Optimization of UV laser scribing process for light emitting diode sapphire wafers

Ashwini Tamhankar[a)] and Rajesh Patel
Spectra-Physics Lasers, Newport Corporation, 3635 Peterson Way, Santa Clara, California 95054

(Received 28 February 2011; accepted for publication 13 April 2011; published 23 May 2011)

Billions of light emitting diodes (LEDs) are used today in traffic control, automotive headlights, flat panel display technology, mobile devices, back lighting, projection, and general illumination applications. With the dramatic growth in LEDs, manufacturers are looking for technologies to increase production yield and decrease cost. Sapphire wafer singulation into miniature dies is one of the critical steps used in blue LED manufacturing. Typical dicing techniques used in wafer singulation process include laser dicing, laser scribing and breaking, mechanical scribing and breaking, and diamond blade sawing. In recent years, laser scribing and breaking has proven to be very efficient for volume LED manufacturing. In this paper, we have characterized the effect of 355 nm *Q*-switched diode-pumped solid-state (DPSS) laser parameters such as fluence, pulse width, and repetition rate on laser scribing process by measuring sapphire wafer cutting depth and scribe kerf width. Furthermore, we have also explored the techniques to increase process efficiency while maintaining quality of scribes using different laser sources. © *2011 Laser Institute of America.*

Key words: LED, sapphire wafer, singulation, laser, UV

I. INTRODUCTION

Light-emitting diodes (LEDs) are one of the most widely used optoelectronic devices today. LEDs are used in automotive, consumer electronics, displays, illumination, transportation, and photosensor applications.

With increasing demand for LEDs, the process technology continues to advance as manufacturers pursue brighter, more efficient and less expensive LEDs. LED devices are fabricated on a hard substrate material such as single crystal sapphire (Al_2O_3) material. Sapphire has excellent thermal conductivity and is a popular substrate material for epitaxial growth of indium gallium nitride (InGaN) based LEDs.

A typical LED wafer contains several thousand LED devices. These devices are cut apart or singulated to produce individual LED dies. The street widths available between dies for singulation are very narrow, approximately 20–50 μm. To achieve higher yield die count, it is of utmost importance to scribe narrower and cleaner cuts.

There are several traditional methods such as diamond sawing, mechanical scribing and breaking used to singulate LED dies. Kerf width achieved with diamond sawing method is in the 50-250 μm range. To create narrow kerf widths of 20 μm or less, extremely thin saw blades, which can easily wear and break, need to be used. Also, mechanical dicing can produce chipping, cracking, and delamination along the scribe cuts, thereby reducing electrical performance and yield of the LEDs. Among the methods used to date for LED singulation, laser scribing and breaking shows the most promise. Laser scribe-and-break method is a noncontact process that is very efficient for high volume production. It helps reduce the cost of LED manufacturing over traditional diamond scribing. The laser scribed cutting depth is easy to control, leading to reduced stress on wafer during the break process. Also laser scribing facilitates precise positioning of scribes within a few microns of active features along with narrow scribe width (as small as 5 μm) with less chipping, resulting in uniform die size, consistent shape, and improved electrical performance of LEDs. Thus, laser scribing technology has overall advantages of increased throughput, low cost, ease of use, and high yields compared to traditional die separation technologies.[1]

The choice of laser wavelength is a very important factor for the laser scribing process. Laser wavelength is selected based on the optical absorption properties of sapphire material. The optical curve of percent transmission versus wavelength shown in Fig. 1 indicates that sapphire is mostly transparent in visible and near visible wavelength region.[2]

Laser scribing of sapphire wafers has been investigated with laser systems having various wavelengths in the DUV (157 nm) to UV (355 nm) range, pulse widths (in nanosecond regime), beam shaping, and power levels.[3–7] The impact of laser scribing on trench quality and LED device performance has also been characterized in the literature.[8–10] Through this large body of work, it has been established that 266 nm and 355 nm DPSS pulsed lasers are best suited for laser scribing of LEDs. For 266 nm laser based processes, the laser is typically irradiated on the front side of the sapphire wafer, while using 355 nm wavelength lasers with sapphire wafer thicknesses <150 μm, backside scribing is a preferred technique. Scribing from the backside of the device has been shown to have an advantage of reduced impact on LED performance.

