High power UV q-switched and mode-locked laser comparisons for industrial processing applications

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ABSTRACT

It has been shown that micromachining of polymer materials using mode-locked, high repetition rate, 355nm picosecond lasers is more efficient in respect to ablation rates and processing speeds, than using q-switched lasers at the same wavelength and same average power level. In this study we present a systematic comparison of application results obtained with q-switched nanosecond and mode-locked picosecond ultraviolet (UV) lasers. From the results, guidelines are derived as to which laser type to use for best results depending upon material type and thickness. Additionally, recent results obtained using a high power mode-locked UV picosecond laser – the Pantera™ - are described, along with implications of how scaled-up power can significantly enhance processing efficiency in manufacturing environments.

Keywords: laser, q-switched, mode-locked, UV, micromachining, microelectronics, polyimide

1. INTRODUCTION

High power Diode Pumped Solid State (DPSS) UV lasers have become established processing tools in OEM and industrial applications, enabling ever smaller feature sizes, higher throughput and lower costs per part. Currently, Q-switched lasers with pulse lengths in the nanosecond range are already in use for some of the most demanding applications in microelectronics manufacturing [i]. It has also been often suggested that shorter picosecond pulses may represent an advantage in machining certain materials, especially when highest precision and smallest features are required. The higher peak power and shorter pulse widths associated with picosecond lasers are known to be correlated with greatly reduced thermal damage zones, allowing processing of finer, more intricate features. In recent years, industrial versions of mode-locked, quasi-CW infrared lasers have begun making inroads in applications such as thin film metal processing, silicon drilling, ceramic and glass cutting [ii,iii]. Typically these lasers are operated at wavelengths around 1 µm.

Mode-locked, quasi-cw high repetition rate, ultraviolet (UV) lasers were first introduced in early 2000. Picosecond pulses, combined with a shorter wavelength of 355 nm and excellent mode-quality allow these lasers to be focused to a much smaller spot size, achieving higher resolution with minimal thermal impact. In 2003 industry-grade UV lasers became available with power levels high enough for materials processing applications. In particular, it is expected that at UV wavelengths, picosecond pulses could be applied at very high repetition rates (on the order of 100 MHz) to significantly increase material removal than currently possible with Q-switched UV lasers at the same average power levels. Higher processing speeds coupled with the greater precision associated with shorter pulses are highly attractive features when higher throughput rates are demanded alongside increased feature resolution.

Currently, both nanosecond and picosecond UV lasers are being adapted as high precision tools in microelectronics, flat panel display, and solar cell manufacturing industries. However, the availability of a variety of lasers in the marketplace raises questions that warrant greater analysis as to the comparative utility of shorter versus longer pulse lasers in specific applications – especially with regards to relative processing speeds and etch depths achieved in materials of different type and thickness. In recent years, the availability of commercial DPSS UV lasers with power output capabilities in the 10-20 W range for both nanosecond and picosecond regimes further highlights the need to develop guidelines as to which technology best matches specific applications.

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For example, Spectra-Physics (a division of Newport Corporation) is one company that currently offers both Q-switched and mode-locked technologies at comparable UV power levels for industrial and OEM applications. Models are available with power levels ranging from up to 20 W for a q-switched nanosecond laser (Pulseo™) and 12 W for the mode-locked picosecond Pantera™ fiber-based UV laser, introduced in 2007 [iv]. With both technologies available, customers expect laser manufacturers to provide guidance as to the type of laser best suited to the needs of a specific application. However, until recently, no guidelines have been available as to the type of laser best suited for a given application and the dependencies of material type and thickness.

Earlier experiments demonstrated that a 355 nm mode-locked laser can process materials such as polyimide and FR4 resin at significantly higher speeds than a 355 nm q-switched laser operated at comparable average power [v,vi]. By contrast, it was found that materials such as silicon and copper could be processed more efficiently with nanosecond q-switched lasers. This is usually attributed to the considerably lower pulse energy associated with the picosecond mode-locked lasers. In a recent study by Patel and Bovatsek [vii], the authors presented results that systematically compared key process parameters for the two types of lasers applied to several materials types such as dielectrics, semiconductors, and metals. Polyimide, silicon, and copper were selected as representative materials to better characterize the advantages and disadvantages of both mode-locked and q-switched 355 nm lasers as a function of material thickness. Major results of this study are summarized here, followed by additional analysis addressing key processing characteristics of aspects such as the processing speed and the edge depth. In addition, new results are also presented demonstrating higher powers with the Pantera™ laser and discussing the implications of scaled-up laser performance for further enhancement of processing capabilities.

