AlN substrates propel performance improvements in **ultraviolet** LEDs

Single-crystal, high-quality AlN substrates underpin the production of bright, reliable ultraviolet LEDs delivering superior wavelength stability

BY LEO SCHOWALTER of CRYSTAL IS

TO ANALYSE AND MANIPULATE DNA, scientists begin by determining the purity of this life-determining molecule. Purity and concentration levels are exposed by measuring the absorption associated with DNA and protein, which have peaks in the ultraviolet region of the electromagnetic spectrum at wavelengths of 260 nm and 280 nm, respectively. Armed with this information, it is then possible to uncover genetic disorders, create DNA fingerprints of individuals, and make genetically engineered organisms that enable the manufacture of products such as insulin, antibiotics, and hormones.

Absorption measurements of DNA and proteins are often carried out using mercury, deuterium and xenon flash lamps, which can also serve many other established markets, such as those involving the disinfection of water and air and the curing of resins. However, that does not imply that these lamps, which emit in the UVC range that spans 280 nm to 100 nm, are great sources of ultraviolet radiation: They are fragile, bulky, lack portability, and are not particularly efficient.

A very attractive alternative to these ultraviolet lamps is the LED that emits in the UVC range. This solid-

state light source can be an efficient, cost effective, and more environmentally friendly replacement that is wavelength specific. What's more, it promises high optical output, long lifetime, low power consumption and low maintenance costs.

UVC LEDs are already available today, having been introduced to the marketplace several years ago. Unfortunately, initial products failed to live up to their billing, delivering a low output power and suffering from a lack of reliability. These weaknesses have impeded the uptake of this technology.

Today, this situation has changed, with far better devices available. Improvement in the marketplace has been driven by our efforts at Crystal IS of Green Island, NY, where we manufacture a portfolio of high-performance UVC LEDs. These products owe their superiority to their foundation – high quality, single-crystal AlN. Depositing epilayers on this substrate, rather than the more conventional sapphire, allows the growth of pseudomorphic $Al_xGa_{1-x}N$ layers with very low defect densities. The devices that result, which premiered earlier this year under the brand name Optan, are made with processes employed for

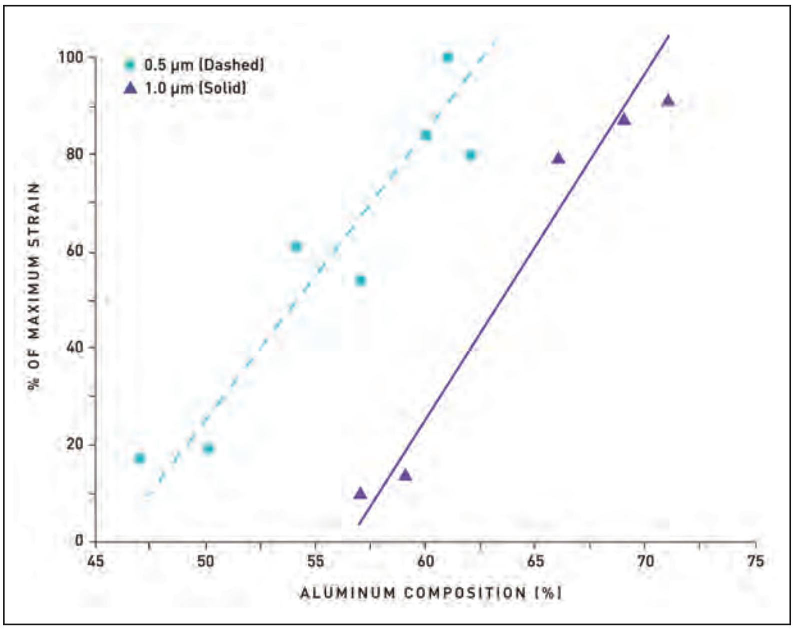


Figure 1. The percentage of maximum (psuedomorphic) strain as a function of aluminium composition for layers with different thicknesses. Dashed and solid lines are provided as guides to the eye for each thickness.

manufacture of visible LEDs. They offer industry-leading light output, superior lifetime and reliability, and excellent spectral quality.

Building on AlN

Ultraviolet LEDs and their visible cousins have several things in common – they are both formed by depositing, via MOCVD, a stack of epilayers from the AlN/GaN/InN materials system. However, they differ in material composition. For devices emitting in the visible or near ultraviolet and serving the multi-billion dollar lighting industry, aluminium content is low, and the LED is rich in gallium with indium. To reach the far shorter wavelengths of the ultraviolet UVC range, far more aluminium is required, along with proportional decreases in gallium.

