

The wide blue yonder

Dr Mike Cooke looks at blue laser developments in the light of the recent market introduction of HD-DVD and Blu-ray optical storage disks, and surveys future applications and prospects for improvements in the technology.

With blue-light high density optical storage entering the market earlier this year, more than 10 years of development towards a commercial GaN-based laser diode (LD) seems to have achieved a successful outcome. Many difficulties have been met, but there is still immense room for improvement. Also, having focused on creating one market for the product, it is now time to look for further applications and variations.

High-density pressure

Much of the pressure for high-density storage systems such as HD-DVD and Blu-ray, which are currently being introduced, comes from high-definition (HD) TV systems that increase both image resolution and frame rates. Current DVD and digital TV image resolutions are typically 720x480 pixels (NTSC, National Television System(s) Committee) or 720x576 pixels (PAL, phase-alternating line) with frame rates of less than 30 per second (fps). Proposed HD formats are 1280x720 pixels or even 1920x1080 pixels at up to 60fps. Also the maximum number of color levels per channel is increasing from 8-bit (256) to 10-bit (1024). Naturally, the bit rate for HD video is much increased. Naively, one could end up increasing data rates by a factor of almost $(1920/720) \times (1080/480) \times (60/24) \times (10/8)$,

i.e. a factor of about 19x. However, the higher picture resolutions are generally used with lower frame rates and vice versa, so, with the usual compression techniques, a full 19-fold increase is not intended. While single-layer DVD disks have a capacity of just under 5 Gigabytes (GB), HD-DVD offers 15GB and Blu-ray 25GB. Double-layer disks offer twice the capacity.

Blu-ray and HD-DVD are essentially developments of compact disk and DVD technology. Data is encoded either as a series of pits (read-only) or crystalline/amorphous (read-write) regions, typically on 120mm diameter disks. Laser light is used for its coherence benefits in terms of focusing and interference. Data is written or erased by the laser melting the phase-change medium, which is cooled either 'slowly' to achieve crystallization or quickly to produce amorphous material, affecting the reflectivity of the surface. For greater storage density, the laser light has to be focused to a smaller spot, which means reducing the wavelength to about the same size.

The Blu-ray laser has a 405nm (blue-violet) wavelength, compared with 635nm or 650nm (red) for standard DVDs and 780nm (infrared) for CDs. HD-DVD also uses the 405nm wavelength, but differences in disk structure (such as a thicker protection layer) and other system features mean that the spot is less tightly

HD-DVD and Blu-ray formats see first commercial launches

The high-density DVD (HD-DVD) format is supported by the DVD Forum, while Blu-ray is an independent format that some see as analogous to the difference between the DVD Forum's 'dash' rewritable format (DVD-RW) and the 'plus' of the DVD+RW Alliance.

The DVD+RW Alliance split away from the DVD Forum "to develop and promote a universally compatible, rewritable DVD format to enable true convergence between personal computing and consumer electronics products" (for further information, see www.dvdrw.com/alliance/history.htm).

Toshiba released the first HD-DVD player in Japan on 31 March 2006, and a number of players debuted in the USA in April (e.g. the RCA HDV5000; below, left). The US release for Blu-ray was first set for 23 May, but was delayed to 25 June, when Samsung launched its BD-P1000 player (below, right). Another round of Blu-ray players is due for launch in third-quarter 2006. Sony's Playstation 3 will use Blu-ray, at an increased price, and is due for release in November (already represents a postponement for this application).

www.blu-ray.com/players



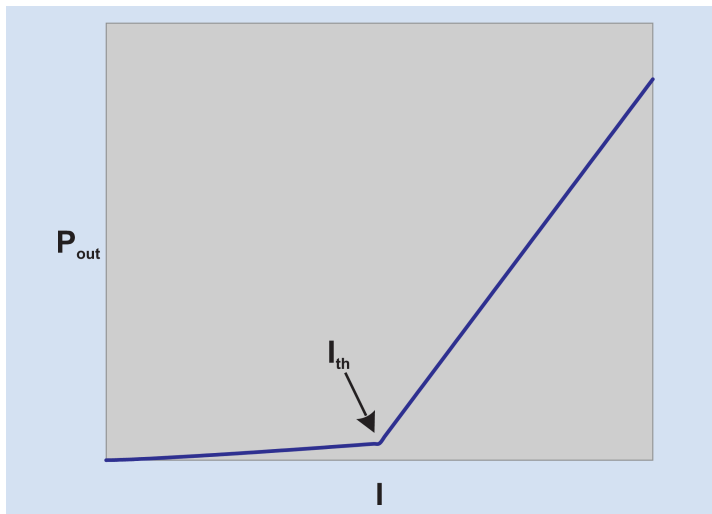


Figure 1: Light output power characteristics of a laser diode. The slope efficiency of laser power above the threshold current is given by dP_{out}/dI .