2. Overview: Experimental Set-up, Lasers and Materials

To allow meaningful comparison between process results of different material types, it is important to conduct all experiments using lasers with identical wavelengths and average power level at the sample. The experiments presented in [vii] were conducted using a Q-switched nanosecond laser, (Hippo™**)** and a mode-locked picosecond laser (Vanguard™). Both lasers were adjusted to provide exactly the same average power levels of 2.5 W on the surface of the work piece at 355 nm wavelength. While the average power and wavelength are the same, the pulse durations and pulse repetition rate are different by three orders-of-magnitude. The Q-switched nanosecond laser (Hippo™) provides 12 ns at 80 kHz while the mode-locked picosecond laser (Vanguard™), provides 12 ps at

80 MHz. Since the pulse length and the pulse repetition rate are inversely related, both lasers provide the same peak power of 2.6 kW. Table 1 summarizes the key laser and process parameters used for the experiments. The focused beam spot sizes at the target material shown in the Table 1 were selected to ensure that each material was scribed at fluence and intensity levels that are well above the individual material's ablation threshold at either pulse duration regime.

Table 1. Summary of process parameter conditions (from ref. vii).

	Polyimide		***Silicon***		***Copper***	
	Hippo	Vanguard	Hippo	Vanguard	Hippo	Vanguard
Wavelength, nm…………	355	355	355	355	355	355
Rep. Rate, kHz………….	80	80000	80	80000	80	80000
Pulse Width, ns…………	12	0.012	12	0.012	12	0.012
Max. Power, W…………..	2.5	2.5	2.5	2.5	2.5	2.5
Max. Peak Power, kW….	2.6	2.6	2.6	2.6	2.6	2.6
Spot Size, um……………	10	10	8	8	4	4
Fluence, J/cm^2 ………….	40	0.040	62	0.062	249	0.249
Intensity, GW/cm^2 ………	3.3	3.3	5.2	5.2	20.7	20.7

A scanning beam system was utilized as part of the experimental set-up as shown in Fig. 1. It includes the laser, a beam expander, a scan head, and a sample stage. The scanner card controls the laser, in case of the q-switched nanosecond laser, or the AOM, in case of the mode-locked picosecond laser, respectively. While the q-switched laser can be triggered externally, the AOM is required for the mode-locked laser since it is free-running at a constant repetition rate.

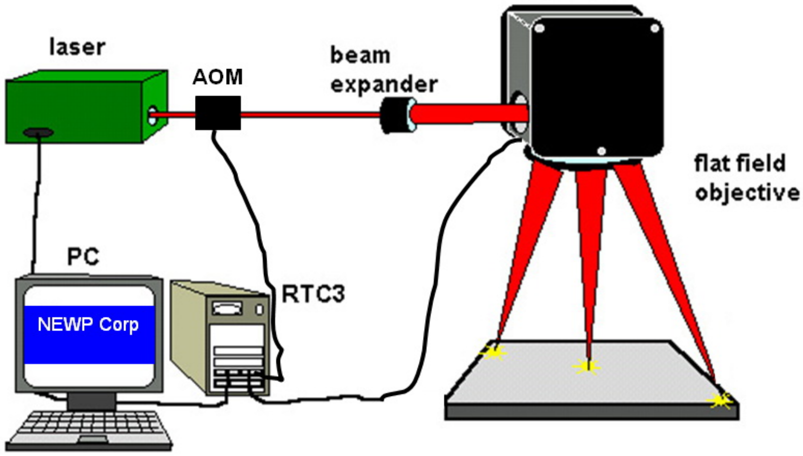

Fig. 1: Experiment Set-up of the scanning beam projection system

The study was carried out by scanning a laser beam across the work piece at select speeds while maintaining constant spot size on the target. An optimum spot size on the target was selected for each material, which was then maintained constant for each set of experiments. This experimental setup was chosen to closely reflect procedures typically employed in most industrial material processing systems. By maintaining constant peak and average power levels, the effects of different laser technologies (nanosecond vs. picosecond) for different materials were compared in a meaningful way and correlated with specific material processing metrics. These metrics included parameters of interest such as cutting speed, etch depth and cut quality.

