

BLUE DIODE LASERS

The recent achievement of compact blue-emitting gallium nitride semiconductor lasers is likely to have far-reaching technological and commercial effects. The lasers' short wavelengths—around 400 nm, half that of gallium arsenide-based lasers—permit higher spatial resolution in applications such as optical storage and printing. And the high photon energy will open up new applications for these inexpensive, compact light sources. An aesthetic satisfaction with these devices stems from finally extending the existing and mature semiconductor laser technology for the near-infrared and red to encompass the “new frontier” blue and near-ultraviolet regions, thereby bridging the entire visible spectrum. At the same time, there are significant research opportunities arising from a plethora of poorly understood microscopic issues in the underlying material system, which include such fundamental properties as charge control, transport, and formation of optical gain for stimulated emission.

The nitride materials represent a class of so-called wide bandgap semiconductors, anchored at GaN with its room-temperature bandgap of 3.4 eV (corresponding to a wavelength of 365 nm, in the ultraviolet). The other constituent materials used in the layered light-emitting heterostructures are aluminum and indium alloys, $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and $\text{In}_x\text{Ga}_{1-x}\text{N}$, which have bandgaps that are compositionally adjustable over much of the near-ultraviolet and visible ranges. The bandgaps possible in these alloys are bracketed by those of the three binary nitride compounds shown in figure 1. The technologically mature semiconductors based on GaAs, which also consist of III-V compounds, cannot reach these short wavelengths; the only comparable choice is offered by the II-VI semiconductors centered around zinc selenide. The first diode lasers at short visible wavelengths (in the blue-green, 480–520 nm) were indeed demonstrated in ZnSe and related II-VI alloys nearly a decade ago (see the article by Gertrude Neumark, Robert Park, and James DePuydt in *PHYSICS TODAY*, June 1994, page 26), but these have not met the crucial yardstick demanded of a technologically viable device: long component lifetime.¹

The first major commercial impact of blue diode lasers will likely occur in high-density optical storage,

Layered light-emitting heterostructures based on gallium nitride are quite different from their gallium arsenide cousins. Empirical development is advancing rapidly, and fundamental understanding is struggling to catch up.

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for traffic lights and violet LEDs that can be combined with phosphors to produce white lighting, a possible replacement for the ubiquitous incandescent lightbulb. In addition, blue and green nitride LEDs are already being integrated into large-scale outdoor displays.

In striking contrast with other advanced semiconductor devices, it is remarkable the extent to which technological progress in the nitride laser field, spearheaded by Shuji Nakamura at Nichia Chemical Industries in Japan,² has outpaced fundamental understanding. To start with, understanding of the epitaxial growth process at a microscopic level is inadequate at best and is guided by individual craftsmanship—much more so than, say, in the case of epitaxy of GaAs or silicon. Owing to the very large covalent and ionic components in its chemical bond, idiosyncrasies abound in GaN, such as the presence of large internal electric polarizations that offer more than a taste of ferroelectric flavor. In terms of their physical properties, the nitride materials represent a special class of unconventional semiconductors that skirt dangerously close to being dielectric insulators, which makes them particularly difficult to “tune” electronically—a major reason for decades of frustrated efforts to manipulate GaN for device purposes.

Inception of blue diode lasers

Two laboratory achievements in the late 1980s were seminal for the development of nitride light emitters, starting with blue LEDs in 1993 and followed by blue and violet diode lasers in 1995. The first advance involved a new twist in the old growth process that results in films of significantly improved quality. The most successful way of making GaN thin films is epitaxial growth through metal-organic chemical vapor deposition (MOCVD). The basic MOCVD reaction involves decomposition of ammonia and a metalorganic group-III precursor, such as trimethylgallium. Temperatures above 1000°C are required for practical growth rates because of the high strength of the N–H bond in ammonia. High-quality single crystal films of GaN are difficult to obtain, however, because of the significant differences (evident in figure 1) between the crystal's lattice constant and those of available substrates such as sapphire and silicon carbide. For example, GaN

specifically in digital versatile disks (DVDs). Other applications include full-color projection displays and high-resolution laser printers. A closely related sphere of potentially huge technological opportunity is offered by GaN-based light-emitting diodes (LEDs), in which incoherent light is produced by spontaneous as opposed to stimulated emission. Examples of commercial uses include green LEDs