focused, leading to lower storage density. HD-DVD systems tend to be lower cost (~\$500) compared with Blu-ray (~\$1000).

As with DVDs, one demand is that the HD-DVD and Blu-ray optical disk systems also handle the previous formats (DVD/CD). This requires three-laser systems, preferably in a module. For DVD, the laser is typically built using the AlGaInP quaternary system, while the requirements of CD storage are met by AlGaAs. The 405nm laser is based on wide-bandgap AlGaInN nitrides. While AlGaAs and AlGaInP can be grown on a single GaAs substrate, it is difficult to achieve monolithic three-laser systems. Instead, GaAs-based DVD/CD laser chips are mounted on the GaN substrate alongside the blue laser chip. In terms of thermal performance, GaN has comparable thermal conductivity (200W/m/K) to those of the usual two-laser mounting materials (Si, 130W/m/K; AlN, 285W/m/K).

Blue lasers

For DVD use, lasers must have high output power and reliability. A typical definition for the mean time to failure (MTTF) reliability measure involves a certain percentage increase in current that is required to maintain light output power at a given temperature. The device "fails" when the operating current has increased to this level (e.g. a 20% current increase for 50mW output power at 70°C). High operating temperatures are used to accelerate degradation and to perform burn-in testing for weeding out early failure modes.

In a laser diode, the light emission is non-lasing (and incoherent) until the threshold current is reached (see Figure 1). This threshold represents the point at which the gain from stimulated emission equals the absorption in the active layer. This requires a large amount of carriers (electrons/holes) and light in one place. Since the production of non-lasing light is inefficient, it is neces-

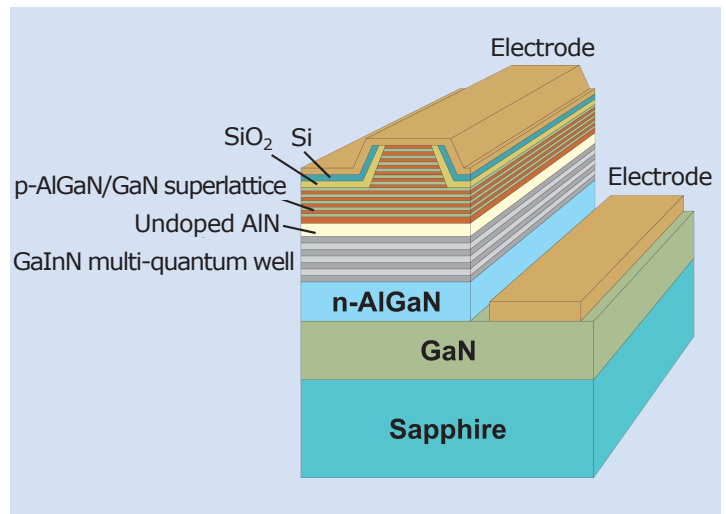


Figure 2: Laser structure on sapphire substrate. Since the substrate is insulating, electrical contact has to be made on one-side of the chip surface.

sary to reduce the threshold current as much as possible. A high threshold current indicates that most of the energy going into the device is being wasted and this raises operating temperatures, increasing the likelihood of failure. Also, once reached, one requires as much of the extra current above the threshold to be converted into laser light as possible (slope efficiency = dP_{out}/dI).

Since one is also trying to control the laser for the purpose of reading or writing data, low-noise operation is also vital. This is enabled through control of the horizontal and vertical transverse properties of the light wave in the active layer of the laser device. One wants a single wavelength mode to emerge from the waveguide structure formed from the active and associated barrier and cladding layers. Fortunately, the correlation between bandgap energy and refractive index in a semiconductor laser diode structure generally allows one to confine carriers and light together.

