EFFICIENT USE OF SHORT PULSE WIDTH LASER FOR MAXIMUM MATERIAL REMOVAL RATE

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Ashwini Tamhankar and Rajesh Patel

Spectra-Physics Lasers, Newport Corporation, 3635 Peterson Way, Santa Clara, CA 95054, USA

Abstract

Majority of high volume laser manufacturing processes require high throughput, improved accuracy, and minimal thermal damage to the target material. Diode pumped solid state (DPSS) Q-switched nanosecond pulsed lasers are routinely being used today in the manufacture of semiconductor, microelectronics and solar cells. They offer low noise, high stability, and reliability required for a robust manufacturing process. Over the past few years the energy available per pulse and the repetition frequency of such lasers have increased dramatically. In this paper we describe three different fluence management techniques to effectively use the high energy and repetition frequency available from a short pulse width 355 nm DPSS Q-switched laser to maximize the material removal rate and maintain the highest possible quality. Experimental data for ceramic scribing is presented to demonstrate the advantages offered by the proposed techniques.

Introduction

The consumer demand for a multi functional high performance smaller size electronics gadgets continues to grow. This puts heavy demand on semiconductor and microelectronics manufacturing industry to develop manufacturing technologies that can enable them to meet the demand. Microelectronics packaging plays a major role in delivering solutions that can meet the demand.

Microelectronics packaging is fundamentally an interconnection technology. Printed wiring boards (PWBs) OR Printed Circuit Boards (PCBs) are the primary structure in microelectronic packaging containing the wirings required to interconnect various electronic components. PWBs are fabricated using ceramic or organic dielectric materials. The ceramic materials offer several advantages over organic dielectrics e.g. the ceramic dielectric material has higher mechanical strength and is inherently more rigid. Additionally, ceramic can withstand temperatures up to 1600°C which is well above the component soldering temperature of 183 to 240°C, thus minimizing the risk of damage to PWBs. High thermal conductivities available with ceramic material is effective in conducting away the heat generated by electronic components. On the flipside, there are some disadvantages as well that come with the use of ceramic material, some of which include increased weight, design time, and higher material and manufacturing cost [1].

Lasers play a major role in enabling the development of newer packaging technologies in the most cost effective ways. One such example is use of DPSS Q-switched nanosecond pulsed lasers for scribing of alumina ceramic (Al_2O_3) substrates that are typically used in the manufacturing of microelectronics packages. After laser scribing, the substrate containing multiple electronic components is cleaved apart (this process is also known as “singulation”) to form individual microelectronic device packages. The entire process is commonly known as a “scribe and break” process in the industry.

Over the past few years there has been rapid advancement in laser technology. The energy available per pulse and the pulse repetition frequency (PRF) of DPSS nanosecond ultraviolet (UV) lasers have increased dramatically. This requires utilizing these lasers’ capabilities more efficiently for material processing applications to define cost effective processes. The techniques for efficient material processing of different materials have been studied in the past [2, 3, 4]. However, on the specific topic of alumina ceramic scribing using a 355nm wavelength laser, limited information is available in the literature about comparative data for the various techniques used to increase process efficiency. In this research, we have characterized the effect of short pulse width DPSS Q-switched 355nm laser fluence on scribing depth for alumina ceramic material. Furthermore, we have investigated three techniques, for effective and efficient use of the high energy and PRF available from the laser source to maximize the material removal rate while maintaining good scribe quality.

Experimental Details

The sample material used for all of the experiments in this study was ~180 µm thick blank alumina ceramic substrate. This material is representative of the material used for various microelectronics packages including substrates used for chip resistor fabrication. All of the laser processing was performed at room temperature with no process assist gas.

Laser System

A Spectra-Physics® Pulseo® 355-20 DPSS Q-switched laser with short pulse width and high peak power was used in this study. Several key laser specifications are outlined in Table 1.

Table 1 Specifications of the Spectra Physics laser system used in the ceramic scribing experiments.