Three representative materials - polyimide, silicon, and copper - which are commonly used in semiconductor and microelectronics industry were selected for processing. Polyimide, for example, is widely used for various chip and electronic component packaging applications in the printed circuit board industry, as well as in the medical device industry for specially designed drug packets [viii].

3. Evaluation of Test Results - Comparison between Picosecond and Nanosecond Lasers

As a general rule, when material thickness decreases, laser processing speed increases. However, with decreasing material thickness and increasing processing speed, a maximum processing speed ("speed limit") can be found which is dependent upon the pulse repetition rate rather than on the average laser power. For example, the cutting of material relies on the cumulative effect of overlapping pulses. As the scanning speed increases, the pulse overlap decreases and the laser pulses become more and more spatially separated on the work piece surface. This can be expressed by the formula:

$$\text{LFO}\ (\%) = (1 - (v / (f \times d))) \times 100\% \quad (1)$$

LFO denotes the Laser Focus Overlap (percentage), v is the cutting speed (mm/sec), f is the repetition rate or frequency of the laser (Hz), and d is the beam spot diameter (usually focus beam diameter) at the work piece (mm). For example, if the cutting speed (v) is 500 mm/s, and the beam spot diameter (d) is set to 10 µm, a q-switched nanosecond laser with a repetition rate (f) of 100 kHz results in a laser focus overlap (LFO) of 50%.

Further increase in the processing speed leads to less laser focus overlap and at a certain critical point, results in 0% LFO and then completely spatially separated imprints or ablated spots on the work piece (with negative LFO).

By contrast, mode-locked picosecond lasers have much higher repetition rates – around 100 MHz in free-running mode. With such a high repetition rate, there is sufficient pulse overlap even at very small spot sizes and extreme processing speeds. Thus repetition rate is not a limiting factor for mode-locked laser processing, however, the low energy per pulse and resulting low fluence can be limiting.

In practice, the laser focus overlap (LFO) has to exceed a certain value to achieve the required results in regards to quality, accuracy, or ablation depth. Therefore, the required LFO_{req} is determined by the application. We can then derive the maximum processing speed or "speed limit" by rearranging the equation (1) as:

$$V_{max} = (f \times d)\,(100\% - LFO_{req}) \qquad (2)$$

Then for a q-switched nanosecond laser operating at 100 kHz and focused beam diameter of 10 µm, the speed limit (maximum processing speed) achievable is 500 mm/s. By contrast, a mode locked laser with the same focused spot diameter but with the much higher repetition rate of 100 MHz could ablate the same material at maximum speeds of up to 500 m/s. In other words, under similar conditions of laser spot size and average powers, the speed limit scales linearly with the repetition rate and is therefore up to three magnitudes higher for mode-locked lasers than for q-switched lasers.

Further differences between the effects of the two laser types have been described in detail in [vii]. To illustrate other key differences between the lasers in achieved processing speed with increased material thickness, this article presents the results for the case of polyimide. Fig. 2 depicts cutting speed as a function of the polyimide thickness for both mode-locked and Q-switched lasers, operating at the same average power and using the parameters shown in Table 1.