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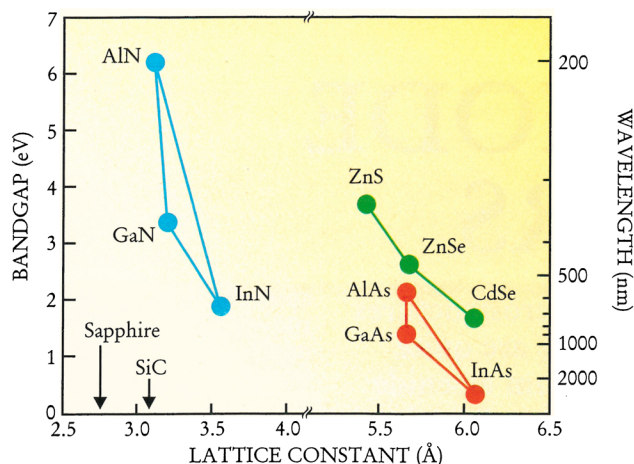


FIGURE 1. BANDGAP ENERGY versus lattice constant for the AlGaInN wide-bandgap semiconductor family, which has a wurtzite structure, compared with the cubic zincblende GaAs-based and ZnSe-based semiconductors. Sapphire and SiC, the presently used substrates in nitride light emitters, have a significant lattice mismatch with GaN.

on sapphire has a 16% mismatch, which is extreme in conventional semiconductor epitaxy. In 1986, Isamu Akasaki and coworkers at Nagoya University in Japan inserted a thin “buffer” layer, 10–20 nm of AlN grown at lower temperatures near 500°C, to provide large-area seeding for subsequent heteroepitaxial crystal growth.³ On sapphire, this nucleation layer remarkably improves the structural quality of subsequent InAlGaIn heterostructure layers grown above 1000°C.

Even with a buffer layer, the lattice mismatch induces a high density of so-called threading dislocations—lines of crystal defects that start at the substrate and propagate vertically up to the surface. The density of these dislocations can exceed 10^{10} cm^{-2} . In conventional GaAs-based semiconductor lasers, such a high defect density would doom a device to a nearly instantaneous death due to local heating created by nonradiative energy release. It remains to be determined how the various materials properties—including the electrical activity of the dislocations, the intrinsic mechanical strength of the GaN lattice, and carrier transport and recombination—conspire to permit viable device performance in the presence of such exceptionally adverse conditions.

The second pivotal advance was the realization of practical p-type electrical conductivity in GaN. (In sharp contrast, n-type doping of GaN is easily accomplished.) Although p-doping remains a central issue in nitride devices, as described later, this development paved the way for crafting p–n junctions, which were first demonstrated in LEDs that Nichia commercialized in 1993, followed by Cree Research Inc in Durham, North Carolina, and LumiLeds Lighting in San Jose, California.

The first nitride diode laser, operating near 420 nm, was demonstrated in 1995 by Nakamura and coworkers at Nichia. The initial nitride lasers could only be operated under pulsed conditions and at huge threshold current densities (up to tens of kA/cm^2), but progress was swift. Underscoring their exceptional underlying material robustness, the nitride lasers by 1998 had surpassed the II–VI lasers in longevity of continuous-wave (cw) operation. In particular, Nichia researchers have reported a projected lifetime in prototype diodes of 10 000 hours, a crucial enabler for technology applications.⁴ Cw operation of blue laser diodes has now been demonstrated by many additional groups—including teams at Sony, Fujitsu, Xerox, NEC, Matsushita, and Toyoda Gosei—although few approach the device lifetimes achieved at Nichia.

The basic structure of an edge-emitting laser diode is illustrated in figure 2a. The active region, where the optical gain necessary for lasing is generated, consists of a multiple quantum well (MQW)—a series of several 30–40 Å thick InGa_xN quantum wells with their accompanying GaN barriers—housed within a p–n junction. The spatially varying conduction and valence band energies are shown in figure 2b. The MQW confines high-density two-dimensional gases of electrons and holes (around 10^{19} cm^{-3}). Electrons and holes entering the active region are trapped in the wells. When they recombine, the electron–hole pairs give off photons with energies determined by the QW bandgap (that is, depth) and width. By varying the In/Ga composition ratio,