Visible and ultraviolet LEDs are often formed on sapphire. This foundation meets the temperature and chemical compatibility requirements for hetero-epitaxial growth of III-nitride semiconductors, but film deposition is hindered by large lattice and thermal expansion mismatch. This gives rise to a high density of defects, which is a far more significant problem in UVC LEDs than those emitting in the visible, because as the emission wavelength gets shorter, the defects have a bigger impact on internal quantum efficiency.

It is possible to reduce the density of defects in GaN-on-sapphire UVC LEDs by employing novel epitaxial growth techniques. However, a far bigger gain is made by turning to pseudomorphic growth of high-aluminium-content AlGaN layers on AlN substrates. To realise this, we have developed a technology to grow large diameter boules of high quality AlN; and developed techniques to obtain high quality, pseudomorphic growth of AlGaN on this single-crystal foundation.

Here we will focus on describing our efforts at addressing the latter challenge – the pseudomorphic growth of AlGaN on AlN (note that the growing of high-quality boules of AlN by our team is described in many papers, such as *Structural and Surface Characterization of Large Diameter, Crystalline AlN Substrates for Device Fabrication* (published in *Journal of Crystal Growth* **310** 887 (2008))).

Development of our AlGaN-on-AlN growth process began with a project to determine the pseudomorphic limit for these substrates. We carried out various growth experiments, using different compositions and thickness for *n*-type $Al_xGa_{1-x}N$ layers. This led to the deposition of a range of layers – from almost completely relaxed to completely strained (Figure 1).

This series of experiments determined that if the aluminium content is around 60 percent, layers can be grown fully pseudomorphic up to a thickness of 0.5 mm; and if the aluminium content is as high as 70 percent, layers with a thickness of 1 mm can be formed that are pseudomorphic. The great strength of pseudomorphic growth is that it does not lead to the generation of misfit dislocations, so no new threading dislocations are

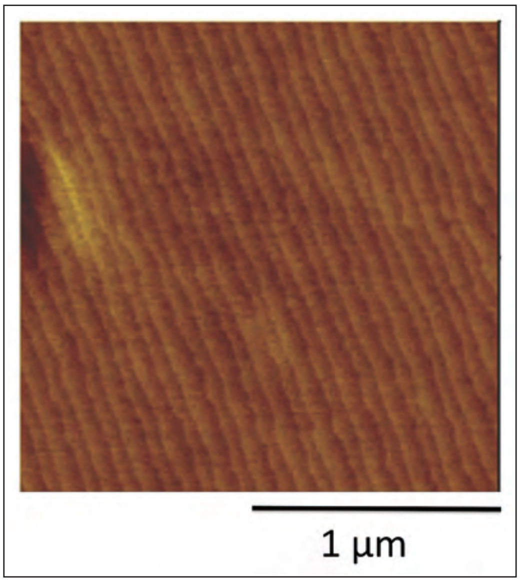


Figure 2. Step-flow growth is revealed by atomic force microscopy images of pseudomorphic $Al_{0.7}Ga_{0.3}N$. The root-mean-square roughness is just 0.1 nm, and the height range of the image is 1.7 nm.

generated. Consequently, it is possible to grow thick layers with a density of threading dislocations comparable to that found in the starting substrate. Armed with the information uncovered in this study of AlGaN films, we can ensure that very few dislocations are generated during hetero-epitaxy.

To realise high-quality epistructures, we have produced *n*-type $Al_xGa_{1-x}N$ with a smooth surface, in order to create sharp interfaces in the *p–n* junction and thin active region. Through experimentation with roughening surfaces and optimisation of the proportion of aluminium in $Al_xGa_{1-x}N$ layers, we found that $Al_{0.7}Ga_{0.3}N$ layers can be deposited with very smooth surfaces (see Figure 2). According to atomic force microscopy, these layers typically have a step flow growth pattern with atomically smooth surfaces over areas of 2 x 2 μm^2.

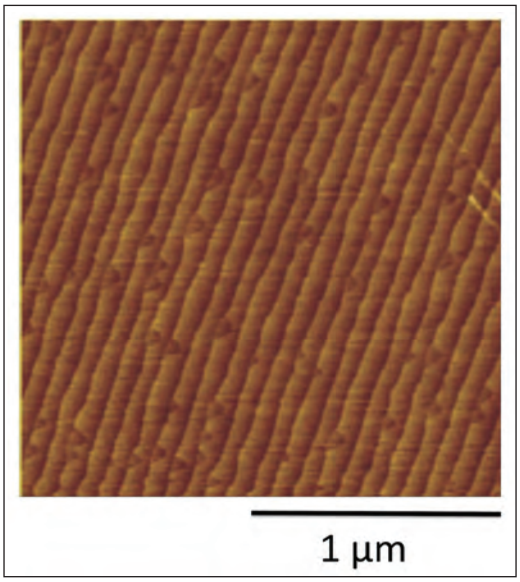


Figure 3. Step-flow growth during the deposition of the UVC LED structures is revealed by atomic force microscopy. The root-mean-square roughness is just 0.2 nm, and the height range of the image is 1.6 nm.