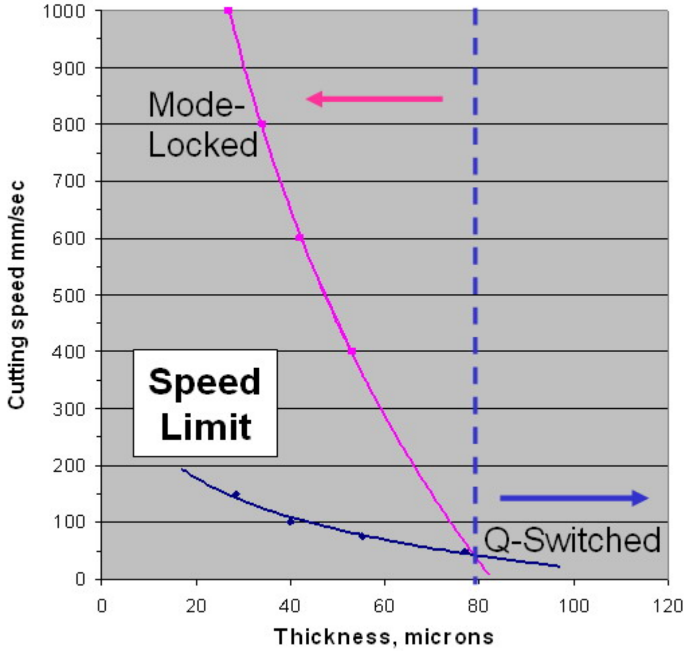

Fig. 2: Polyimide machining comparing scribe depth achieved at a given cutting speed

Fig. 2 shows cutting speed over material thickness for polyimide. As expected, cutting speed increases for both laser types with decreasing material thickness. For the given average power of 2.5 W at the work piece, a cross over point can be observed at approximately 80 µm. Below 80 µm, the mode-locked laser has increasingly higher material removal efficiency and allows scribing of polyimide film at a significantly higher cutting speed.

The same general behavior was also observed with both silicon and copper materials also (see details in [vii]), but the cross over points occur at different thicknesses due to the different material removal rates for silicon and copper as compared to polyimide. In the case of silicon, the cross-over point occurs at ~8 µm. Thus, the Q-switched laser can achieve a higher processing speed at thicknesses greater than 8µm while the mode-locked laser has the speed advantage below that point. In the case of copper, the crossover point is expected to occur at an even smaller thickness, and in fact, in the experiments described in [vii], no crossover point was observed, meaning that it had to be much lower than 1 µm, the limit of the measurement accuracy and capability of our instruments. The data thus far indicate that for materials with a very high thermal conductivity, the low energy pulses of the mode-locked laser cannot remove material as efficiently as the higher energy - and higher fluence - nanosecond laser. This is attributed to the fact that the higher energy per pulse available from a q-switched laser is required to overcome thermal dissipation effects in metals. Although, as mode-locked lasers with higher UV pulse energy outputs become available, this limitation can be overcome for some materials.

Another set of data we examined is the difference in abilities of q-switched and mode locked lasers to remove material at a given average power, focus spot size and three different processing speeds. We measured the etch depth (ED) achieved by each laser for a given processing speed from the data given in [vii]. We then calculated the ratio of the etch depth of the mode-locked picosecond laser (ED_M) over that of the q-switched nanosecond laser (ED_Q) for different materials at three different processing speeds. Table 2 shows the data collected.

Table.2: Etch depth (ED) and etch depth ratio at three processing speeds

Etch Depth (ED) in microns			
	Cutting Speed, 100 mm/sec		
	Mode-locked	Q-switched	$(ED)_M/(ED)_Q$
Polyimide	77	40	1.9
Silicon	8.8	14	0.6
Copper	3.5	20	0.18
	Cutting Speed, 200 mm/sec		
	Mode-locked	Q-switched	$(ED)_M/(ED)_Q$
Polyimide	66	23	2.9
Silicon	7.4	7.2	1.0
Copper	2.3	11.7	0.19
	Cutting Speed, 500 mm/sec		
	Mode-locked	Q-switched	$(ED)_M/(ED)_Q$
Polyimide	47.5	11.8	4.0
Silicon	6.3	3	2.1
Copper	1.3	5.5	0.23

Table 2 indicates some remarkable differences between the etch depth ratios of the three materials studied. For polyimide, the mode-locked laser provides the higher etch depth at all three processing speeds. For silicon, the q-switched laser provides the higher etch depth at speeds lower than 200 mm/sec, however the mode-locked laser provides higher etch depth at speeds higher than 200 mm/sec. Lastly, for copper the q-switched laser provides higher etch depth at all three processing speeds. These results would indicate that the mode-locked picosecond pulse laser has an advantage for etching dielectric materials such as polyimide, as well as thin layers of semiconductor materials such as silicon. By contrast, the q-switched nanosecond laser appears to have an advantage for processing metals and thicker layers of silicon materials, a consequence of the higher pulse energies available from such lasers for ablation.