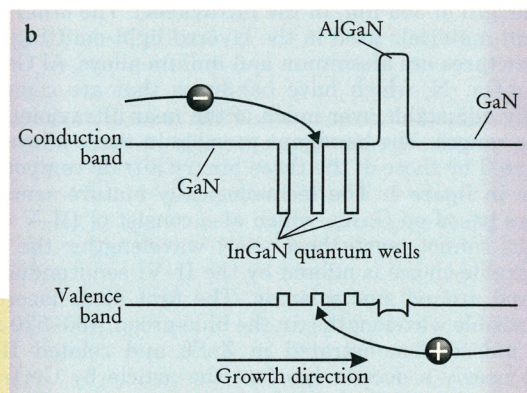


FIGURE 2. TYPICAL STRUCTURE of an edge-emitting blue multiple quantum well (MQW) diode laser. (a) Schematic of the layered heterostructure for electronic and optical confinement, with electrical contacts. (b) Energy band representation of the active region, with InGaIn quantum wells separated by GaN barriers. Injected electrons and holes are trapped in the MQW, where they radiatively recombine. The AlGaIn electron confinement layer keeps the electrons from leaving the active region.

researchers have fabricated laser devices operating over a range of wavelengths, from 390 nm in the violet to 450 nm in the blue.

The MQW is sandwiched by layers of doped GaN about 100 nm thick. These layers play the dual role of an optical thin film waveguide (along the layer plane) and local reservoirs of electrons and holes for injection into the active region. The waveguide, in turn, is completed by AlGaIn cladding layers, which have a lower index of refraction than GaN. At the ends of the roughly 500- μm long structure, the etched or cleaved facets of the heterostructure act as partial mirrors, providing the feedback for stimulated emission. While this type of structure closely resembles conventional semiconductor lasers, the specific material arrangement hides a veritable cornucopia of research opportunities.

p-type doping

The development of GaN optoelectronic applications gained significant impetus with the achievement of p-type doping. The search for a suitable dopant had historically focused on column-II elements, such as magnesium. With one less electron per atom than the Ga family, these elements are a natural choice for acceptors, or hole contributors, in III-V semiconductors. Upon the introduction of acceptor dopants, however, GaN has the tendency to electrically self-compensate through the generation of donor-like native defects. Another concern was the presence of compensating donorlike contaminants such as oxygen and Si. Efforts to achieve p-doping were frustrated until 1989, when Akasaki and colleagues reported that postgrowth, low-energy electron-beam irradiation of Mg-doped GaN significantly lowered the electrical resistivity. Subsequently, Nakamura and coworkers achieved high levels of p-doping and spatially uniform activation of Mg by annealing Mg-doped GaN at high temperatures in a nitrogen atmosphere.

We now understand that during epitaxial growth of GaN, Mg forms complexes with hydrogen that remove the acceptor energy level from the bandgap. This behavior has previously been observed with acceptors in Si and GaAs. In MOCVD growth, there are numerous sources of hydrogen, such as the primary source for nitrogen, NH_3 , as well as several metalorganic compounds. Interstitial hydrogen is incorporated into the GaN during growth and forms Mg-H complexes during cooling. It turns out that the hydrogen is actually beneficial: Because the Mg-H complexes do not act like acceptors, the GaN doesn't develop the self-compensating native defects. The complexes can be subsequently thermally dissociated, with the creation of p-type conductivity as the hydrogen migrates out of the material or to other stable, electrically inactive sites, thereby freeing the Mg to act as acceptors. Using a H-free atmosphere during the high-temperature anneal pre-