Parameters	Pulseo 355-20
Wavelength	355 nm
Average Power	>20 W at 100 kHz
Peak Power	~10 kW
Rep Range	0-300 kHz
Pulse Width	<23 ns
M^2	<1.3
Beam Diameter	3.6 mm

Optical Setup

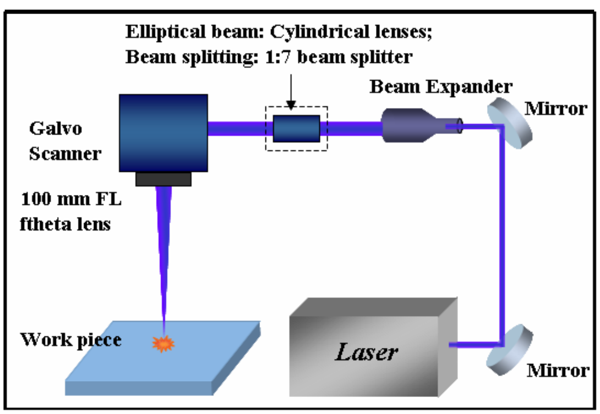

Figure 1: Experimental optical setup for ceramic scribing.

A schematic representation of the optical setup used for the experiments is shown in Figure 1. It consists of a scanning galvanometer system with 100 mm focal length telecentric f-theta lens integrated with Newport Corporation's linear motorized XYZ positioning stage systems. The motion system facilitates sample positioning under the galvo scanner and focusing of the laser beam onto the work piece. The laser beam was expanded by a factor of 1.5X to generate ~10 µm ($1/e^2$) theoretically calculated focal spot size. For such a focusing condition, the corresponding Rayleigh Range is ~200 µm. For the elliptical beam shaping tests, pair of +/- 300 mm focal length cylindrical lenses was introduced into the optical system, as shown in the schematic. For the beam-splitting experiments, a diffractive optical element (DOE) designed for 1:7 beam splitting capability was introduced into the optical system.

Experimental Procedure

The ceramic plates were secured to the flat surface of the XY motion stages with the mounting surface finely tuned to maintain the focal plane along the ceramic scanning area. To generate laser scribes, the laser beam was scanned at various speeds across the ceramic plate material using the galvo scanner. For all of the experiments, a single scan was used.

Precision linear motorized Z positioning stage (Newport Corporation IMS series) was used for accurate beam focusing. To determine the location of the focal plane, test scribes were generated at various focal positions along the optical axis by moving Z stage in ~100 micron increments. The focal plane was defined corresponding to the narrowest and deepest scribe achieved for a given set of laser parameters; this likely corresponds to the optical focus being approximately coplanar with the surface of the ceramic plate.

Cut depths of the scribes were measured by cleaving the material and inspecting the resulting cross-section under an optical microscope. To cleave the ceramic plate, cleaving scribes were generated on the opposite side of the sample, perpendicular to the direction of the test scribes. The samples were cross-sectioned at several different locations along the scribes, and the average of several depth measurements was used to obtain a single data point. The uncertainty in the depth measurement through this technique is estimated to be in the range of 2-4 microns.

Results and Discussion

Fluence management is one of the main key for any kind of laser material processing application. The optimal laser fluence on the material ensures that the incident energy is used primarily for removing, rather than merely heating of the material. In other words, at the point of optimal fluence the laser pulse energy is used effectively in maximum possible material removal with minimal heat affected zone (HAZ).

The short pulse width and high energy lasers available in the market today present an opportunity to increase the process efficiency while maintaining the machining quality with minimal HAZ formation. The following experiments demonstrate couple of ways how this may be achieved.

Circular Single-Beam Processing

The purpose of this preliminary study was to establish a baseline result for scribing alumina ceramic using a circular focused Gaussian beam. A wide range of scribe depths data at various scribe speeds and laser fluence was generated at the 100 kHz laser PRF. The scribing speed data for generating a scribe depth of 30 µm as a function of fluence is shown in Figure 2.

