The New Horizon is Vertical in HB-LEDs. Excimer Lasers Excel in Sapphire Substrate Removal.

Next generation vertical, GaN-based, high-brightness light emitting diodes (HB-LEDs) depend on sapphire growth substrate release. To this end, 248 nm excimer lasers provide second-to-none optical performance, and power and pulse stability ideal for fast, high yield laser lift-off (LLO) processing.

Introduction

The performance of commercial GaN-based, white-light HB-LEDs has rocketed over the last decade (Fig.1) [1].

Relative cost and performance evolution of LEDs

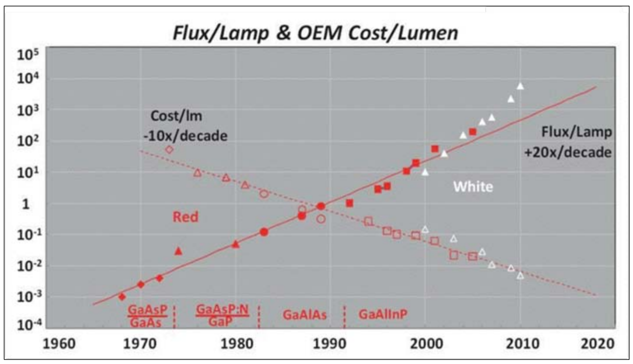

Figure 1

Competition has fueled the creation of novel device architectures with improved photon-extraction efficiencies, which have increased the LED chip's luminous flux, leading to substantially reduced cost per lumen. This has opened up the range of solid-state lighting applications for these devices, and brought their characteristics in line with the requirements for deployment in automotive, display backlighting and general lighting.

Vertical Architectures

There are two fundamental ways to envisage an LED chip, i.e. a lateral and a vertical die architecture (Fig.2). The choice of the design is ultimately driven by the material.

Lateral and vertical LED designs

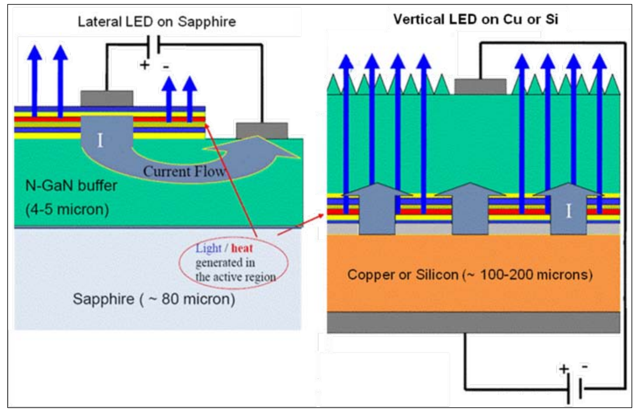

Figure 2

Sapphire is primarily used as the standard growth substrate for the GaN layers due to its low cost and good lattice matching. Sapphire is a good electrical insulator, thus, the contacts are to be placed next to each other on the front-side contacting the p- and the n-GaN layer, as depicted in Fig.2 left. If, however, a conductive carrier material such as copper, silicon or silicon carbide replaces the sapphire as carrier substrate, a front-side and a back-side contact is applicable resulting in a vertical design.

As a matter of fact, a vertical LED die (Fig.2, right), involving removal of the non-conductive sapphire substrate goes along with several inherent performance advantages over the lateral LED approach [2]:

i) A vertical structure avoids the inhomogeneous current distribution through the active multiple quantum well (MQW) region including the current crowding towards the n-contact as indicated in Fig.2 by the broad arrows.

ii) A vertical LED structure has a significant advantage in terms of substrate heat dissipation. This is key in obtaining higher light output from a single LED i.e. increasing the LED die size.

iii) In a vertical LED, the sapphire is lifted-off and does not need to be diced. Moreover, with non-destructive excimer laser lift-off removal of the sapphire wafer as a whole, the same sapphire wafer can be used repetitively as GaN growth substrate. This is a significant cost-saving aspect in HB-LED production.