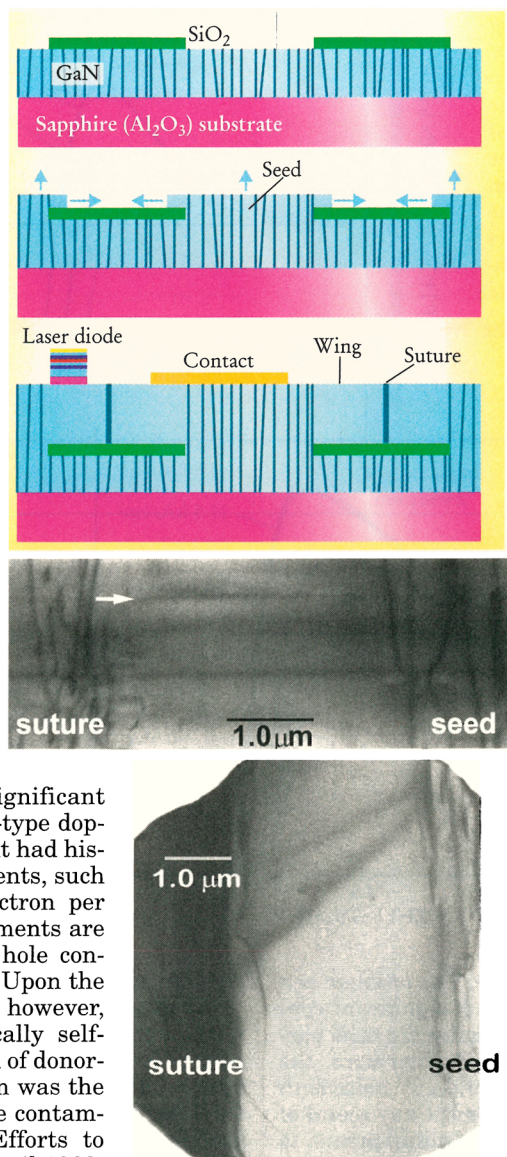
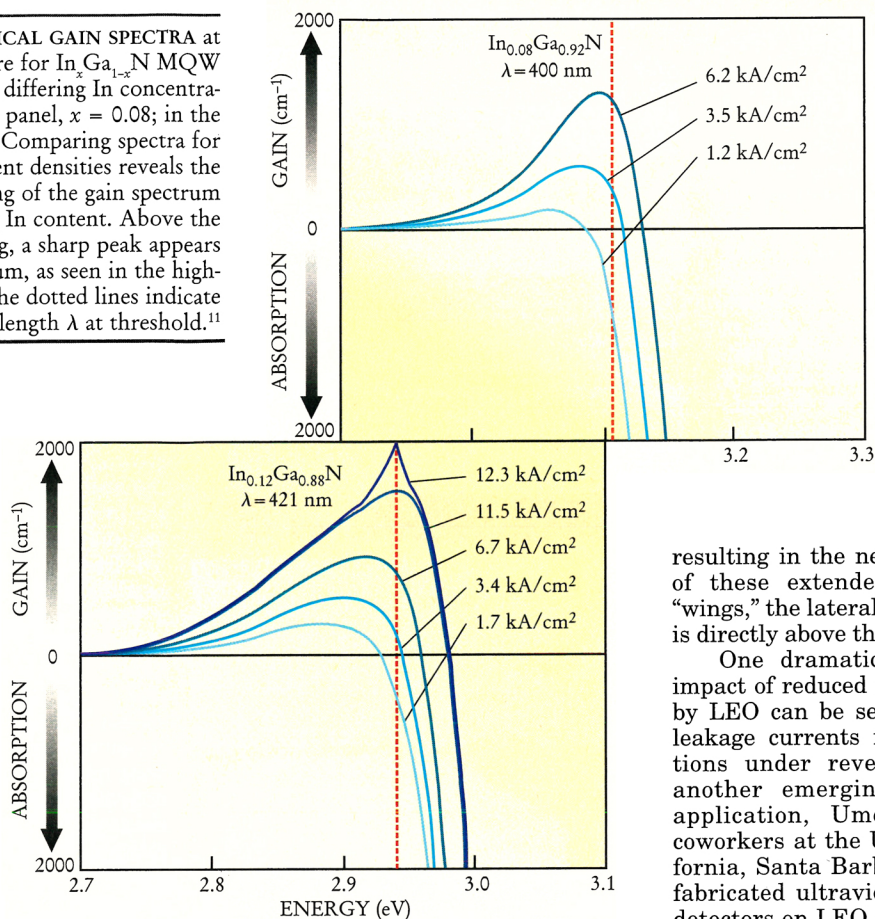


FIGURE 3. LATERAL EPITAXIAL OVERGROWTH (LEO) is a technique to reduce the defects caused by the mismatched lattice constants of GaN films and available substrates (such as sapphire). The fabrication steps are illustrated on the left. First, a GaN seed layer (blue) is placed on the substrate (red). A thin film of a dielectric such as SiO_2 is then deposited and photolithographically patterned to produce stripes that are oriented along the proper crystallographic direction of the GaN. The spaces between the stripes form windows or seed regions for subsequent growth. When GaN deposition is resumed, the film grows between the stripes and then laterally and vertically over the dielectric mesas. The lateral growth fronts coalesce near the center of each mesa to form a “suture” region that commonly contains voids and extended defects. The “wing” regions between the seed areas and the sutures have significantly fewer defects. The active region of a laser diode is placed in a wing region. The structural improvement from LEO is seen in the two transmission electron micrographs of a laser diode heterostructure. The top, cross-section image is taken transverse to the growth direction near the top of the heterostructure and includes the InGaIn MQW layer (indicated by the arrow). The bottom image shows a top view of the heterostructure. (Images courtesy of L. T. Romano, Xerox PARC.)