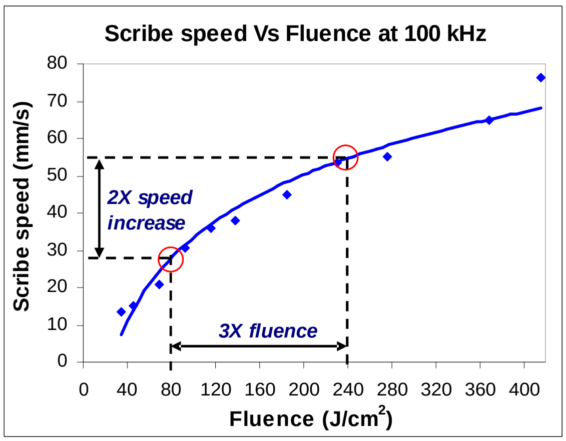

Figure 2: Plot of scribe speed as a function of laser fluence at 100 kHz PRF for scribing 30 µm deep scribe.

The experimental data shown in Figure 2 fits nicely to a logarithmic trend line with R^2 close to 1. The data shows clear trending of gradually flattening slope with the increase in fluence value. For the PRF of 100 kHz, we observe that initially, small increments in fluence value results in rapid increase in scribe speed; however, beyond fluence value of ~100 J/cm^2 the rate of increase in the scribe speed with increasing fluence begins to slow down and finally flattens out. This seems to indicate that for a very high-fluence, ablation process saturates and additional laser energy imparted to the material is not being used effectively in material removal. The additional energy is perhaps not coupled into the material due to interference with the material being ejected from the surface OR it is being diffused into the material as heat.

The process inefficiency of machining at higher fluence to achieve higher speed can be seen clearly in Figure 2. The data shows that fluence of 80 J/cm^2 yields a scribe speed of ~27 mm/s, whereas the fluence of 240 J/cm^2 yields a scribe speed of ~54 mm/s. This clearly shows that 3X increase in the fluence results in only 2X increase in the scribe speed. It is evident from this result that increase in the laser fluence does not increase the throughput linearly. This proves that at higher fluence, not all of the laser energy is being fully utilized to ablate and remove material and lot of it is perhaps dumped into the material as heat.

This is somewhat evident from the microscope pictures shown in Figure 3 (a) and (b). The pictures indicate that at higher fluence, the quality of scribes also degrades resulting in ~36 µm scribe width including a HAZ compared to 17 µm scribe width observed at lower fluence.

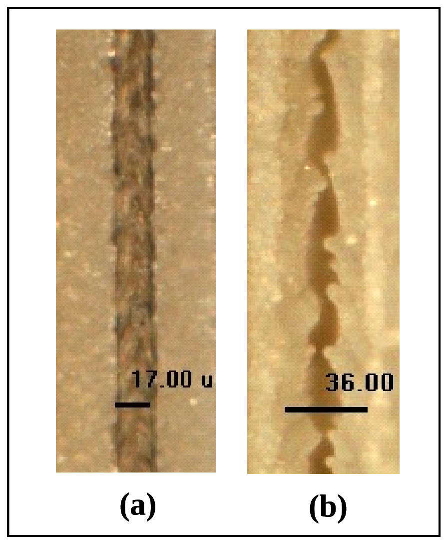

Figure 3: Top-view microscope picture showing quality of 30 µm deep laser scribe at 100 kHz PRF (a) 80 J/cm^2 (b) >400 J/cm^2

Hence, a conclusion can be drawn that, the use of a low-fluence processing regime is preferable for efficient material processing. Indeed, this approach seems to maximize material removal without sacrificing scribe quality. However, one limitation of operating in a low fluence regime is the low processing speed which limits throughput.