[a)]Electronic mail: ashwini.tamhankar@newport.com

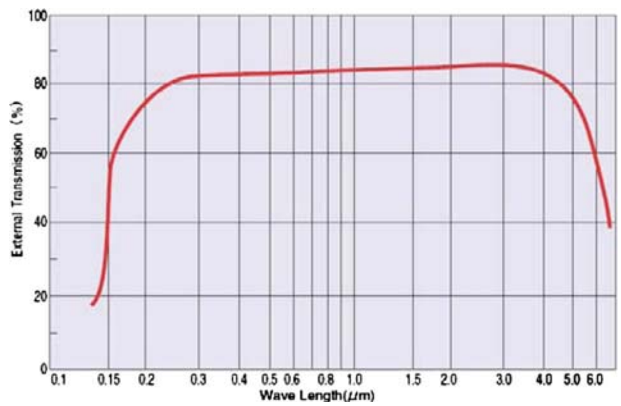

FIG. 1. Transmission versus wavelength curve for 1mm thick sapphire wafer.

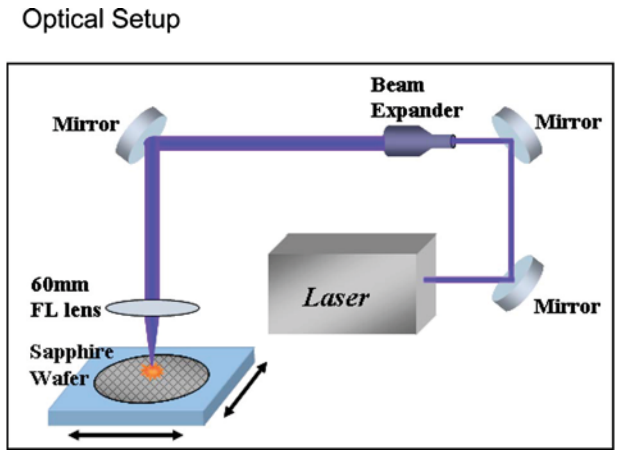

FIG. 2. Experimental optical setup for LED sapphire wafer scribing.

Among the research conducted for sapphire scribing application with 355 nm wavelength, limited information is available in the literature about the effect of laser parameters on the laser scribing process. In this paper, we characterize the effect of 355 nm *Q*-switched DPSS laser parameters such as fluence, pulse width, and repetition rate on laser scribing process by measuring sapphire wafer cutting depth and scribe kerf width. Furthermore, we have explored techniques to increase process efficiency while maintaining quality of scribes using different laser sources and beam delivery systems.

II. EXPERIMENTAL DETAILS

The sample material used for all the experiments in this study was 2 in. diameter, ~400 μm thick blank single crystal sapphire wafer with diffused and polished sides. All of the laser processing was performed at room temperature on the diffused back side of the wafer with no assist gas.

A. Laser system

Two different Spectra-Physics® 355 nm DPSS *Q*-switched lasers with short pulse widths and high peak power were used in this study. The Tristar™ 355-3 laser is a compact low power UV laser and the Pulseo® 355-10 laser is a high power UV laser. Detailed key laser specifications are outlined in Table I.

TABLE I. Specifications of the Spectra Physics laser systems used in the LED sapphire wafer scribing experiments.

Parameters	Tristar 355-3	Pulseo 355-10
Wavelength	355 nm	355 nm
Rep rate, nominal	90 kHz	90 kHz
Average power	>2 W at 90 kHz	>10 W at 90 kHz
Peak power	0.9 kW	~5 kW
Pulse width	~19 ns	~18 ns
M^2	<1.2	<1.3
Beam diameter	0.24 mm	1.75 mm

B. Optical setup

The optical setup for the experiment is shown in Fig. 2 and involves a fixed beam delivery optical setup. It consists of the laser beam routed via mirrors and then expanded to ~13 mm beam size using a beam expansion telescope. The expanded beam was incident on a 60 mm focal length lens to generate ~2.5 μm $(1/e^2)$ theoretically calculated spot size.