vents hydrogen from diffusing back into the material. Fundamental understanding of the local electronic structure of these complexes has been advanced through computational studies of Joerg Neugebauer and Chris Van de Walle at Xerox,⁵ and the existence of the Mg-H complexes was experimentally demonstrated by combined vibrational mode spectroscopy and Hall-effect measurements by Werner Götz and colleagues at Xerox.⁶ Still, many aspects of the chemistry of hydrogen in GaN remain to be worked out.

Achieving high hole concentrations at room temperature, necessary for laser devices, is further frustrated by the high activation energy required to ionize the Mg acceptors in GaN and put holes in the valence band. Several investigators have measured this energy at low Mg densities to be about 200 meV, much higher than thermal energies. In the independent-electron approximation, the ionization energy depends on the dielectric constant and effective mass of the material. The nitride system possesses low dielectric constants ($\epsilon \sim 9.5$, compared to 13 for GaAs) and large effective hole masses, which together result in large binding energies and only partial ionization of the available acceptors—on the order of 1% at room

FIGURE 4. OPTICAL GAIN SPECTRA at room temperature for $\text{In}_x\text{Ga}_{1-x}\text{N}$ MQW laser diodes with differing In concentrations. In the upper panel, $x = 0.08$; in the lower, $x = 0.12$. Comparing spectra for comparable current densities reveals the enhanced broadening of the gain spectrum with increasing In content. Above the threshold for lasing, a sharp peak appears in the gain spectrum, as seen in the highest curve below. The dotted lines indicate the lasing wavelength λ at threshold.¹¹



resulting in the nearly total absence of these extended defects in the “wings,” the laterally grown GaN that is directly above the dielectric stripes.

One dramatic example of the impact of reduced dislocation density by LEO can be seen in the reduced leakage currents in GaN p-n junctions under reverse bias. In yet another emerging nitride device application, Umesh Mishra and coworkers at the University of California, Santa Barbara (UCSB) have fabricated ultraviolet AlGaIn photo-detectors on LEO wafers that exhibit a reduction of the reverse-bias

temperature under thermal equilibrium. The problem can be further exacerbated by the presence of significant concentrations of n-type background contaminants that partially compensate the p-type dopants. Furthermore, the low p-type conductivity (with typically mid- 10^{17} holes/cm³) leads to high contact resistance with almost any metal of choice. Ongoing research is focusing on finding means to increase the hole concentration and to identify a p-type dopant with a smaller ionization energy that would improve the operating voltage and power efficiency of nitride lasers and LEDs.

Lateral epitaxial overgrowth

While nitride lasers can operate even with extremely high densities of dislocations, the defects do impact electrical transport properties and optical losses, resulting in device performance that is not optimal. An effective growth strategy has been recently developed that reduces the density of the extended defects arising from the use of lattice-mismatched substrates. The method of lateral epitaxial overgrowth (LEO), pioneered by Robert Davis and collaborators at North Carolina State University,⁷ involves interrupting the initial growth of the GaN layer to deposit and pattern a dielectric film before resuming growth. As shown in figure 3, a deposited stripe of an amorphous dielectric film such as SiO_2 defines windows of exposed GaN that seed the subsequent crystalline regrowth. With proper orientation of the stripes relative to crystallographic axes of the underlying GaN, there is rapid lateral growth over the dielectric and planarization of the growing GaN layer. The dielectric truncates the threading dislocations that originate at the substrate-GaN interface,

leakage current by up to six orders of magnitude!⁸

The use of LEO has also improved the performance of nitride lasers. Nakamura and coworkers have demonstrated lasers with a threshold current density—a crucial figure of merit in device performance—as low as 1.2 kA/cm² for a two-QW device fabricated on the wing portion of the LEO wafer. In a systematic investigation of the characteristics of lasers fabricated on LEO wafers, researchers at UCSB have demonstrated the anticipated variations in threshold current density for diodes placed above the wings, windows, and coalescence regions where the lateral growth fronts meet above the dielectric. Technologically very important, the use of LEO is expected to stabilize and extend the longevity of nitride lasers. Yet the threshold current density even in the best nitride lasers remains high—an order of magnitude higher than that for GaAs lasers—raising questions about the microscopic machinery involved in the formation of optical gain and stimulated emission in the InGaIn/GaN QW system.

