HVPE offers alternative route to AlGaN-based UV emitters

The combination of higher growth rates and a lower defect density gives HVPE an edge over techniques such as MOCVD for the growth of UV LEDs. TDI's **Vladimir Dmitriev** and **Alexander Usikov**, and **Heikki Helava** and **Barney O'Meara** from the Fox Group outline their progress.

Today, semiconductor LEDs emitting in the blue, ultraviolet (UV) and deep UV spectral regions are the subject of intense development. Interest has been driven by technical achievements in GaN and AlGaN materials, which cover bandgaps from 3.4 to 6.2 eV, and the growth of commercial devices by MOCVD technology. However, despite this substantial progress, allied to outstanding results obtained in the blue spectral range, several challenging problems remain, preventing the routine production of efficient UV light emitters. These barriers include reducing defect density in UV-emitting epitaxial structures; achieving reliable and controllable growth of AlN and AlGaN alloys; and obtaining p-type doping of AlGaN materials.

At TDI, a novel epitaxial approach, hydride vapor phase epitaxy (HVPE), has been developed to produce advanced GaN and AlGaN materials and device structures for UV optoelectronic applications. One key outcome of this work, involving a multidisciplinary team of scientists and industrial engineers, is the formation of several proprietary processes for commercial production of UV LEDs operating at wavelengths of 365 nm and below. This effort was a logical extension of the team's previous accomplishments that led to successful commercial production of blue LEDs by the "dismissed" HVPE process (*Compound Semiconductor* August 2004 p23).

HVPE, a technique developed in the 1960s, was the first epitaxial method used for the fabrication of single GaN crystals. Thanks to its high growth rate (at up to 100 μm per hour, it is two orders of magnitude faster than typical MOCVD and MBE processes), thick GaN layers and free-standing GaN wafers can be produced. The fabrication of a thick GaN layer is critical, since the defect density of GaN layers decreases dramatically as the layer thickness increases. Since both MOCVD and MBE have relatively low growth rates, HVPE is the only practical technique available for growth of thick, low defect density GaN layers.

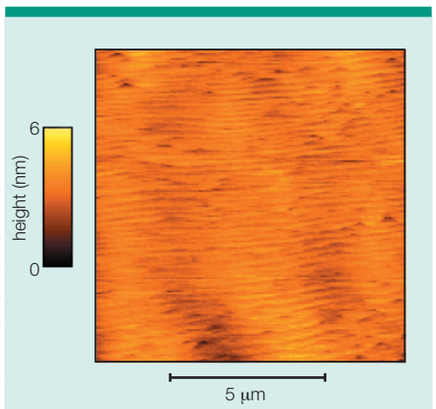

Fig. 1. The surface morphology of TDI's HVPE-grown GaN layers is suitable for LED production. This AFM image reveals a surface roughness (root mean square) of 0.44 nm, for a 17 μm thick GaN layer deposited on sapphire substrate.

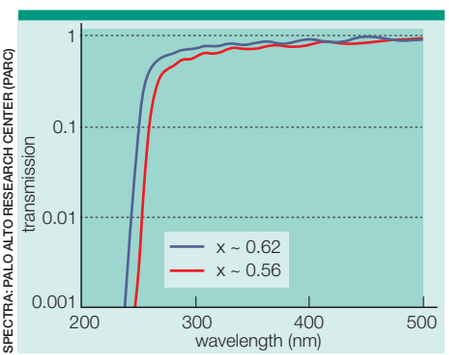

Fig. 2. Optical transmission spectra of HVPE-grown $Al_xGa_{1-x}N$-on-sapphire templates with two different aluminum concentrations. Transmission in the deep UV improves with higher aluminum content.

Other significant advantages of HVPE are the low costs associated with raw materials, the deposition process and capital equipment. All these benefits are exploited by the Fox Group, which is the exclusive licensee of worldwide rights from TDI for certain patents related to HVPE for light-emitting applications. It has recently started commercial production of GaN-based blue LEDs by HVPE, and will compete with manufacturers using MOCVD and MBE processes for blue light emitters.

HVPE cuts defect densities

As well as the low manufacturing cost, HVPE has other inherent advantages for producing shorter-wavelength emitters. First, it allows growth of low defect density material that incorporates a high proportion of aluminum in the AlGaN layers without severely degrading the crystal quality. In addition, the technique is suitable for growing thicker high-quality AlGaN-based active regions which have a high radiative recombination efficiency, an essential feature for high-efficiency UV LEDs. The HVPE process is also a "carbon-free" technology, as gaseous hydrogen chloride (HCl) used in the epitaxial growth provides an impurity self-cleaning effect. This results in low background material contamination and more efficient doping. Finally, HVPE's high growth rate allows favorable batch cycle times, an important consideration for volume production.

TDI's HVPE development has enabled the fabrication of an entire family of III-N devices and structures, including HVPE-grown p-n diodes, p-type GaN and AlGaN layers, and low-defect AlN and AlGaN epitaxial layers (Usikov *et al.* 2004). The surfaces of GaN layers have a very smooth morphology with a roughness of less than 0.5 nm (root mean square value), even for thick layers (figure 1). TDI has also demonstrated the industry's first HVPE-grown, multilayer, sub-micron AlGaN/GaN heterostructures, including AlGaN/GaN/AlGaN double heterostructures for optically pumped lasers (Lam *et al.* 1998)

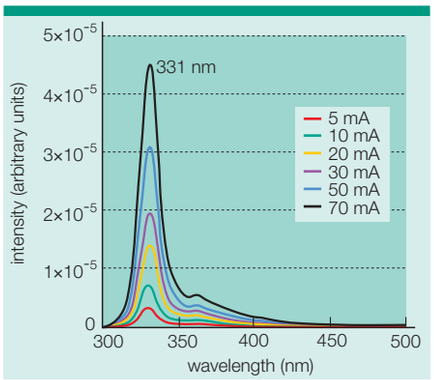

Fig. 3. Electroluminescence spectra of HVPE-grown LED structure based on p-AlGaN/n-AlGaN/n-AlGaN heterostructures.