C. Experimental procedure

The sapphire wafers for this experiment were secured on the flat linear motorized X-Y positioning stage platform constructed from Newport Corporation XML series stages with XPS motion controller. The stage angle was finely tuned to maintain the focal plane along the sapphire scanning area. To generate laser scribes, the laser beam was scanned on sapphire substrate by precisely moving the X-Y stages. For all of the experiments, a single scan was used for each scanning speed. The polarization direction of the laser pulses was maintained parallel to the scanning direction to generate V-shaped grooves to achieve deeper cuts while maintaining narrow kerf widths.[4]

D. Defining the focal position

Prior research shows that for sapphire scribing, placing the laser focal spot inside the material has the advantage of machining deeper cuts.[6] Hence during our experiments instead of defining focal plane corresponding to the smallest spot size, we defined a "processing focal plane," which corresponds to the deepest scribe achieved.

Precision linear motorized Z positioning stage (Newport Corporation IMS series) was used for beam focusing capabilities. To determine the location of the "processing focal plane," test scribes were generated at various focal positions along the optical axis by Z stage motion in ~10 μm steps. These scribes were processed using slow scan speeds to obtain >80% spatial pulse overlap. Figure 3 shows the top view picture of an example scribes.

Cut depths of the scribes were determined by cleaving the material. To cleave the sapphire substrate, cleaving scribes were generated on opposite side of the wafer in

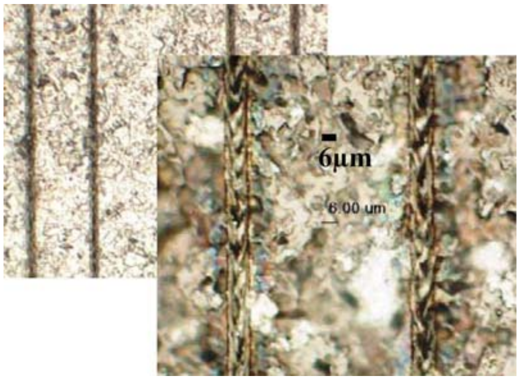

FIG. 3. Top-view microscope picture of example scribes on sapphire wafer.

perpendicular direction to the test scribes. Each wafer was cleaved, and scribe depths were measured using an optical microscope. The samples were cross sectioned at several different locations along the scribes, and the average of the depth measured was considered. The uncertainty in the depth measurements is estimated to be 2–3 μm due to random variations in scribe depth due to surface roughness. Figure 4 is an edge view cross-sectional picture showing scribe depths at different focal positions. The processing focal plane corresponding to the deepest scribe was selected for further laser processing. With the theoretical spot size of 2.5 μm, groove widths achieved at the processing focal plane during all of the experiments were between 5–9 μm.

III. RESULTS AND DISCUSSION

A. Threshold fluence determination

For any laser micromachining process, it is important to apply the optimal laser fluence to achieve a reasonable amount of material removal. Laser fluence slightly above the removal threshold of the material results in efficient material processing with meaningful ablation depth. This laser fluence is commonly referred as the optimal laser fluence. If the applied laser fluence is below the ablation threshold of the material, no material would be removed. On the other hand, at high fluence levels, excess energy is put into the material above that required for material removal, and only the optimal energy is utilized to ablate the material while the remainder of the energy is wasted in heating the material.

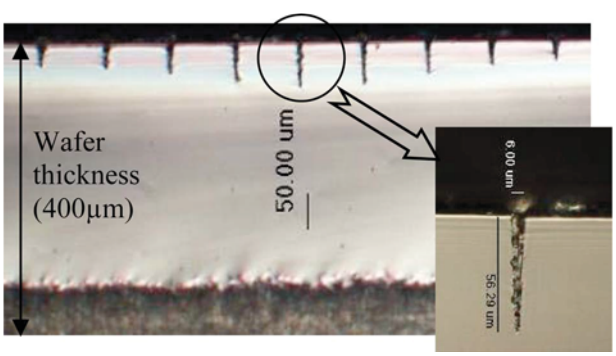

FIG. 4. Edge-view cross-sectional picture of scribe depths corresponding to various focal planes.

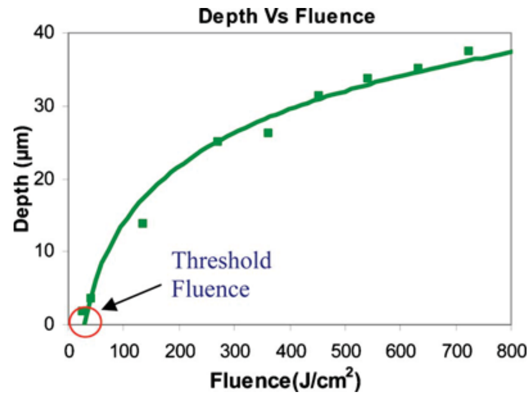

FIG. 5. Plot of scribe depth as a function of laser fluence illustrating the threshold fluence.