<u>Pulse Repetition Frequency Increase</u> One of the simplest way to work in the low fluence regime during the material processing without compromising the throughput is to operate the laser at higher PRF. For a typical DPSS Q-switched laser output power

drops with the increase in the PRF. Hence the fluence available at higher repetition frequencies is lower; however faster scribe speeds can be achieved due to higher PRF.

As an illustration to this phenomenon, the scribe speed versus fluence data was generated at 200 kHz PRF for 30 µm deep scribes and is plotted along with 100 kHz data in Figure 4.

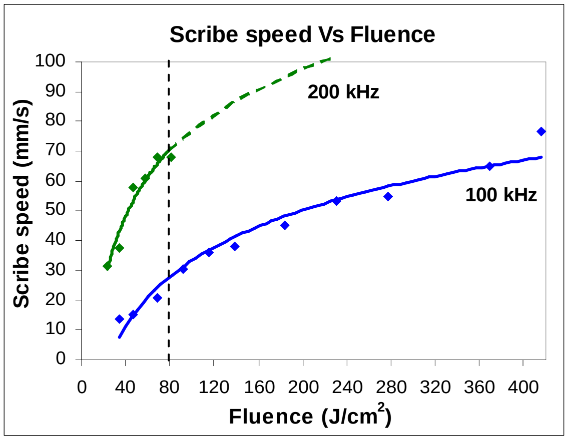

Figure 4: Plot of scribe speed as a function of laser fluence at 100 and 200 kHz PRF for 30 µm deep scribe.

At 200 kHz PRF the highest fluence from the laser based on highest energy available is 80 J/cm^2. Green dotted curve in the plot at 200 kHz is an extrapolation of the trend line to show expected scribe speeds that could be achieved at higher fluence values. As expected the data for 200 kHz PRF also follows a logarithmic trend line. However at higher PRFs, faster scribe speeds are achieved at lower fluence values. The scribe speed data to generate 30 µm deep scribe at lower fluence of 80 J/cm^2 at 100 and 200 kHz PRF is shown in Table 2.

Table 2 Scribe speeds for 30 µm deep scribe using 80 J/cm^2 fluence at 100 and 200 kHz PRF.

Pulse Repetition Frequency (kHz)	100	200
Scribe speed (mm/s)	27	70

The data shows that at 80 J/cm^2 a 30 µm deep scribe can be generated at 70 mm/s speed for 200 kHz PRF, whereas speed had to be reduced to 27 mm/s at 100 kHz PRF to generate the same scribe depth. It is observed that while PRF is doubled the scribe speed is more than doubled. We attribute this boost in speed to accumulation of heat due to increase in rate of incoming pulses arriving at the material surface. We also observe that for a low fluence and high speed process at 200 kHz PRF, the scribe quality is not compromised showing clean scribe with the width of ~17 µm as shown in Figure 5.

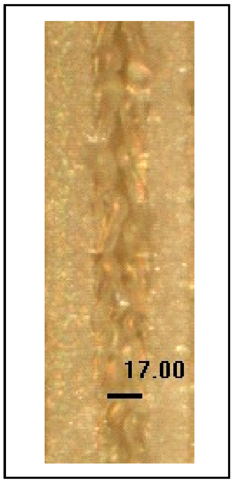

Figure 5: Top-view microscope picture showing clean quality laser scribe using 80 J/cm^2 fluence at 200 kHz PRF.

Fluence Management

Thus far, it seems clear that operating a short pulse width high-power UV laser in a higher fluence regime to achieve higher throughput is not the best way to take advantage of the power and pulse energy that is available.

One approach that seems to increase the scribing speed is increasing the PRF of laser. Besides operating the laser at higher PRF, which is essentially a *time domain* adjustment of energy distribution in the material, we investigated *space domain* energy distribution adjustment techniques, such as elliptical beam shaping and beam splitting, in an effort to increase the scribing speed and improve the overall process efficiency.