The transverse modes are also important for controlling the nature of the output light such as its far-field properties. 'Astigmatism' results when the light appears to diverge from different points relative to the horizontal and vertical transverse directions. Such astigmatic light is difficult to focus, which is a key requirement for reading off and writing on small areas. To stabilize the transverse modes, a very narrow 2µm-wide dielectric ridge is currently used, but this results in the p-type electrode having a very small surface area, which increases the contact resistance to tens of ohms, pushing up the operating voltage of blue-violet lasers and creating heat.

The most reliable blue-violet nitride semiconductor lasers so far have been based on a GaInN active layer. The first reports of GaN-based pulsed blue-violet laser operation appeared in 1995 (Nakamura *et al* (1996) *Jpn J. Appl. Phys.* **35**, L74; Akasaki *et al* (1996) *Elec. Lett.* **32**, p1105). Stimulated emission can be

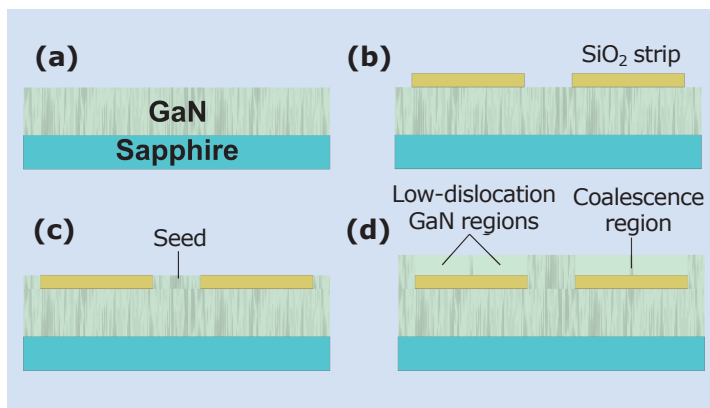


Figure 3: Epitaxial lateral overgrowth: (a) GaN layer on sapphire (or SiC) substrate; (b) silicon dioxide mask; (c) epitaxial growth in window; and (d) lateral growth over mask creates areas with reduced dislocations.

achieved from transitions between the base of the conduction band to a state in the heavy-hole band (the recombination of an electron and a hole). The layer absorbs radiation (negative gain) when the excited carrier density is below $10^{19}/\text{cm}^3$, a level that is an order of magnitude greater than in GaAs-based lasers. The result is that the threshold current in GaN-based lasers is large.

The 'traditional' substrate material (since the early 1990s) for GaN devices has been sapphire, based on the independent work of the groups led by Akasaki and Nakamura. However, sapphire is insulating and requires the etching of elaborate step 'mesa' structures to make electrical contact with the n-type nitride layers (see Figure 2). Further, since there is a large mismatch between the GaN and sapphire crystal structures, it is necessary to use dislocation-reducing techniques such as epitaxial lateral overgrowth (ELO) to create lasers with a reasonable lifetime (see Figure 3). Typical lifetimes for lasers on sapphire without dislocation-reduction techniques are a paltry 40 minutes of continuous-wave 1 mW output power. Nakamura *et al* (1997 *Appl. Phys. Lett.* **70**, 868) describe this as a 'long lifetime' for room-temperature continuous-wave operation of InGaIn multi-quantum-well laser diodes.

Dislocations are observed as dark spots in photoluminescence measurements excited, for example, by a 325nm He-Cd laser, with a detection wavelength of 363nm. Where the regions of ELO meet (coalescence), dislocations are also observed (Figure 3(d)). ELO laser structures have to be grown over the regions between the growth seed windows and coalescence. While sapphire substrates have dislocation densities of more than 10^8 – $10^{10}/\text{cm}^2$, using ELO allows this to be reduced to 10^5 – $10^6/\text{cm}^2$ away from the coalescence and seed regions. Other heteroepitaxial substrates, such as silicon carbide and spinel (MgAl_2O_4), have been used to try to improve matters, but with only limited success.

