Accelerating adoption of GaN substrates for LED manufacture

Recycling native GaN substrates via chemical lift-off promises cost-competitive manufacture of high-performance vertical LEDs

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COMMERCIALISATION of the GaN LED can be traced back to the development of *p*-type doping of this wide bandgap semiconductor in the early 1990s. Since then, the performance of this device has improved exponentially, enabling it to progress from use in the backlighting of mobile screens to providing a source for solid-state lighting. However, although LED lighting is now commonplace, its cost-performance profile has a long way to go untill the incumbent vacuum-tube-based lighting technologies will cease to dominate.

One of today's key bottlenecks is the requirement to use a 'non-native' substrate. Currently about 95 percent of GaN-based LEDs are grown hetero-epitaxially on *c*-sapphire, because the ideal 'native' GaN substrates, which are limited in availability, are prohibitively expensive. A 2-inch substrate, for example, retails for thousands of dollars, and is primarily used for laser manufacturing.

Sapphire is far from the ideal foundation for the GaN LED. Two of its biggest downsides are that its lattice constants and its thermal expansion coefficient are markedly different from those of GaN. This creates strain in the epilayers, which leads to the generation of point defects and dislocations that limit the potential light output.

The insulating properties of sapphire are another impediment to the manufacture of high-performance LEDs. The high electrical resistivity of sapphire imposes a non-ideal lateral LED device architecture with top-contacts and a confined lateral current flow. This results in current crowding and localized thermal hot spots, which are detrimental to the efficiency, lifetime and maximum brightness of the device.

Compounding these issues is the thermally insulating nature of sapphire, which dramatically restricts heat dissipation. In turn, this further limits efficiency, lifetime and brightness.

Alternative platforms

To combat these issues, producers of chips for high-end LED applications transfer the GaN-based epilayer to a substrate with superior electrical and thermal conductivity. Often this is accomplished with a laser-lift-off and wafer bonding process to remove the LED from the sapphire and transfer it to an alternative substrate. The laser lift-off process involves firing a short wavelength laser beam – typically the 248 nm emission line from a KrF excimer – through the sapphire substrate. Light is absorbed in the first 100 nm of GaN, which decomposes to liberate the LED from the sapphire.

After bonding the LED to an electrically and thermally conductive substrate, this device can exhibit much better heat dissipation and vertical LEDs (VLEDs)

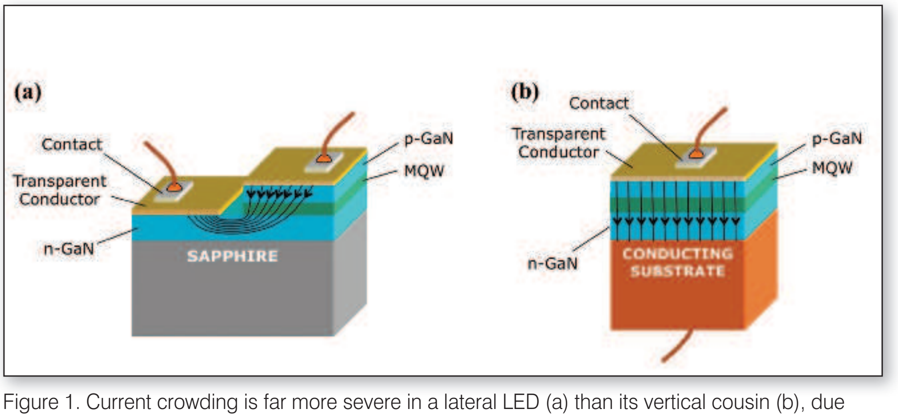

Figure 1. Current crowding is far more severe in a lateral LED (a) than its vertical cousin (b), due to the insulating substrate.