<u>Elliptical Beam Processing</u> One of the beam shaping techniques that has been studied in the past to improve laser process efficiency is the use of an elliptically-shaped beam [3]. To realize an elliptically-shaped beam, the beam focal spot size is maintained along the "minor axis", while the beam spot is stretched along the "major axis". The beam is then scanned along the major axis to generate a scribe. The main advantage of an elliptical-shaped beam is that, the high energy available from the laser

is spread spatially to achieve desired fluence at the surface. It is possible to maintain desired narrow kerf width along the minor axis and vary laser fluence by changing the major axis. At a faster scribe speeds sufficiently beam pulse overlap is maintained due to longer length of major axis.

In this study we generated an elliptical beam using a pair of +/- 300 mm focal length cylindrical lenses. The lenses were inserted into the optical path immediately before the galvo scanner aperture as shown in Figure 1. Beam ellipticity, defined here as major axis beam diameter divided by minor axis beam diameter (fixed at ~10 µm in our study), was varied along the major axis by changing the separation distance between the two cylindrical lenses.

With ~20 W average output power available at 100 kHz from the laser, the incident power upon the work piece after optical losses was measured to be ~17 W. Various scribes at different scan speed and beam ellipticities were created. The scribe depth achieved depends on beam ellipticity (since the change in beam ellipticity changes laser fluence) and % of pulse-to-pulse overlap or scribe speed. The data generated was parsed to determine the maximum scribe speed that can generate a 30 µm deep scribe for a given ellipticity. The data obtained for eight different ellipticities is shown in Figure 6.

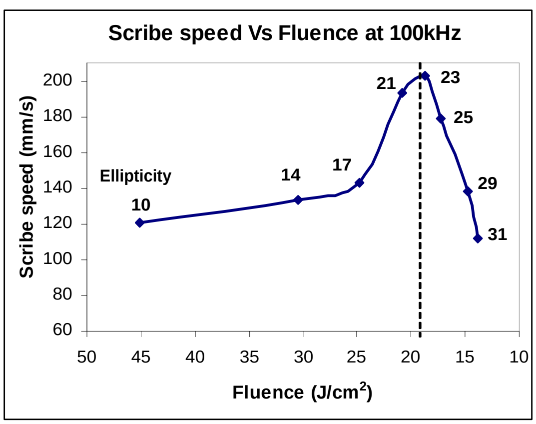

Figure 6: Plot showing maximum scribe speed achieved for a given ellipticity for scribing 30 µm deep scribe.

Figure 6 shows that scribe speed initially increases at a slower rate with the increasing ellipticity values (approaching towards optimal ellipticity OR fluence value). For an ellipticity value of around 23, scribe speed is observed to reach its maximum value; beyond this point scribe speed decreases upon further increase in the ellipticity. The drop in speed is attributed to drop in fluence value beyond the optimal value. The data indicates that the laser can achieve 30 µm scribe depth at a highest processing speed of 200 mm/s, which occurs with a beam ellipticity value of ~23. For this optimal ellipticity, the corresponding fluence is ~19 J/cm^2, which is considered to be optimal for the scribe geometry and the laser output parameters we have studied. Below this ellipticity value, fluence to cut the material is higher than optimal value and energy is not being fully used in removing the material while above this value fluence is too low and ablation rate for the material seem to drop significantly. Even at high scribing speed of 200 mm/s, the quality of the scribe appears to be quite good, with scribe width ~18 µm and very minimal melt / HAZ, as shown in Figure 7.