THE FOX GROUP

Fig. 4. Monochromatic 32 × 194 pixel sign, with dimensions of 0.45 × 1.2 m, using Fox Group's blue LEDs. The devices were not subjected to binning for color or forward voltage. Halftones were achieved by employing lower drive currents.

and AlGaN/GaN high electron mobility transistors.

For UV optoelectronic applications, recent modifications to TDI's HVPE technology has enabled fabrication of UV transparent AlGaN-on-sapphire templates spanning the AlGaN composition range from 5 to 85 mol.% of AlN. These AlGaN layers typically exhibit a standard deviation in alloy composition over a 2 inch diameter wafer of less than 2%. The templates are targeting substrate applications for deep UV AlGaN-based emitters, and provide a suitable lattice-matched foundation for device fabrication. The excellent UV transparency (figure 2) improves the device efficiency by allowing light extraction through the substrates. TDI will start volume production of UV transparent AlGaN-on-sapphire templates in 2005.

Advanced HVPE developments at both TDI and the Fox Group have been incorporated in complete UV LED structures, such as devices based on AlGaN/AlGaN p-n heterostructures with a peak wavelength of 305–350 nm (figure 3). The diode structures consist of a silicon-doped n-type AlGaN photon-emitting layer with a thickness of typically 50–100 nm sandwiched between n-type and magnesium-doped p-type AlGaN cladding layers with a higher AlN concentration (Smith *et al.* 2004). These structures, with chip dimensions of 330 × 330 μm, were processed and subsequently packaged into TO cans. The packaged LEDs have a peak wavelength of 341 nm and a full-width half maximum of typically 14 nm, and generate output optical powers of 0.5 mW and 2 mW for pulsed injection currents of 20 mA and 110 mA, respectively. Although this LED structure is not optimized for UV light extraction and contains a partially absorbing p-GaN cap layer, output powers are still comparable to state-of-the art MOCVD-grown UV light emitters.

Commercialization of the UV LEDs will be pursued by the Fox Group, which has already successfully launched production of blue LEDs on customized, automated epitaxial reactors based on designs pioneered by TDI. These blue-emitting devices have achieved a very high color consistency (dominant wavelength typically 460 ± 1 nm), a very good forward voltage consistency (Vf typically 3.6 ± 0.1 V), and reasonable uniformity, repeatability and yields. Today's available products, all measured in continuous-wave mode, include blue (460 nm) epitaxial wafers and LED lamps, die with typical optical powers of 2 mW and die brightness of more than 30 mcd, and lamps of more than 1000 mcd in narrow viewing angle packages. Superior color consistency is a significant issue for display and sign manufacturers, who are beginning to utilize the Fox Group's blue LEDs (figure 4).

Commercialization of UV emitters

Although the current blue LED production at the Fox Group is based on 2 inch diameter sapphire substrates, scalability of HVPE technology to 3 and 4 inch technology has already been proven. Further progress in this direction was achieved very recently, when TDI demonstrated the world's first 6 inch GaN epitaxy (see p7).

The Fox Group has also started to test third-generation prototypes of its 360–365 nm UV LEDs, and plans to offer UV dies and lamps before the end of 2004. Preliminary specifications, measured in continuous-wave mode and at 20 mA, include a peak wavelength of 361 nm, a radiated power of 0.5–1 mW and a forward voltage of 3.7 V. The structures are reasonably robust, and with proper thermal management they will operate continuously at currents of more than 100 mA.

TDI and the Fox Group are also investigating the use of UV LEDs to generate more aesthetically pleasing white light by pumping a mixture of currently available phosphors, such as those developed for the fluorescent lighting industry. Both companies acknowledge that low-cost, high-efficiency white light emitters are the key to enabling rapid adoption of solid-state lighting, but in the short term they will target the attractive niche markets that exist for UV LEDs, such as medicine, biomedicine and industrial applications.

The key scientific challenges to achieving high-power UV LEDs by HVPE are similar to those faced by MOCVD, MBE or any other deposition process: to improve carrier injection in the light-emitting active area of the device structure and to increase the internal and external quantum efficiencies. The HVPE process enables competitively priced high-quality growth of GaN and AlGaN materials with low background impurities and level characteristics, and may provide the winning ingredients for cost-effective, high-efficiency UV light emitters.

Further reading

B Lam *et al.* 1998 *Mater. Res. Soc. Symp. Proc.* **639** G6.4.1.
G A Smith *et al.* 2004 *J. Appl. Phys.* **95** 8247.
A Usikov *et al.* 2004 UV Solid-State Light Emitters and Detectors. *NATO Science Series* **144** 15–29.

Vladimir Dmitriev, TDI's president and CEO, can be contacted at vladimir@tdii.com. Barney O'Meara, the Fox Group's VP of marketing and sales, can be contacted at bomeara@thefoxgroupinc.com.