One of the biggest challenges in incorporating $Al_{0.7}Ga_{0.3}N$ into our LEDs is that it can be plagued with a low conductivity. As aluminium concentration increases, conductivity tends to fall, due primarily to the reduced mobility and deeper level for the donors in the conduction band. However, by optimizing doping levels and growth conditions, it is possible to increase conductivity to a level suitable for incorporation in LED structures.

We have produced LEDs containing a high aluminium-content electron-blocking layer, a *p*-type $Al_xGa_{1-x}N$ hole injection layer and a *p*-type GaN contact layer. Thanks to a low surface roughness, as verified by atomic force microscopy (see Figure 3), allied to a low defect density, these devices deliver a very high level of performance.

This is only possible when a device has a low density of defects, because these imperfections give rise to non-radiative recombination, with injected carriers generating heat rather than ultraviolet emission.

Driving down defects and realising high internal quantum efficiency is not a guarantee of great performance – to do that, photons must also be extracted from the chip with high efficiency. This is non-trivial, because nitride semiconductors have a relatively large index of refraction, which results in a relatively narrow escape cone for photon extraction. If photons approach the semiconductor-air interface at an angle greater than the escape cone they undergo total internal

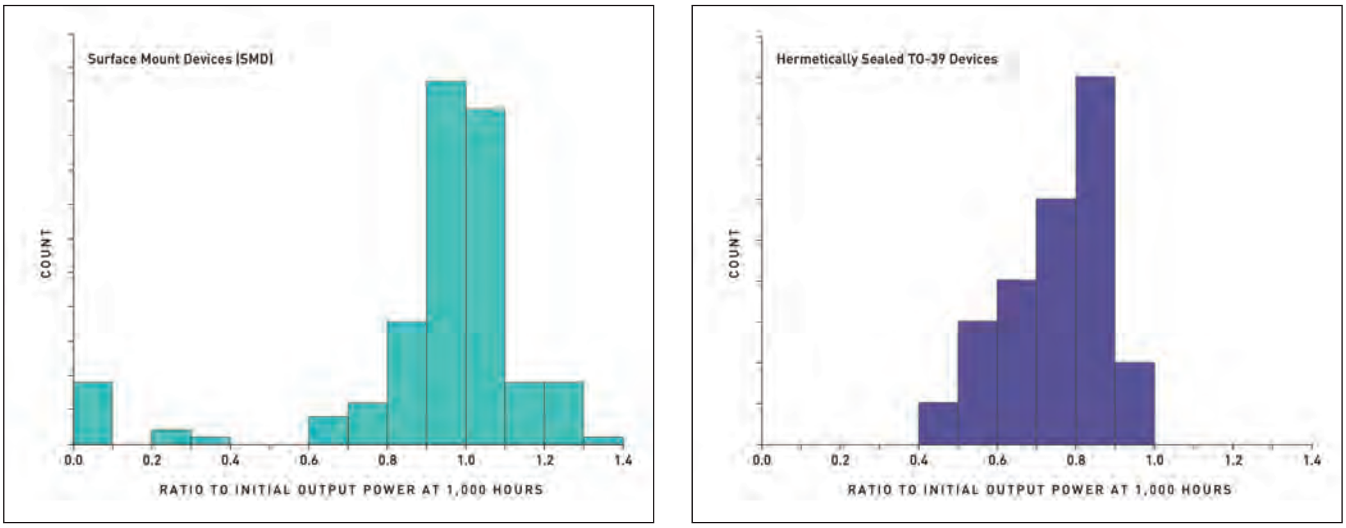
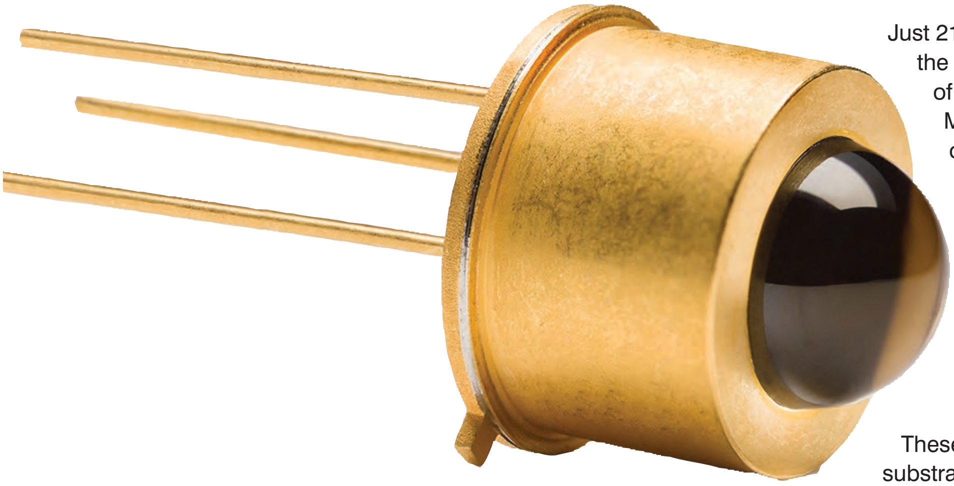