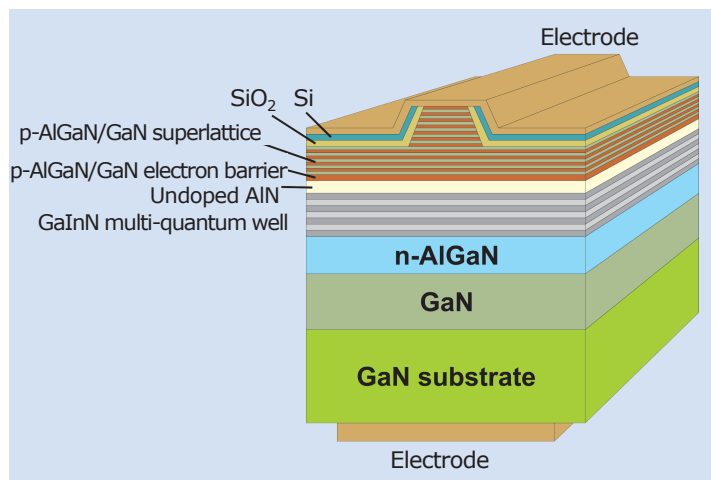


Figure 4: With a conducting GaN substrate, electrical connections can be made to the top and bottom of the device, simplifying the manufacturing process.

Despite the expense, for laser diode production it has been found that pure GaN substrates have many attractions, such as much reduced dislocation levels. Further advantages of pure GaN are its conducting nature, so that lasers with more traditional top and bottom electrodes can be created, easing the manufacturing process (see Figure 4), and better cleavage properties for producing the mirror facets of the active region. Thermal conductivity also favors pure GaN ($200\text{W}/\text{m}/\text{K}$) over sapphire ($40\text{W}/\text{m}/\text{K}$), since thermal control is more critical for laser diode systems compared to conventional light-emitting diodes.

The first lasers on free-standing GaN (Nakamura *et al* (1998) *Jpn J. Appl. Phys.* **37**, L309) used resistive substrates, so mesa structures were needed, as for sapphire-based devices. The first attempt at using conducting substrates (Kuramoto *et al* (1999) *Jpn J. Appl. Phys.* **38**, L184) was hampered by high dislocation densities (2 – $4 \times 10^7/\text{cm}^2$). By 2001, low-defect-density GaN substrates ($\sim 10^5/\text{cm}^2$) were available (Motoki *et al* (2001) *Jpn J. Appl. Phys.* **40** (part 2), L140), enabling high-performance laser diodes to be produced with a much simplified manufacturing process. The width of the low-dislocation-density regions is expanded from $\sim 6 \mu\text{m}$ for ELO/sapphire to $\sim 150 \mu\text{m}$ for low-defect-density GaN substrates.

Some of the developments leading to better devices include the use of low-temperature buffer layers, the formation of low-resistance p-type layers using Mg doping and electron radiation anneals, and improved growth of GaInN crystal layers.

A large number of structures have been tried, particularly for the GaInN active layer. Here, multi-quantum wells are common, but early attempts using up to 26 layers have been scaled back to around three. One reason for reducing the number of wells is to reduce threshold currents, as happens with conventional semiconductor lasers. In nitride lasers, in particular,

when there are too many wells, non-uniform hole injection results in a large overflow current (which overshoots the intended recombination region and hence does not produce laser light). In general, non-uniform hole injection hits both the threshold current and the slope efficiency.

P-type conduction is often difficult to achieve, and hole masses tend to be large in nitride semiconductors. To reduce operating voltages, a superlattice p-type clad layer is used (e.g. p-GaN/AlGaIn) — see S. Nakamura *et al* (1997) *Jpn. J. Appl. Phys.* **36**, L1568. To keep the electrons in the active layer and to stop them overshooting into the p-type layers, an electron barrier (p-AlGaIn) is often used. Also, the p-type layers are commonly produced by Mg doping. It has been found that Mg-doped layers tend to absorb light, which is counter-productive in a light emitting device. One response has been to shift the light towards the less absorbing n-type region (M. Kuramoto *et al* (2002) *Phys. Stat. Sol. (a)* **192**, 329). Another approach is to use an 'intermediate' layer (GaInN and AlGaIn) to separate the Mg-doped regions from the active layer (M. Takeya *et al* (2002) *Phys. Stat. Sol. (a)* **192**, 269). Using an intermediate layer can cut absorption losses from up to 43/cm down to ~5/cm, which is a figure comparable with conventional lasers. If the distance between the active layer and the Mg-doped layer is kept to less than or around 100nm, then the internal quantum efficiency of the laser can be maintained. Reduced carrier overshoot also results in better temperature performance. The lower threshold resulting from the intermediate layers also suppresses noise. However, blue-violet laser diodes still have a larger relative noise intensity figure during high-frequency modulation and a larger temperature dependence of the threshold voltage compared with red lasers.