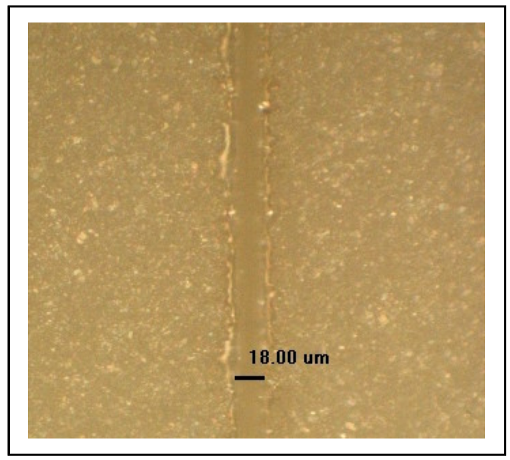

Figure 7: Top-view microscope picture of 30 µm deep laser scribe generated using elliptical beam at speed of 200 mm/s

Circular Split-Beam Processing In a second space domain energy distribution scheme to improve process efficiency we used laser beam splitting technique. The main goal of this technique is to split the high energy available from the laser into N different beamlets. In the ideal scenario, each beamlet will have the optimal fluence value for achieving best process efficiency.

Splitting of the beam is achieved by introducing a custom designed diffraction optical element (DOE) into the optical beam path immediately before the galvo scanner aperture as shown in Figure 1. Beam splitting number N is chosen depending on the energy available from the laser and optimal fluence needed to ablate the material.

We chose 1:7 beam splitting DOE for the experiments to split a laser beam into 7 equal-energy beamlets with a certain separation distance. The separation distance depends on the focal length(s) of subsequent optic(s) in the optical beam delivery system. With a 100 mm focal length f-theta lens after the DOE, we were able to generate seven 10 µm diameter beamlets with a spacing of ~90 µm on the work piece. The laser was operated at system-optimal 100 kHz PRF. With ~20 W average output power available at 100 kHz from the laser, the incident power upon the work piece was measured to be ~17 W, similar to what we achieved for elliptical beam processing set up. The 17 W power was distributed equally among seven beamlets, which provided ~ 2.4 W of power on the work piece corresponding to a fluence of ~61 J/cm^2 in each beamlet. Various scribes were generated with this set up at different scribe speeds. The data obtained was parsed to determine the scribe speed corresponding to 30 µm scribe depth. We observed that each beamlet achieved a scribe depth of 30 µm at a scribe speed of ~25 mm/s, which corresponds to the effective scribe speed of 175 mm/s (7 beams X 25mm/s).

In addition to higher effective scribing speed, the features generated with the beam splitting technique also exhibit clean quality scribes with no apparent HAZ with a scribe width of ~15 µm, as can be seen in Figure 8.

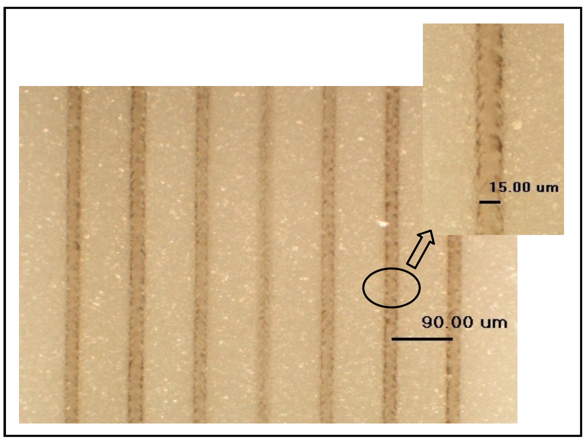

Figure 8: Top-view microscope picture of 30 µm deep scribes generated using 1:7 split beam at effective speed of 175 mm/s

Table 3 Data showing advantage of fluence management techniques to increase process efficiency for generating 30 µm deep scribe.

Fluence management technique	PRF increase (200 kHz)	Elliptical beam	1: 7 split beam
Fluence (J/cm^2)	80	19	61
Scribe speed (mm/s)	70	200	175

The data in Table 3 show the maximum scribe speed that generated a 30 µm deep scribe using different fluence management techniques. By efficiently distributing the full energy available from the laser source, high quality and high throughput is achieved for generating 30 µm deep scribes in alumina ceramic. The results clearly demonstrate the huge advantage of fluence management—either by beam-shaping or beam-splitting—for the ceramic scribing application.