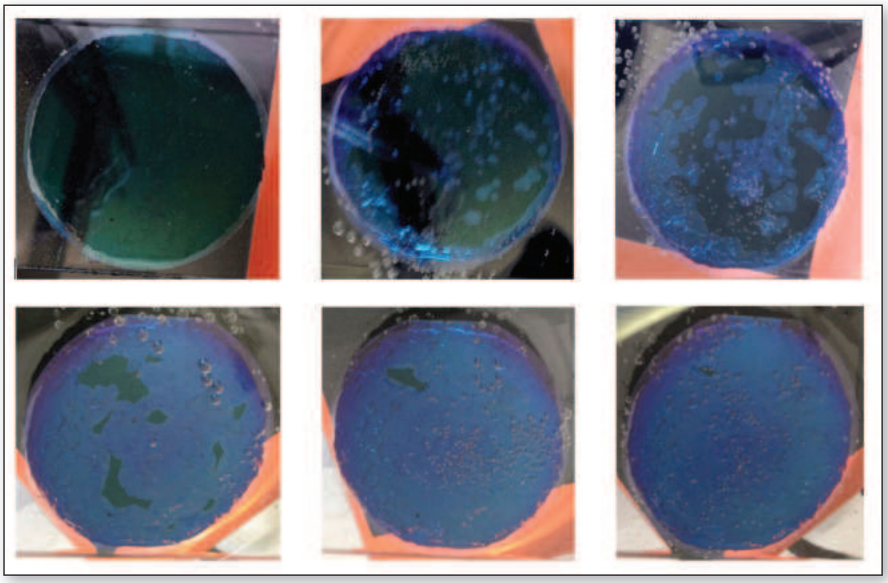

Figure 2. Photographs taken through the backside of a 2-inch GaN/ZnO/sapphire wafer (immersed in ~ 1M HCl) showing a time sequence of the chemical dissolution of ZnO & the progressive detachment of the substrate.

can be formed (see Figure 1), which have current flow through the substrate. Such devices have a much more homogeneous current distribution than a conventional lateral LED, enabling them to be driven up to 25 times higher. VLEDs also avoid complex, costly lithographic steps required to make the top contacts, and have a footprint at least 30 percent smaller than a conventional LED, which means that manufacturers of these devices benefit from a significantly higher chip yield per wafer.

What's more, a flipped device geometry can increase overall light extraction, thanks to laser-induced roughening of the GaN, which reduces the proportion of light trapped by total internal reflection. And on top of this, the substrate can be reclaimed and reused after polishing away the surface residue left by the laser ablation. However, despite all of these advantages associated with laser lift-off, the performance of the transposed LED is still held back by the quality of the original expitaxy on the mismatched sapphire.

It might seem that the ultimate way forward is to grow such VLED structures on GaN substrates (because this would lead to very high crystal quality) and then perform laser lift-off in order to reclaim/reuse the expensive GaN substrate. However, it is not possible to remove this native platform with laser lift-off, because GaN substrates are not transparent to the requisite short-wavelength lasers.

Another substrate option that has attracted a significant amount of attention is ZnO, which not only has the same crystal structure as GaN, but also very similar lattice parameters and comparable thermal expansion coefficients. However, ZnO is much more chemically reactive than GaN.

Due to this, attempts by numerous groups to adopt bulk ZnO substrates have met with problems of back-etching of ZnO by the process gases used in the MOCVD process.

This problem is not insurmountable, however, and it has been overcome, by our ZnO team at Nanovation of Châteaufort, France, working in partnership with the GaN group of Abdallah Ougazzaden at the joint Georgia Tech and CNRS lab in France.

Nanovation is a ZnO dedicated epiwafer foundry, founded in 2001 by four research scientists who identified the commercial potential of ZnO for emerging opto-semiconductor markets: extending from transparent conductors and electronics through to LEDs, lasers and photovoltaics.

To this end, we have pioneered the adoption of pulsed laser deposition as a production tool in the semiconductor industry, based on its unique capacity for forming state-of-the-art ZnO layers with a huge range of properties on almost any substrate.

This remarkable propensity for tuneability results from the exceptionally high energy of the adatoms in the laser ablation plume – they typically have energies of 10 eV to 100 eV, compared to 1 eV to 10 eV for sputtering and 0.1 eV to 1 eV for more common semiconductor deposition methods, such as MBE and CVD.

