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White Paper

Micromachining of Sapphire Wafers for LED Production using Picosecond Lasers

High intensity, blue light emitting diodes (LEDs) are finding use in a rapidly growing range of applications, including display backlights for handheld devices and flat panel televisions, automotive headlamps and general lighting applications. To support further market growth, LED manufacturers are working to improve device output efficiency and to lower production costs. One particular focus of these efforts is in the area of singulation, that is, the process of dicing a wafer containing many LEDs into individual devices. Traditionally, this has been accomplished using either mechanical means or laser ablation based Q-switched, diode-pumped, solid-state (DPSS) lasers. However, both these approaches have limitations, especially for high brightness, high value LEDs. Now, the development of industrial lasers with ultrafast (picosecond) pulsewidths is enabling a new type of singulation by creating internal modifications that subsequently allow the substrate to be separated. While patents have been granted for internal modification to several companies [1], the purpose of this article is not to compare the specific patents, but to discuss the general characteristics of various dicing methods. In addition, this paper will discuss the particulars of a cost effective, high reliability picosecond laser source, called the Talisker, which is well suited for this next-generation internal modification dicing application.

LED Background

Most LEDs with output in the blue end of the spectrum are formed by growing GaN epitaxial layers with a total thickness of about 100 µm on top of a sapphire substrate. These sapphire substrates are usually about 2 inches (50 mm) in diameter, while the individual LEDs might cover an area of about 300 µm x 300 µm. Thus, a single sapphire wafer can contain 20,000 or more devices. After epitaxy, the wafer must be cut to separate out (singulate) the individual LEDs for packaging.

Sapphire is used as the substrate material for several reasons. First, it provides an excellent lattice match for the GaN, and, second it is transparent to LED output wavelengths, which is important since some of the light emitted by the LED partially passes through the edge of the sapphire substrate. Finally, sapphire is a fairly good thermal conductor, which helps in heat sinking the LEDs.

Mechanical Singulation

Sapphire is extremely hard (second only to diamond) making it difficult to cut. Older, conventional, mechanical methods for sapphire wafer singulation are diamond scribing and blade dicing. Unfortunately, when using these methods, the low depth of the scribe can lead to failure of the substrate to break along the scribed line, which lowers yields. The major negatives of blade dicing are the large amount of debris formed which necessitates post-cutting cleaning, the stress induced into the substrate which can lower LED operating efficiency, and the relatively large width of the cut. This latter necessitates greater spacings between LEDs on the substrate, therefore lowering process utilization and increasing device cost. From a practical standpoint, mechanical singulation is difficult to control because the process is highly dependent upon operator skill level. The disposable diamond tools themselves are expensive and are used up rapidly. Finally, the process has relatively low throughput so large scale production requires that numerous machines be utilized.

Laser Ablation

In order to increase process efficiency, reduce production costs and improve device characteristics, most blue LED manufacturers have now switched from mechanical singulation methods to some form of laser scribing and breaking. Here, a focused, ultraviolet (UV) beam from a Q-switched, DPSS laser is used to partially cut through the sapphire substrate. Typically, several passes are used to go through approximately 30% of the wafer thickness. This is then followed by some mechanical separation technique, such as tape expansion.

This type of laser material removal works by ablation. In the ultraviolet, this is a combination of bulk heating of the material, as well as avalanche ionization; the net result is that the substrate material is vaporized. In

order for this process to work, it is necessary to employ lasers with output in the ultraviolet (below 400 nm to get as close as possible to the band gap of sapphire and GaN, thus increasing the efficiency of the photoionization process.

A side benefit of using ultraviolet DPSS lasers is that their combination of short wavelength and high beam mode quality enable the beam to be focused to smaller spot sizes than visible or infrared lasers, thus achieving narrower cut widths. With focused spot sizes of a few microns or less, the cut widths obtained with laser ablation are also substantially narrower that those produced with a saw. Furthermore, laser ablation yields significantly less edge damage (cracking and chipping) than mechanical cutting, which means that the LED devices can be packed closer together with narrower gaps, called "streets." All this translates into higher yields and therefore lower unit cost. In addition, laser ablation is a consistent and fully automated process requiring very little operator intervention. It is also much faster than mechanical methods.

Even though laser ablation produces good quality scribes, there is still some thermal damage at the cut edge. This is because the heat from the absorption of the laser beam has time to diffuse somewhat into the substrate which, for a Q-switched laser, is in the tens of nanoseconds and is longer than the heat diffusion time for the material.

There are actually two main ways that laser ablation is implemented in practice. The most common is back side (through the sapphire) singulation using a 355 nm, Q-switched DPSS laser. This creates some minor debris which is deposited on the backside, away from the LEDs themselves. This approach has, to date, been the most economical method for sapphire scribing. Some manufacturers scribe from the front (epitaxy) side, which typically employs a 266 nm, Q-switched DPSS laser. This shorter wavelength minimizes kerf width, heat affected zone and debris generation thus improving the LED performance.

The Internal Modification Process

An alternative approach is to scribe and break along internal modification regions inside the sapphire. This is accomplished by focusing the output of a picosecond laser inside the sapphire substrate. This creates cracks within the substrate but does not affect the top and bottom surfaces. Once these cracks are produced, the individual devices are broken out from the substrate using mechanical means, typically tape expansion.