A general aspect of HB-LEDs is the unavoidable trapping of light inside the chip by total internal reflection. Specific roughening of the emitting surface of the vertical LED can reduce the internal reflection losses by far. Such surface roughening is obtained e.g. in a wet etching process following sapphire substrate removal carried out using an excimer laser system.

Sapphire Substrate Removal via Laser Lift-Off

After epitaxial growth of the film stack and the patterning of the LED chip, a carrier substrate of high thermal conductivity is bonded to the p-layer side of the LED wafer (Fig.3). This carrier wafer provides both good electrical contact and good heat dissipation. Accordingly, silicon or a specific metal alloy is employed. Substrate transfer is completed by removing the sapphire substrate via Laser Lift-Off (LLO).

Since the functional GaN layers are a few microns thin, chemical etching or polishing of the sapphire wafer without damaging the GaN structure is a cumbersome task with adverse effects on the overall yield.

Laser Lift-Off (LLO) is the method of choice for obtaining selective separation that leaves the active materials unaffected.

In the LLO process, the LED wafer is exposed to high intensity UV laser light pulses directed through the sapphire substrate, which is transparent at a wavelength of 248 nm (Fig.3). GaN, however, strongly absorbs the UV photons in the adjacent interface layer of ~20 nm in depth. At a laser fluence of ~600 mJ/cm2, the GaN interface layer locally heats up to ~1000°C and decomposes into metallic gallium and nitrogen gas. Upon heating the wafer to 30°C, Ga becomes liquid and the sapphire wafer can be removed from the liquid interface [3].

Typical vertical LED manufacturing process flow

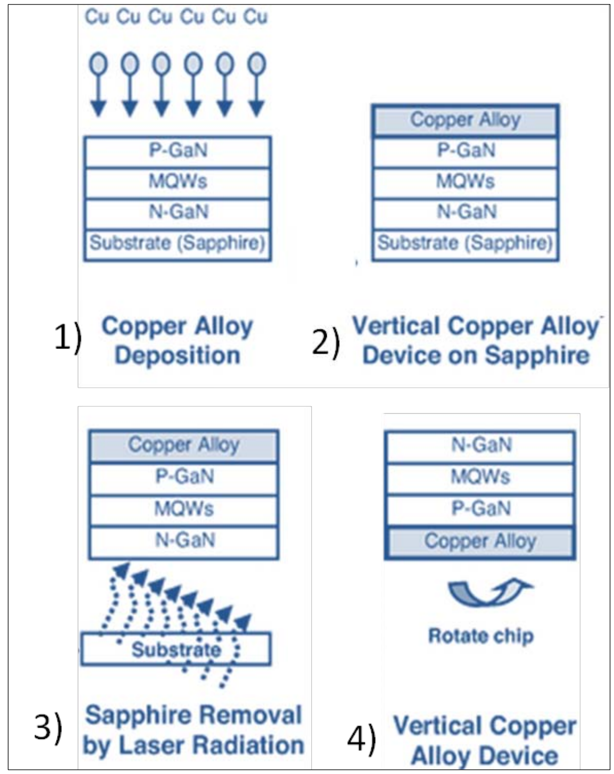

Figure 3

LLO with the Excimer Laser

The LLO process works by sequentially exposing areas of the wafer to a single UV laser pulse until the entire surface area is covered. The laser for LLO must meet requirements as to wavelength, pulse energy and stability, in order to ensure a controlled process.

i) First, it must emit pulsed UV-light with a wavelength of below 350nm, since this corresponds to the GaN bandgap of 3.5eV and is hence absorbed at the GaN interface. UV laser technologies comprise excimer lasers at 248 nm, and high harmonics of Nd:YAG lasers.

ii) Second, in order to enable a fluence of more than 600 mJ/cm^2 over large per-shot-areas of several sq mm, high laser pulse energies of 400 mJ or more are needed. The per-shot-area is limited by the final size of the LED die which for HB-LEDs can have an area of up to 5mm^2. If the per shot-area is larger or the LED dies are smaller in area, many dies can be separated within a single laser shot (Fig.4).