This material heating can cause unwanted debris, cracking, melting, and stress in the surrounding material, or what is commonly referred as “HAZ” (heat affected zone).

In this study, preliminary tests were conducted to determine the removal threshold of the sapphire material. We define the removal threshold as the fluence that results in crater formation due to material removal to the extent that is detectable with an optical microscope. We used the Tristar™ 355-3 laser at 90 kHz repetition rate to generate a plot of scribe depth as a function of laser fluence at 30 mm/s scan speed, as shown in Fig. 5. All fluence values referred to in this paper are peak fluences of a spatially Gaussian beam distribution considering ~2.5 μm theoretically calculated $(1/e^2)$ spot size.

From Fig. 5 it is observed that the removal threshold fluence of sapphire material is ~30 J/cm^2. Also the plot shows that there is logarithmic relation between scribe depth and laser fluence, thereby indicating that the rate of increase in depth slows at high laser fluence. Based on the threshold fluence value and logarithmic curve, it can be predicted that fluence between 30 and 400 J/cm^2 should achieve reasonable sapphire scribing depth.

B. Pulse width effect

It is well known that material removal threshold is also dependent on pulse width. Shorter pulse width lasers tend to have lower threshold for material removal than a longer pulse width laser.[11] To study this effect for our samples, scribes were generated on sapphire wafer samples by varying the laser fluence while maintaining a constant repetition rate and scan speed. The data were generated using two different lasers at 18 ns and 42 ns pulse durations. Pulseo® 355-10 laser was used to generate data at 18 ns pulse width while Navigator™ 355-4 laser was used to generate data at 42 ns pulse width. Both the Pulseo and Navigator lasers were operated at 50 kHz repetition rate. Scribe depth at various fluence values corresponding to 18 and 42 ns pulse widths are graphically displayed in Fig. 6. The data plot indicates that a clear processing advantage exists with shorter pulse duration (18 ns) over longer pulse duration (42 ns). Extrapolation of these logarithmic curves toward lower fluence values clearly demonstrates that the

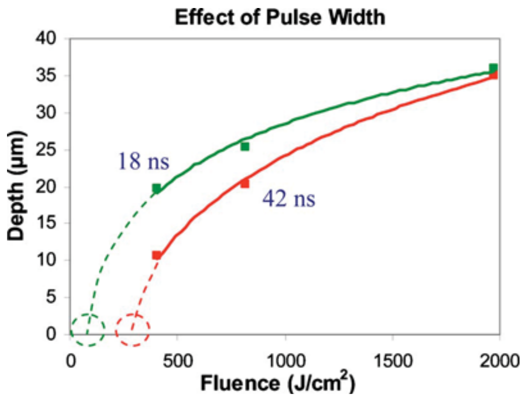

FIG. 6. Plot of scribe depth vs fluence, showing advantage of short pulse widths.

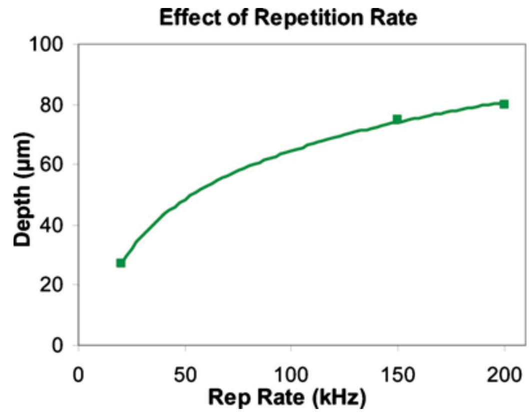

FIG. 7. Plot of scribe depth vs repetition rates showing advantage of high repetition rate.

material removal threshold with 18 ns pulse duration is lower than that with 42 ns pulse duration. From the plot, we also observe that initially in the low fluence regime close to 500 J/cm^2, an 18 ns pulse duration results in deeper scribes compared to that for 42 ns pulse duration. As we increase the laser fluence, the difference in scribe depth observed between 18 ns and 42 ns is reduced. The data in Fig. 6 indicate that in the case of short pulse widths, deeper scribes are achieved at low fluence levels, whereas for longer pulse widths more energy is needed to achieve the same depth.