Figure 4. Housing UVC LEDs in a hermetically sealed TO-39 package, as the devices in the right figure, prevents the failure of devices after 1000 hours of continuous-wave operation at a drive current of 100 mA



reflection, and it is likely that they will be absorbed before multiple reflections bring them to within the escape cone.

To minimise the proportion of photons trapped and lost within the ultraviolet LED, we employ a variety of extraction techniques. They have been adapted from standard techniques used to increase the output of visible LEDs, with processes tailored for the materials used in ultraviolet emitters.

Better, brighter devices

Devices that result combine high brightness with a high level of reliability. Optical measurements on 170 LEDs in a lead frame package, run at 100 mA for 1,000 hours in continuous wave (CW) operation, reveal that the median LED emits just over 97 percent of its initial output (see Figure 4).

Just 21 devices, equating to 12.4 percent of the sample size, emit less than 40 percent of their initial output after 1000 hours. Many of them deliver no light by the end of the test, due to a malfunction of the contact metallization or packaging. Analysing the failed devices reveals corrosion and metal migration, often exacerbated by environmental conditions. Encouragingly, a sample of 40 devices in a hermetically sealed TO-39 package exhibited no failures of this nature.

These results show that single-crystal, AlN substrates can lead to brighter, more reliable devices. But that's not all: This superior foundation also leads to LEDs that deliver a more consistent emission wavelength and emission peak fidelity, without sacrificing efficiency gains. This means that they are better suited to satisfying the needs of those looking to determine the purity and concentration of samples, such as DNA. The increased light output stability – which ensures consistent and repeatable measurements – can be seen in tests that compare our LEDs to those of UVC LEDs produced by other chipmakers (see Figure 5). These investigations highlight the stability of our LEDs with a peak wavelength of 260 nm and 280 nm.

Our efforts at developing AlN substrates will continue, and in turn this should lead to further gains in the performance of UVC LEDs. Brighter, more reliable devices will follow, and the number of applications that can be addressed by the ultraviolet LEDs will continue to rise.

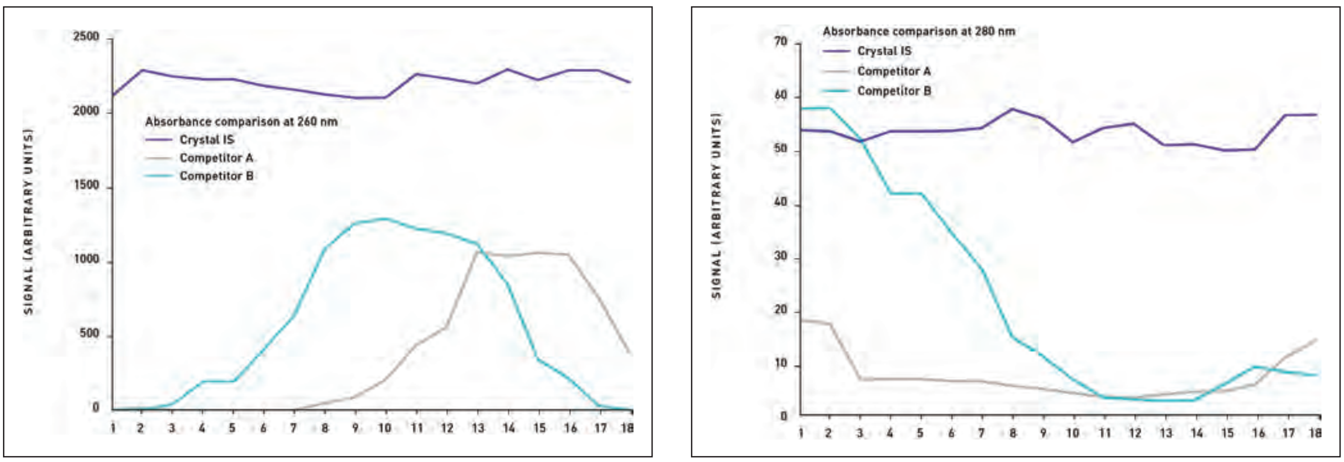


Figure 5. Thanks to a high-quality, single-crystal AlN substrate, the wavelength stability of UVC LEDs manufactured at Crystal IS is superior to that of rival devices.