Twelve LED dies separated with a single pulse (Photo: JPSA)

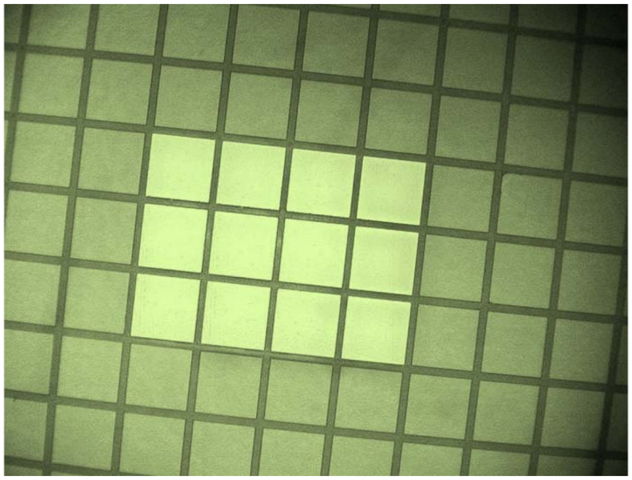

Figure 4

Excimer lasers directly emit UV laser pulses with high energy and high peak power. They do not operate on higher harmonics like Nd:YAG lasers. Thus, even compact excimer lasers put out more than 500 mJ/pulse whereas conversion efficiency limits Nd:YAG pulses to 200 mJ even for powerful systems (Table 1).

Table 1: Excimer versus Nd:YAG laser parameters.

Parameter	Excimer Laser	Photon Energy	Flash-Lamp Nd:YAG Laser
Wavelength	351nm, 308nm, 248nm 193nm	1.17eV 2.33eV 3.53eV 4.02eV 4.66eV 5.00eV 6.42eV	1064nm (fundamental) 532nm (2nd harmonic) 355nm (3rd harmonic) 266nm (4th harmonic)
Output Energy	248nm: 100 to 1200mJ 193nm: 50 to 600mJ		355nm: 60 to 200mJ 266nm: 40 to 100mJ
Repetition Rate	variable, 1 to 200Hz		fixed, 10Hz or 20Hz
Shot-to-Shot Stability	typ. 0.5%, rms		typ. 2%, rms
Long Term Drift, 4hrs	0 to 1%, rms		10 to 15%, rms
Ablation Geometry	Flat-top profile		"distorted Gaussian"
Pulse Width, FWHM	15 to 20ns		5 to 8ns
Consumables	Gas bottle		Flash-lamps, crystals

iii) A pivotal laser performance aspect in LLO processing is the uniformity of the fluence over the entire per-short area.

Excimer lasers emit a large beam cross section and have inherently low coherence. Their beam profile is shaped and homogenized by high grade UV optics. The beam homogenizer is based on cylindrical lenslets that homogenize the beam in both axis individually. The combination of high quality optics with the low coherence input beam of the excimer laser results in a large, speckle-free field size with extremely homogeneous fluence exhibiting a sharp fall-off at the edges (Fig.5).