In the LED die singulation process, minimizing thermal effects during sapphire scribing is critical for the optimization of the device electrical performance. When a high fluence is applied during long pulse duration machining, only a fraction of the laser energy is utilized efficiently for material removal. The excess energy is dispersed as heat in the surrounding material, resulting typically in wider kerf widths; whereas, shorter pulses tend to exhibit the advantage of "cooler machining" at a low fluence regime. Along with low material removal thresholds, machining with shorter pulses at low fluences also results in cleaner and narrower scribes and reduced potential damage to the device electrical performance.

C. Repetition rate effect

The benefit of operating lasers at high repetition rates to increase throughput in laser processing is also well known. To investigate whether higher repetition rates result in other effects on sapphire scribing, we generated data for scribe depth versus repetition rates. Scribes were processed on sapphire wafers by varying repetition rates while maintaining constant pulse energy ($\sim$8.5 μJ) and pulse duration ($\sim$27 ns). Scan speeds were varied with repetition rates to maintain constant spatial pulse overlap.

The data in Fig. 7 indicate that scribe depth increases with increasing repetition rate. At the higher repetition rates, the time between pulses is shorter and hence the thermal energy is deposited in the material at a faster rate than the rate at which it is dispersed from the focal volume by thermal diffusion. This facilitates increased heat accumulation at the focal volume resulting in localized heating and melting of the material leading to an increase in material removal. Based on the results observed, it is beneficial for sapphire substrate machining to operate the laser at a low energy per pulse and at high repetition rates of up to 200 kHz to take full advantage of laser energy for material removal.

D. Laser optimization

In this part of the study, we characterized the relationship between sapphire scribe depths and scan speeds for 70%–90% spatial pulse overlaps using DPSS Q-switched lasers with short pulse width and high repetition rates. The emphasis was on achieving 25 μm scribe depth at the fastest possible scribing speed since that is a common targeted depth during LED wafer singulation. We have attempted to determine a technique that utilizes the available laser pulse energy most efficiently for material removal.

Low Power Laser: Spectra-Physics® Tristar™ 355-3 laser system generates $>$2 W output power at 90 kHz with 22 μJ pulse energy and $\sim$19 ns pulse duration. A detailed specification for this laser system is mentioned in Table I.

By determining the optimal fluence available corresponding to higher repetition rates, the laser was operated at high repetition rate of 150 kHz with corresponding pulse width of 28 ns, and data for scribe depth versus scan speeds was generated. A data plot generated at 150 kHz, 7 μJ pulse energy (285 J/cm^2) is shown in Fig. 8 and indicates that a scan speed of $\sim$60 mm/s corresponding to a high spatial pulse overlap of $\sim$85% is necessary to achieve 25 μm deep scribes. The limited fluence available with the laser was effectively used to scribe 25 μm deep cut in sapphire wafer by operating the laser at higher repetition rate. Again, selecting high repetition rate corresponding to low fluence value was possible only because of short pulse width of the laser.

High Power Laser: Spectra-Physics Pulseo 355-10 high power laser system is optimized for 90 kHz performance and generates $>$10 W for $>$110 μJ pulse energy output with $\sim$18 ns pulse durations. A detailed specification for this laser is mentioned in Table I.

The laser was operated at a high repetition rate of 200 kHz where a high energy is available compared to the

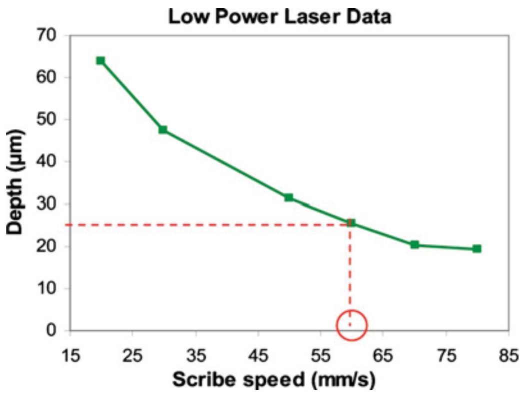

FIG. 8. Plot of scribe depth vs scribe speeds for the Tristar 355-3 laser operated at 150 kHz.