Optical gain

The key concept of population inversion, a prerequisite for optical gain, is well understood in semiconductor lasers. In an independent-electron picture, inversion is obtained through a degenerate Fermi gas of electrons occupying the conduction band minima and another gas of holes in the valence band maxima. The main experimental manifestation of many-body interparticle interactions is the shrinkage of the bandgap (the “renormalization effect”)—by as much as 100 meV in GaAs-based lasers.

The microscopic processes underlying optical gain in the nitride lasers differ markedly from those in conven-

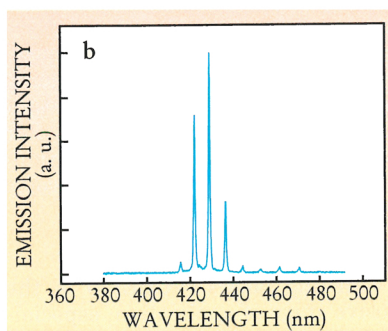
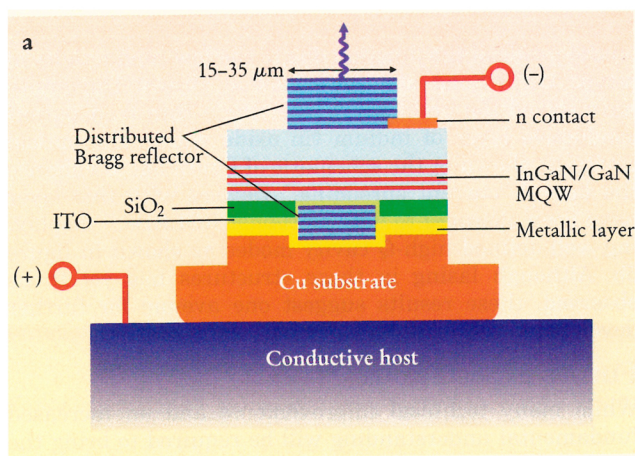


FIGURE 5. RESONANT-CAVITY LED (RCLED) with an InGaN/GaN MQW light-generating layer. (a) Schematic of a blue RCLED incorporating two dielectric distributed Bragg reflector mirrors of periodic layers of SiO_2 and HfO_2 and featuring an indium tin oxide (ITO) layer to spread holes into the active region between the mirrors. (b) Diode emission spectrum displaying several narrow vertical-cavity modes.¹⁵

tional GaAs semiconductor lasers. One idiosyncratic feature in InGaN QWs is the apparent local compositional fluctuations in the In and Ga concentrations. There is accumulating evidence showing that instead of a simple random statistical distribution of In and Ga atoms, there is a preponderance of In-rich clusters with a broad distribution of sizes (ranging from the atomic scale up to 100 nm) as soon as the concentration of indium in the alloy exceeds a few percent. This clustering creates a complex spatial landscape for the electronic states and leads to the presence of localized states with energies that extend into the bandgap by several hundred meV. Precise characterization of the localized electronic states is an ongoing subject of research, complicated by the additional presence of very large piezoelectric fields (up to 1 MV/cm) in the strained nitride heterostructures that can strongly affect the electronic bands.⁹

Interestingly, these localization effects strongly benefit InGaN blue and green LEDs (especially in the 460–540 nm range for display devices) because the injected carriers are unable to reach nonradiative recombination centers. For laser devices, however, the alloy disorder is an unwelcome guest. In any QW laser, the threshold current density can ideally be very low—below 100 A/cm^2 —due to the sharp rises in the electronic density of states at edges of the conduction and valence bands. But with disorder, electron-hole pairs injected into an InGaN QW must first be expended to fill the localized states, which don't participate in the lasing action, before useful optical gain can be formed in the extended Bloch-wave states. Hence the compositional inhomogeneities contribute an overhead to the laser operation that leads to a higher than optimal threshold current density. This behavior was shown by Yoon-Kyu Song and coworkers at Brown University, who used gain spectroscopy on the diodes,¹⁰ and by Michael Kneissl and collaborators at Xerox.¹¹ Figure 4 shows actual gain spectra measured in laser devices with different In concentrations in the InGaN QWs. These studies show how the gain spectral width broadens rapidly and the threshold current density increases significantly with increasing In concentration. At present, these effects appear to limit optimized laser operation to the wavelength range of roughly 390–420 nm. In recent work, Nakamura and colleagues have extended the operation of nitride diode lasers up to 450 nm, but at nearly an order of magnitude higher current densities and with greatly reduced diode lifetimes.