Breaking out of storage

GaInN active layers are not restricted to the narrow needs of optical storage devices. The possible GaInN wavelength range (482–365nm) covers blue-green to near-ultraviolet opportunities in medicine, biotech analysis, and full-color displays (see Figure 5). Increasing the indium content in the active layer increases the wavelength. However, for laser operation, the threshold current increases dramatically beyond 475nm, due to spatial fluctuations in the active layer's composition. Even at 482nm, thresholds are larger than for 400nm devices. So, for 'long'-wavelength nitride-based lasers, one not only needs improved substrates but also more uniform levels of In concentration in the active layer. Full-color displays need blue lasers emitting at 440–460 nm wavelengths at high power.

Shorter-wavelengths (UV) have biological applications such as medical sterilization, food processing and treatment of skin conditions such as psoriasis (for

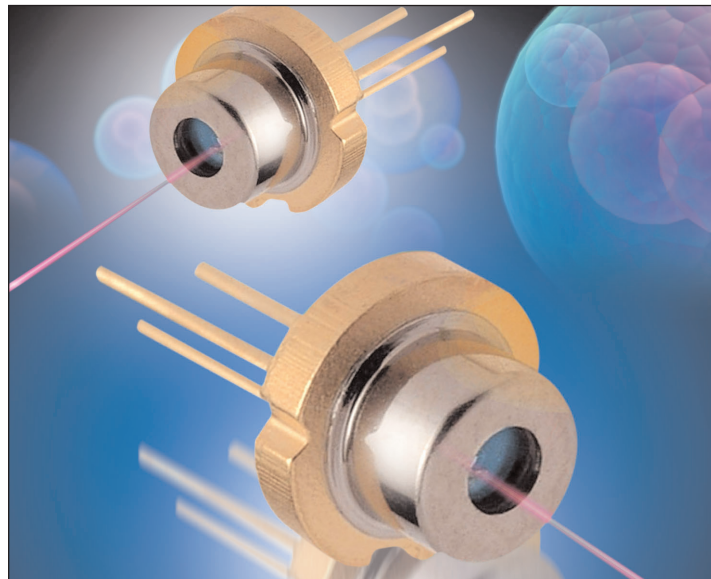


Figure 5: Sanyo's DL-5146-152 blue-violet (405nm), 35mW laser, for DVD and biomedical applications.

which the optimum wavelength is 311 nm). Application as an exposure source for leading-edge microlithography (193nm) would seem to be out of the range of semiconductor laser systems for now, although some of the older microlithographies based on bulky, high-voltage, incoherent mercury lamps, such as i- and g-line (365nm and 436nm, respectively), are in range.

An alternative in the short-wavelength sphere is the use of non-linear optics to up-convert longer wavelengths to short wavelengths. For example, infrared lasers combined with KTP (KTiOPO₄, potassium titanyl phosphate) and other related photonic crystals (e.g. niobium oxide, tantalum oxide lithium) can be used to produce blue or green light. The same principle has been attempted using blue GaN-based laser diodes with BBO (beta-barium borate) crystals to produce laser emission of tens of microwatts output at 210nm, which is not far from the required 193nm. Improvements in 'second harmonic generation' (SHG) crystals can be expected to reduce this to 200nm. However, the SHG crystal route is complicated and expensive. If possible, the direct production of UV laser light from a semiconductor laser diode would be preferred.

AlGaIn laser structures on SiC substrates have managed pulsed operation at 343nm (Edmond *et al* (2004) *J. Crystal Growth* **272**, 242), and the recent production of AlN LEDs at 210nm (Taniyasu *et al*, *Nature*, p325, 18 May 2006) gives hope for further reductions. AlGaIn double heterostructures have produced optically excited gain at 241nm (Takano *et al* (2004) *Appl. Phys. Lett.* **84**, 3567). Development requires improved internal quantum efficiency (the reduction of non-radiative recombination), increases in electron and hole density in the cladding layers, and improved carrier confinement. Also improved doping is needed to allow carriers to be transported more easily into the active region.