Excimer laser beam homogenization principle

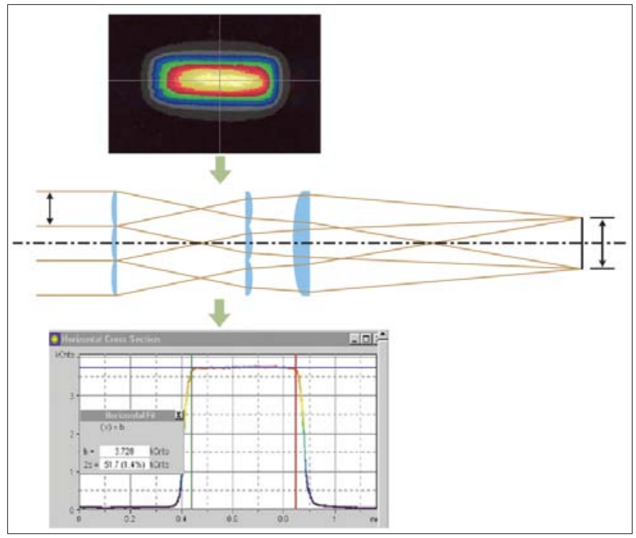

Figure 5

The homogeneous field is subsequently demagnified by a factor of 5 and projected onto the wafer. System parameters of a 248 nm Laser Lift-Off system built on an LPXpro210 excimer laser and capable of processing 50 wafers of 2” to 6” size per hour are summarized below.

Table 2: Excimer laser lift-off system parameters

Laser LPXPro 210	**248nm, 500mJ, 100Hz**
Beam Uniformity	+/- 5%, 2 σ
Homogenized Field (@ mask)	20 x 20 mm
Field Size @ Substrate	3.5 X 3.5 mm
Energy Density max.	1600 mJ/cm^2
Resolution	30 µm L/S
Working Distance	80 mm
Laser Class	4

iv) Fluence uniformity is also to be maintained over consecutive pulses setting severe pulse-to-pulse stability demand on the laser.

Whereas non-linear frequency conversion in Nd:YAG lasers result in high pulse energy fluctuations of typically 2%,rms (Table 1), 248 nm excimer lasers deliver by far better pulse stability of typically 0.5%,rms. Energy and power stability is maintained over more than a hundred hours of non-stop excimer laser operation at 248 nm as shown in Figure 6.

Hands-free operation at 248nm over 120 hours.

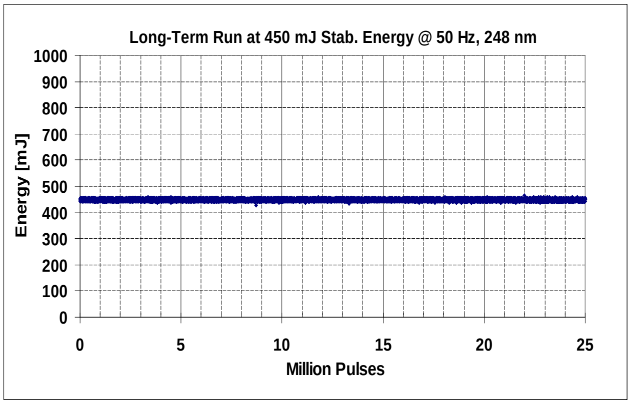

Figure 6

In advanced high power excimer lasers, virtually all maintenance has been eliminated, except for automated gas changing, which takes only a few minutes. Thus, maintenance costs and downtime are comparable to state-of-the-art solid-state lasers [4].

Conclusion and Outlook

HB-LEDs have started to compete with conventional light sources in various markets. From a technical point of view, the general lighting market requires a luminous efficacy beyond 100 lumens per watt in a single die white LED package. Compared to lateral-type LEDs, vertical-type LEDs have significant advantages, such as better current injection, excellent heat dissipation, and resistance to electrostatic discharge damage.

Sapphire substrate removal by excimer laser lift-off is an efficacy enhancing technology which plays a vital role en route to manufacturing next generation HB-LEDs.

A trend in LED high volume manufacturing is the use of larger i.e. 6” wafers. Ultimately the LLO process must provide the throughput to process six inch diameter wafers at a rate of 60 wafers per hour. To this end, excimer laser technology at 248 nm is available over a large output energy range up to 1 Joule/pulse. At 1 Joule pulse energy, about 400 pulses are necessary to cover the entire 6” wafer in a lift-off process which is as fast as 10 seconds at 50 Hz pulse rate. Excimer laser lift-off is thus an enabling technology, providing throughput upscaling by larger illumination fields and higher repetition rates.

References

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