With such disconcerting news, it is comforting to know that there exists a fundamental property that should significantly aid the formation of optical gain in

the nitrides. The electron-hole Coulomb interaction, a many-electron effect, leads to bound electron-hole pairs known as excitons. Exciton binding energies in the nitride QWs are much greater than those in GaAs and can exceed 50 meV. Excitons are generally not expected to survive under the high-density, room-temperature operation typical of GaAs semiconductor lasers. However, theoretical work—for example, by Wen Chow and collaborators at Sandia National Laboratories—suggests significant enhancements to the gain of a nitride laser due to these many-body effects,¹² which could significantly reduce the threshold current density.

As a consequence of the broadening of the density of states near the band edges due to clustering, the fingerprints of the excitonic enhancement to optical gain in InGaN QWs have yet to be clearly identified. Yet we know from past experience with the wide-bandgap II-VI blue-green semiconductor lasers, where disorder effects are small, that the electron-hole Coulomb interaction can have a dominant effect on the optical gain, narrowing its spectrum and increasing the all-important peak value. In the case of nitride lasers, research continues to focus on the role of this many-body effect.

Commercial concerns

The current empirical metric of progress for edge-emitting blue diode lasers is their lifetime to failure. The undisputed leader in this area remains Nichia, which in 1999 was the first company to achieve commercially viable nitride laser diodes. While the microscopic reasons underlying the degradation in the nitride lasers have yet to be identified, several “usual suspects” can be listed, including generation of recombination centers in or near the active region, dislocation motion, dopant diffusion, contact degradation, and catastrophic mirror failure due to local optical absorption.

The threshold current density of even the best nitride laser demonstrations so far is nearly an order of magnitude higher than that of the blue-green ZnSe QW diode laser, despite the comparable values of the key parameters such as effective masses and dielectric constant. This high threshold, due in part to the compositional anomalies in the InGaN gain medium and in part to the numerous defects that even in LEO material contribute to leakage currents and optical losses, means that a considerable

portion of the input electrical energy is wasted. Consequently, the conversion or "wall plug" efficiency for going from DC electrical power to coherent photon output remains low, below 20% in the best nitride lasers. For many technology applications, such a low efficiency reinforces the need for understanding the many microscopic issues within the local machinery of the blue laser.

Vertical-cavity devices: the next challenge

Vertical-cavity surface-emitting lasers (VCSELs) in the infrared are at an explosive stage of application, especially for use as interconnects in very high-speed optical communication systems (see PHYSICS TODAY, September, page 30). In the case of resonant cavity LEDs (RCLEDs), which also have vertical cavities, the almost beamlike directionality of the spontaneous emission can be very useful even in the absence of coherence. Both devices are characterized by the requirement of an optical resonator with a high quality or Q factor and with planar mirrors defining the optical axis parallel to the semiconductor heterostructure growth axis. In contrast to an edge-emitting device (as in figure 2a), the optical gain path length in a VCSEL device is very short—a few hundred angstroms through the QW active layers—so that mirrors with reflectivities exceeding 99% are required to achieve lasing.

The technological prospects for blue and near-ultraviolet VCSELs and RCLEDs are at an early but exciting research stage. These types of microcavity emitters should exhibit special properties in basic physics and device performance. A vertical-cavity nitride device, with single or very few electromagnetic modes present, could allow new, fundamental investigations of laser operation in a regime in which the electromagnetic and electronic degrees of freedom are coupled much more strongly than in conventional GaAs lasers. Such coupled modes, occurring in absorptive optical media when the energy of the spectrally sharp exciton resonance coincides with that of the optical mode, are known as microcavity polaritons and have been extensively studied in GaAs-based vertical-cavity structures.¹³ Because excitons are expected to survive in GaN-based lasers, the energy propagating within a vertical-cavity nitride laser may be in a superposition of electromagnetic and electronic modes.