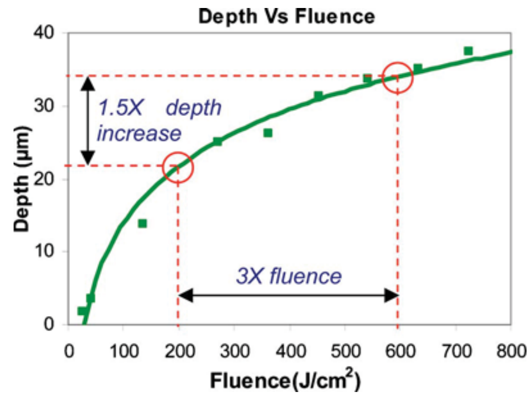

FIG. 10. Plot illustrating the inefficiency expected with excessive fluence levels.

energy corresponding to the optimal fluence needed for efficient material removal. Considering the optimal energy needed to ablate the sapphire material, data of scribe depth versus scribe speed was generated at two different pulse energy levels of 20 and 10 μJ. In the plot shown in Fig. 9, for speeds below 70 mm/s where spatial pulse overlap is >85%, we observe deeper scribes using 20 μJ versus 10 μJ energy; however, for >70 mm/s scribe speeds where the spatial pulse overlap is <85%, no significant gain in scribe depth is observed. At faster scribe speeds, most of the 20 μJ energy is wasted in heating of the surrounding material. This illustrates that applying excessive laser pulse energy for sapphire scribing is not an efficient method to increase process efficiency.

E. Process efficiency

For any laser micromachining process, to achieve maximum material removal, the most efficient use of available energy is a must. This concept can be explained from the data plot in Fig. 5, now shown with additional detail in Fig. 10.

From the data in Fig. 10, at a fluence of 200 $\mathrm{J/cm^2}$, a scribe depth of 22 μm is achieved whereas increasing fluence to 600 $\mathrm{J/cm^2}$ scribe depth of 34 μm is achieved. This shows that increasing fluence 3X yields only 1.5X increase in scribe depth. It is evident from this result that

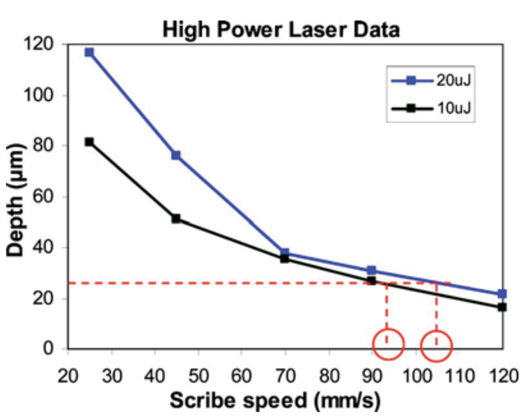

FIG. 9. Plot of scribe depth vs scribe speeds for Pulseo laser operated at 200 kHz.

simply increasing laser fluence does not proportionally yield deeper cuts. At high fluence, laser energy is not fully utilized to ablate material but is instead being inefficiently used in heating up the material. A possible solution for utilizing high fluence effectively would be to split the high fluence (600 $\mathrm{J/cm^2}$) beam into three separate beams with fluence of 200 $\mathrm{J/cm^2}$ in each beam. This would dramatically increase the throughput or effective scan speed by 3X. This type of approach is well suited for lasers with shorter pulse widths. As discussed earlier, shorter pulse widths result in low removal thresholds, which make it possible to achieve the target ablation depths in a low fluence regime.

This illustrates that for high power lasers with shorter pulse widths, rather than focusing all of the available energy into single spot, a potential efficiency gain can be achieved by splitting the energy into multiple beams with optimal energy in each beam. Revisiting the curve shown in Fig. 9, 25 μm ablation depth is achieved at 107 mm/s scribe speed using 20 μJ energy, whereas the same depth is attained at 94 mm/s scribe speed using 10 μJ. It is observed that simply doubling the amount of applied laser energy $(20/10)\ \mu\mathrm{J}=2\mathrm{X}$, process efficiency gain in terms of throughput or scribe speed is only $(107/94)\ \mathrm{mm/s}=1.14\mathrm{X}$. Therefore instead of increasing pulse energy, splitting a 20 μJ beam into two separate beams with 10 μJ energy in each beam, potential efficiency gain would be increase in the effective scribe speed to $2\mathrm{X}94=188\ \mathrm{mm/s}$, thus achieving almost 75% efficiency gain.