Thanks to these higher energies, deposition can occur at lower growth temperatures while using a much-extended working range for oxygen

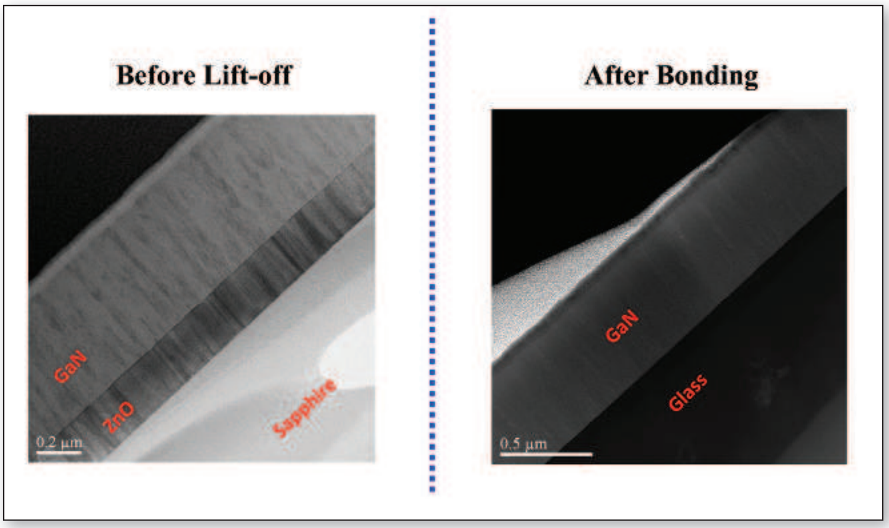

Figure 3. Cross-sectional transmission electron microscope images showing the epitaxial growth of GaN on ZnO/sapphire by MOCVD without back-etching of the ZnO and the excellent GaN/glass interface after chemical lift-off and direct fusion bonding. The lifted GaN layers show no trace of zinc in high-resolution electron microscopy energy dispersive X-ray microanalysis near the interface. [credit: G. Patriarche, LPN, Marcoussis, France].

partial pressure. Thus the oxygen stoichiometry, which is primordial for the properties of oxide-based materials, can be precisely tuned over a much larger range without compromising material quality.

LED structures

The pertinence of ZnO for GaN-based LEDs lies in the optoelectronic grade thin-film pseudo-substrates that we have developed as templates for GaN regrowth.

Over the past few years, the Georgia Tech / CNRS lab has developed a novel MOCVD approach for capping our ZnO epilayers with GaN that is free from back-etching. Once the ZnO layer is encapsulated, a GaN LED structure can be grown under standard MOCVD conditions without damaging the oxide layer.

