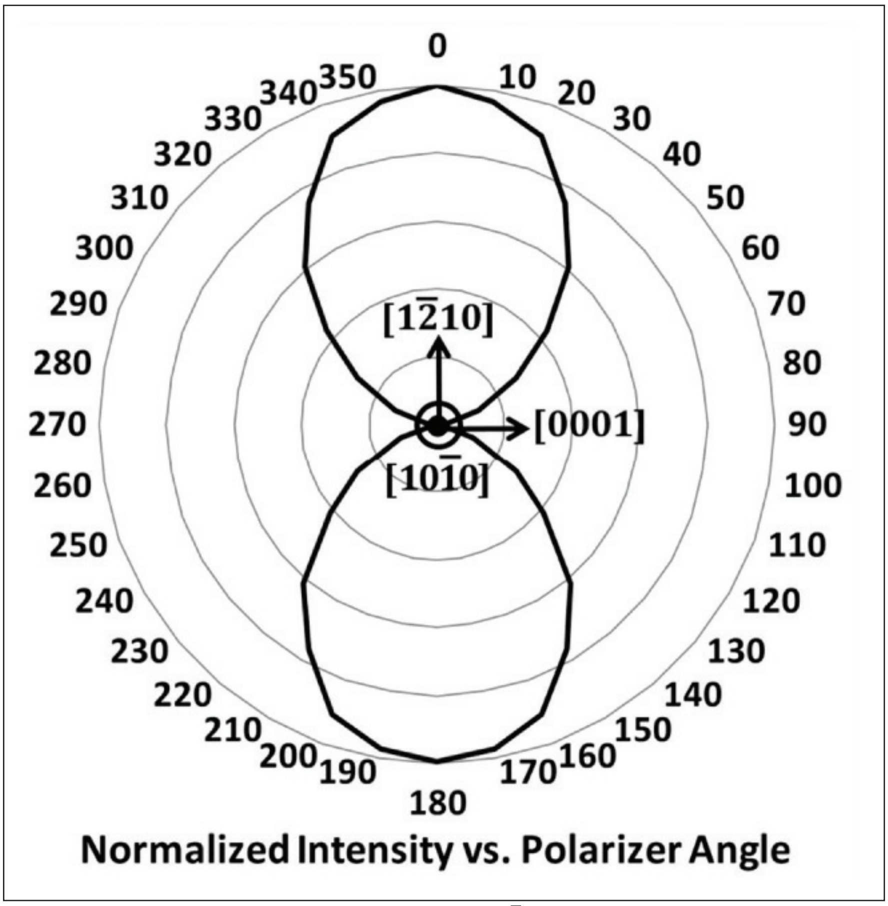


Figure 5. The emission polarization is aligned along the [1$\bar{2}$10] (a-direction) for the non-polar GaN-based VCSEL. Polarization ratio is close to one

Lastly, efforts must be directed at a systematic examination of the non-polar and semi-polar orientations, to uncover their potential for increasing optical gain and reducing threshold current. Increasing the per-pass-gain would permit DBRs with lower reflectivity, relaxing the design space. Success of green edge-emitters built on semi-polar planes motivates exploration of this orientation for green VCSELs. Non-polar and semi-polar orientations might also enable high-power VCSEL arrays with uniformly polarized emission characteristics.

Further reading

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