Conclusions

In this paper we have succesfully demonstrated three different fluence management techniques that can be used to take full advantage of the high-energy and high-PRF offered by today's lasers. Using higher PRF, shaped-beam and split-beam processing approach, the laser energy from Pulseo 355-20 laser was tailored to achieve 30 µm deep scribes in alumina ceramic at maximum possible scribing speed while maintaining a high level of scribe quality.

When operating the laser at 100 kHz optimal PRF with ~17 W on-target laser power, the scanning speed to generate scribe depths of 30 µm are expected to be in the range of ~65-70 mm/s with a fluence of ~430 J/cm^2. However it is clear that at these higher fluence values energy is not being used very efficiently in ablating the material, and that the additional fluence is in fact degrading the quality of scribes showing increased HAZ of ~36 µm. With the laser operating at 200 kHz PRF, a slight improvement in scribe speed of around 70-75 mm/s is observed for the same 30 µm scribe depth. Remarkably, this slightly increased speed is, achieved in a much lower fluence regime of 80 J/cm^2, compared to ~430 J/cm^2 fluence required for 100 kHz PRF. Also, the resulted scribes are much cleaner with reduced HAZ with a scribe width of ~17 µm.

In addition to changing the PRF, other techniques such as beam shaping and beam splitting also showed advantage in improving the process efficiency. In contrast to simply increasing the PRF these techniques have the distinct advantage of allowing the laser to be operated at the condition of maximum output power.

Using elliptically shaped beam with ~10 µm minor axis diameter and ~17 W laser power onto the work piece at 100 kHz PRF providing only 19 J/cm^2 fluence, the highest scribe speed of 200 mm/s to generate 30 µm scribe depth has been demonstrated. This is the fastest scribe speed demonstrated using the fluence management techniques employed in this work. Scribe quality achieved is also high, with minimal HAZ apparent showing scribe width of ~18 µm.

The technique of beam splitting was also explored using a 1:7 beam splitting DOE and by operating laser with ~17 W power onto a work piece at 100 kHz PRF. Splitting a beam into 7 beamlets with equal fluence of 61 J/cm^2 in each beamlet resulted in an effective scribe speed of 175 mm/s for 30 µm deep scribes with cleaner quality and scribe width of ~15 µm.

Overall results presented here demonstrate a very significant advantage, in terms of both processing efficiency and resulting scribe quality that can be gained by optimizing the applied laser fluence. Careful application of such techniques to effectively manage the high energy and high PRF available from today's Q-switched DPSS lasers will likely benefit almost any material processing application.

Acknowledgements

The diffractive optical element (DOE) was designed and fabricated by MEMS Optical, Inc.

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Meet the Authors

Ashwini Tamhankar has over 6 years of experience in the lasers and optics industry. She is currently a senior laser applications engineer at Spectra-Physics, a division of Newport Corporation. She is responsible for design and testing of laser material processing for developing applications in microelectronics, semi-conductor, bio-medical, and the photonic industry using various ns and ps pulsed laser sources. She has gained broad experience in areas such as laser technology development, optical system design, laser beam shaping techniques and laser application development.

Rajesh (Raj) S. Patel has accumulated 23 years of experience in the laser material processing field. He is currently a Director of Strategic Marketing and Applications at Spectra Physics, a division of Newport Corporation. Prior to working at Spectra Physics he has worked in various engineering and senior management positions at IBM, Aradigm, and IMRA. He received his Ph.D. degree from the University of Illinois at Urbana-Champaign. He has worked with various lasers for developing applications in microelectronics, semi-conductor, bio-medical, medical device, photovoltaic, and photonic industry. He has authored 26 U.S. patents and published and presented more than 70 technical papers and articles related to laser processing, optics, and mask technology. He is an active member of Laser Institute of America (LIA), SPIE, and OSA and was elected to serve as a President of LIA for year 2009.