IV. CONCLUSIONS

With 355 nm lasers, we demonstrate that the sapphire material removal threshold is significantly lower at shorter pulse widths. Additionally, we show that shorter pulse widths (18–28 ns) result in deeper scribes at lower fluence levels, whereas at longer pulse widths (>40 ns) more energy is needed to achieve the same depth. The use of low fluence at shorter pulse widths result in cleaner and narrower scribes with reduced HAZ. Also at optimal laser fluence, based on the results we observe that high repetition rates of up to 200 kHz as compared to low repetition rates 20 kHz result in faster scribe speeds and deeper scribes while maintaining cleaner and narrower scribing quality.

For lower power lasers with short pulse width (18–28 ns) operated at high repetition rate (150 kHz) corresponding to optimal fluence, we demonstrate a significant increase in process efficiency in terms of scribe speed as well as scribe depth. Even with fluences as low as 285 $\mathrm{J/cm^2}$ at a high repetition rate 25 μm scribe depth was achieved at 60 mm/s speed. For higher power lasers with short pulse widths a technique to increase the process efficiency by properly utilizing excess energies have also been explored. We show that if the energy available at high repetition rate is in excess of the optimal energy needed to efficiently ablate the material, then splitting the energy into multiple beams with optimal fluence in each beam dramatically increases the throughput and process efficiency. By operating laser at 200 kHz and splitting a 20 μJ beam into two separate beams with 10 μJ energy in each beam, a potential efficiency gain to achieve 25 μm ablation depths is demonstrated to be an increase in the effective scribe speed of $2\mathrm{X}94=188$ mm/s, or almost a 75% scribing efficiency gain. In both lower power and higher power laser machining, cleaner and narrower quality of scribes with 5–9 μm kerf width with reduced HAZ was achieved.

Overall our results indicate that 355 nm *Q*-switched DPSS laser with shorter pulse widths operated at the optimal low fluence regime at high repetition rates is an effective and powerful tool in high throughput LED sapphire scribing.

[1]P. Jongkook, and S. Patrick, "High-speed UV laser scribing boosts blue LED industry," Physics World Journal (2002).
[2]Kyocera Corporation, Corporate Fine Ceramics Group, Japan, website: http://global.kyocera.com.
[3]D. Yutang, X. Gang, C. Jianlei, and B. Fan, "Laser microstructuring of sapphire wafer and fiber," Proc. SPIE **7590**, 75900 (2010).
[4]E. Rea, "Scribing of thin sapphire substrates with a 266-nm Q-switched solid state laser," Proc. SPIE **5339**, 231–240 (2004).
[5]E. Gu C. Jeon, H. Choi, G. Rice, M. Dawson, E. Illy, and M. Knowles, "Micromachining and dicing of sapphire, gallium nitride and micro LED devices with UV copper vapour laser," Thin Solid Films **453–454**, 462–466 (2004).
[6]S. Nagatomo, J. Ogawa, A. Saijo, and N. Kuriyama, "Laser scribing of hard and brittle materials," 65th Japan Laser Processing Society (2005).
[7]M. Mendes and J. Sercel, "Lasers in the Manufacturing of LEDs," Photonics Spectra Magazine (2010).
[8]G. Mak, E. Lam, and H. Choi, "Precision laser micromachining of trenches in GaN on sapphire," American Vacuum Society Journal **28**, 380–385 (2010).
[9]H. Lam, M. Hong, S. Yuan, and T. Chong, "Laser ablation of GaN/sapphire structure for LED," Proc. SPIE **4830**, 114–118 (2003).
[10]E. Illy, M. Knowles, E. Gu, and M. Dawson, "Impact of laser scribing for efficient device separation of LED components," Appl. Surf. Sci. **249**, 354–361 (2005).
[11]R. Patel, J. Bovatsek, and A. Tamhankar, "Why pulse duration matters in photovoltaics," Laser Technik Journal, **7**, 21–24 (2010).