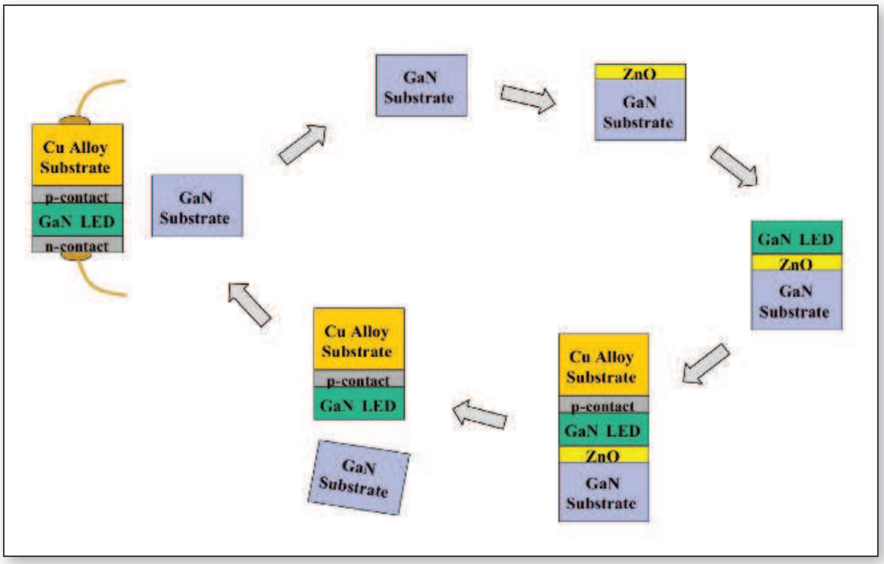

Figure 4. The costs for adoption of a native GaN substrate for vertical GaN LED manufacturing can be slashed by turning to cycles of chemical lift-off and reclaim.

Characterisation of GaN films that are deposited on ZnO reveals a very high material quality. After only 100 nm of growth, these layers are optically active, have a root-mean-square surface roughness of 1 nm, and have much less crystallographic dispersion than GaN films of comparable thickness grown directly on sapphire.

This suggests that a switch from sapphire to ZnO/sapphire for LED production would allow far thinner layers of GaN to be used, which would be advantageous for light out-coupling and external quantum efficiency.

That is not the end of the story, however. We have gone on to demonstrate that ZnO thin-film templates can subsequently be used as sacrificial release layers for the GaN. This process, an alternative to laser lift-off, is based on selective chemical dissolution of the ZnO underlayer. It takes just a few hours and can be performed with a variety of dilute acids or alkalis – because GaN is highly resistant to chemical etching in acids and alkalis other than HF, while ZnO is not (see Figure 2, which is a full 2-inch wafer chemical lift-off progression). The lifted GaN layers show no trace of zinc in high-resolution electron microscopy energy dispersive X-ray microanalysis near the interface.

In parallel work on another materials system carried out at Heriot Watt University in the UK, Kevin Prior's group have developed a process for the full transfer of ZnSe from GaAs to alternative substrates by means of direct wafer bonding after chemical lift-off with a sacrificial MgS underlayer. Mirroring this bonding process, we were able to demonstrate similar transfer of a GaN LED structure from sapphire to an alternative substrate (see Figure 3).

Thanks to funding in 2013 from the European Commission FP7 and the Scottish Universities Physics Alliance, we have been able to unite the partnerships with the groups of Prior and Ougazzaden and go on to demonstrate that a similar process is capable of delivering chemical lift-off of GaN from ZnO-coated bulk GaN substrates.

The advantage of this counter-intuitive approach is the higher quality of the GaN grown on top of the ZnO-coated GaN substrate. Indeed, X-ray diffraction and electron microscopy studies showed that the resulting GaN epilayers had significantly larger grains, less strain and lower defect density than can be obtained by heteroepitaxy on ZnO/sapphire.

Moreover, the GaN film is relaxed, thanks to the underlying GaN substrate straining the ZnO template such that it is lattice-matched to GaN.

X-ray diffraction reveals that a 100 nm-thick overlayer of GaN on the ZnO/GaN template replicates the omega rocking curve linewidth of the GaN substrate (~0.05°), which represents an order of magnitude reduction in crystallographic dispersion compared with GaN layers of similar thickness grown on ZnO/sapphire. In addition to superior epitaxy, the expensive single crystal GaN substrate is not consumed in this process and multiple GaN substrate reclaim and reuse cycles are possible without significant degradation of GaN layer quality (see Figure 4).

Moreover, chemical cleaning suffices and there is, therefore, no wafer loss through repolishing. Consequently, large quantities of GaN substrates are not required for chip production, which means that substrate costs per growth run are compressed to industrially viable levels. This should enable a breakthrough in LED chip manufacturing,in terms of output power per wafer and cost per lumen. There is no reason why this technology cannot even be applied to the rarer, even more expensive, non-polar GaN substrates that are being put forward as a way to combat "droop", the decline in LED efficiency at higher current densities.

This chemical lift-off technique is clearly very promising, and unlocking its true potential could play a major role in the future of solid-state lighting.

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