Two elements are needed to obtain working blue and violet nitride VCSELs: an optical design with sufficiently high Q (on the order of 1000) and a working electrical design for injecting the electrons and holes. The first has been achieved through the combined use of distributed Bragg reflectors (DBRs) made of MOCVD-grown GaN/AlGaIn and dielectric multilayers. The carefully tailored, periodic structure of DBRs makes them highly reflective mirrors. A key step in the device fabrication process, separating the nitride heterostructure from its substrate, has been demonstrated by Michael Kelly and coworkers at the University of Munich and by Timothy Sands and colleagues at the University of California, Berkeley.¹⁴ A collaboration among Brown University, Sandia, and Agilent Technologies has demonstrated efficient VCSEL operation in the 380–410 nm wavelength range using optical pumping at modest levels of excitation to generate the population inversion, which establishes a working optical design for blue VCSELs.

The present challenge is to make the optical resonator structure compatible with electrical injection. The mirrors themselves are poorly conducting at best, so carriers must be laterally fed into the active optical volume defined by the mirrors. The problem is especially severe

on the p-side of the junction due to the low conductivity of p-type GaN. Song and coworkers at Brown University have solved the problem by inserting a thin transparent conductive layer of indium tin oxide within the optical cavity, as shown in the schematic of figure 5a, to enhance the lateral "current spreading." Devices with this layer have been operated to date as robust RCLEDs,¹⁵ displaying well-defined high- Q cavity modes as shown in figure 5b. Although lasing in these structures has yet to be observed, these results suggest one avenue for further development of high-efficiency blue light emitters.

Future expectations

While many technical improvements and an increased fundamental understanding will be required to bring the present blue and violet lasers into full technological bloom, it is clear that these devices, perhaps in spite of themselves, are destined to fill an important role in future optoelectronics applications. Over the longer term, many opportunities beckon at shorter ultraviolet wavelengths where applications of compact, monochromatic coherent sources in biology and biotechnology loom large, to cite but one example. Such lasers will be based on the AlGaIn ternary semiconductor and will further challenge the boundaries of semiconductor physics through the need to extract the requisite electrical and optical properties of a truly "frontier" electronic material. Meanwhile, steady progress has been made in improving methods for growing GaN quantum dots through spontaneous self-assembly, notably by Jean Massies and coworkers.¹⁶ Creating nanometer-sized crystallites of GaN may open new doors for studying light-matter interaction in "artificial atoms," a subject anticipated to be rich both in basic physics and in applications to short-wavelength light emitters.

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References

1. R. Gunshor, A. Nurmikko, eds., *Semiconductors and Semimetals*, Vol. 44, Academic Press, San Diego (1997).
2. S. Nakamura, G. Fasol, *The Blue Laser Diode*, Springer, Berlin (1998).
3. H. Amano *et al.*, Appl. Phys. Lett. **48**, 353 (1986). I. Akasaki, H. Amano, in *Semiconductors and Semimetals*, Vol. 50, Academic Press, San Diego (1998).
4. S. Nakamura, *Semicond. Sci. Technol.* **14**, R27 (1999).
5. J. Neugebauer, C. G. Van de Walle, Appl. Phys. Lett. **68**, 1829 (1996).
6. W. Götz *et al.*, Appl. Phys. Lett. **69**, 3725 (1996).
7. J. A. Freitas Jr., O.-H. Nam, R. F. Davis, Appl. Phys. Lett. **72**, 2990 (1998).
8. E. G. Parish *et al.*, Appl. Phys. Lett. **75**, 247 (1999).
9. J. S. Im *et al.*, Phys. Rev. B **57**, 9435 (1998).
10. Y.-K. Song *et al.*, Appl. Phys. Lett. **72**, 1418 (1998).
11. M. Kneissl *et al.*, J. Lumin. **87–89**, 135 (2000).
12. W. W. Chow, A. Knorr, S. W. Koch, Appl. Phys. Lett. **67**, 754 (1995).
13. M. S. Skolnick, T. A. Fisher, D. M. Whittaker, *Semicond. Sci. Technol.* **13**, 645 (1998).
14. M. K. Kelly *et al.*, Phys. Status Solidi A **159**, R3 (1997). W. S. Wong, T. Sands, N. W. Cheung, Appl. Phys. Lett. **72**, 599 (1998).
15. Y.-K. Song *et al.*, Appl. Phys. Lett. **77**, 1744 (2000).
16. B. Damilano *et al.*, Appl. Phys. Lett. **75**, 3751 (1999). ■