Also, in contrast with laser ablation, the wavelength used (typically 532 nm for sapphire) is one at which the substrate material is highly transmissive rather than absorptive.

The internal modification process utilizes the fact that laser light with ultrafast (picosecond or less) pulsewidths and high peak powers interacts with sapphire in a distinctly different manner than nanosecond (Q-switched) lasers. This is because ultrafast pulses are characterized by very high peak powers, i.e. a 100 microjoule pulse with a duration of 10 ps can have a peak power of 10 megawatts. This high intensity drives a nonlinear, multiphoton absorption process which excites electrons in the material and directly breaks bonds.

To create the internally modified regions, the laser beam must be focused to a small spotsize (~1-2 μm) inside the sapphire. This is necessary to achieve the sufficient intensity to drive the non-linear process and to keep the modified region confined to a narrow, localized area. To achieve such a small focused spotsize, a high NA microscope objective (designed for use with lasers) is required. This lens is used in combination with translation stages capable of extremely flat motion as indicated in the schematic in Figure 1.

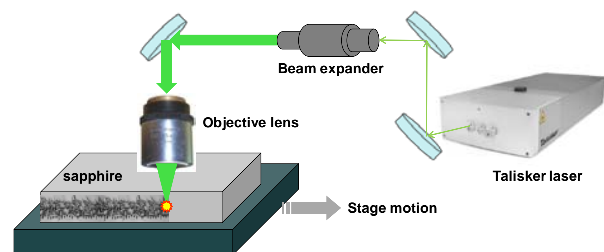

Figure 1. *Setup for internal modification of sapphire using the Talisker laser.*

The high repetition rate (200 kHz) of the laser allows fast scribe speeds of up to 500 mm/s, the speed limit being set by the translation stage motion rather than the laser output. Sapphire scribing by this method results in greater throughput over laser surface scribing techniques, which also require breaking after laser treatment. Figure 2 illustrates the internal modified region obtained in 100 μm thick sapphire substrates using 532 nm, 2 μJ pulses with a translation stage speed of ~300 mm/s. The scanning electron microscope image on the right of Figure 2 gives an indication of the top surface edge quality that can be produced by this scribe and break process.

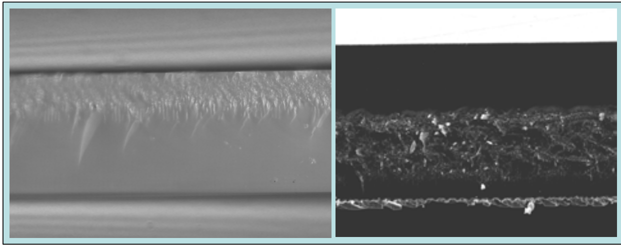

Figure 2, *Internal modification regions produced using 532 nm, 2 µJ pulses at a speed of 300 mm/s.*

Internal Modification Dicing Benefits

Internal modification dicing delivers several important advantages over both mechanical and laser ablation methods. First, multiphoton absorption occurs in just about any material that enables the machining of several high bandgap materials besides sapphire (e.g. glass, certain polymers) that have low linear, optical absorption and are therefore difficult to machine with other lasers. Next, since internal modification dicing occurs within the material, no debris is created at the surfaces. This eliminates the need for post-processing cleaning in LED singulation. Also, internal modification dicing produces very high quality edges with minimal residual stress and thermal damage. This debris-free edge, with its low thermal damage, has been shown to increase the extraction efficiency of light from LEDs, thus resulting in brighter devices. This is because these edge characteristics enhance photon emission from the active multiple quantum well region in the sidewall direction, and also improve reflection from the Ag-coated bottom of the package [2].

In addition, internal modification dicing can be successfully performed at speeds that are up to ten times faster than laser ablation. Specifically, it has already been demonstrated to operate at speeds of up to 500 mm/s, and the upper limitation in this case was caused by the linear motion stage and not the laser process. The narrow scribes and minimal heat affected zone also allow for the narrowest possible streets on the wafer, thus maximizing process utilization.

The table below provides an overview comparison of the various singulation methods [3].

	Mechanical	Laser Ablation	Internal Modification Dicing
Speed	Slow	Medium	High
Yield	Poor	Good	Excellent
Labor Intensiveness	High	Low	Low
Capital Cost	Low	Medium	High
Operating Costs	High	Medium	Low

Summary

Industrial ultrafast lasers, such as the Coherent Talisker, now provide access to picosecond pulses in a package that delivers the practical performance and reliability characteristics necessary for production line applications. These ultrafast lasers enable a range of novel micromachining techniques including internal modification dicing, which has now emerged as a useful singulation technique for LED production. However, since the initial capital cost of the equipment for internal modification dicing is higher than for other methods, it is best employed for high value products, such as high brightness LEDs, where this capital cost can be quickly recovered through increased production yields and higher throughput.

References

1. For example, US Patent 6,992,026 by Hamamatsu Photonics K.K.

2. *Enhanced Extraction Efficiency of InGaN-Based Light-Emitting Diodes Using 100-kHz Femtosecond-Laser-Scribing Technology*, Jae-Hoon Lee, Nam-Seung Kim, Sang-Su Hong, and Jung-Hee Lee, IEEE Electron Device Letters, Vol. 31, No. 3, March 2010 213

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