An interesting trend, observed from the comparisons of Table 2 is that the etch depth ratio for the picosecond mode-locked laser improves with processing speed, independent of the material. This means that the ablation efficiency of the picosecond mode-locked laser improves with increasing processing speed. One possible explanation for this observation is that at lower processing speeds, each subsequent pulse from the mode-locked laser is shielded by the plasma and vapor of the previous pulse. As the speed increases, these shielding effects disappear and the process becomes more efficient. This leads to another recommendation: when processing thicker materials with a picosecond UV laser, it is more efficient to use high processing speeds and work over the same area multiple times.

Another processing metric to be considered is the quality of the cut. It has often been suggested that the smaller heat and shock-affected zones produced with shorter pulse lasers can potentially produce finer cuts with minimal collateral damage**.** Indeed inspection of the cut quality of materials processed showed that the picosecond laser produced cuts that were free of the rugged edges often seen with nanosecond lasers. In particular, we have observed – as many have before – that when processing with nanosecond lasers, droplets from molten material may sometimes fall back onto the work piece and re-solidifies on the surface. However, with the picosecond laser, the debris is much finer and falls back onto the surface only as a fine powder or dust. This “cold debris” does not re-attach to the surface as strongly, requiring virtually no post processing since the fine powder could be easily wiped away.

4. PICOSECOND LASER POWER SCALING AND PROCESSING RESULTS

The advent of fiber lasers and fiber amplifiers has generated considerable excitement in recent years, and much has been reported about the unique advantages of the fiber architecture, including outstanding reliability, misalignment-resistant rugged design features, and smaller footprints enabled by space efficient fiber coils. In terms of performance improvement over other solid state lasers, fiber’s favorable heat distribution properties eliminate thermal lensing, which limit power scaling with conventional rod-based laser designs. Thus, the fiber geometry allows extending the output powers to much higher levels, while maintaining stable beam parameters and excellent beam quality features. Fiber lasers have already made major inroads into the industrial market, most notably for cutting and welding with high power CW lasers. Pulsed nanosecond fiber lasers have also become ubiquitous in marking applications due to their cost, size and handling advantages. A number of picosecond fiber-based commercial products aiming for the industrial market have also been introduced. To date however, the existing products have been mostly limited to 10-20 Watts power at repetition rates of less than a few MHz in the infrared (IR) wavelength region, notably near the fundamental wavelength of Yb-doped aluminosilicate fibers around 1 μm.

The fiber architecture has also been demonstrated as an effective means of amplifying lower power pulsed lasers, even for pulses as short as a few picoseconds. Recently, researchers at Spectra-Physics have demonstrated that a fiber may be used to amplify the output of a low power, mode-locked seed oscillator to considerably higher powers with good reliability features. When properly engineered, coupling the output from a picosecond vanadate laser into an Yb-doped silica fiber amplifier has produced stable output powers as high as 50 W at 1064 nm. Frequency doubling of the output provides upwards of 30 W in the green (532 nm) and tripling converts the laser output to over 12 W stabilized power at 355 nm. At repetition rates of 80 MHz, the laser typically has 40 ps pulse duration and a TEM_{00} beam quality with an M^2 better than 1.3.

Fig. 3 Pantera™ high power UV picosecond laser system

An industrial high power fiber amplified picosecond product based on this performance - the Pantera™ - was recently introduced [iv], and early industrial processing results were presented at the CLEO 2007 conference. The laser system shown in Fig. 3 consists of two components: a laser head which includes a seed oscillator, the fiber amplifier, and the frequency conversion module and a power supply which includes the power supplies, diode drivers, and communication electronics. The package also includes a recirculating air purge, adding another layer of safety and protection to ensure a long lifetime and reliability. The laser is manufactured in a clean room and sealed following a clean room purge. To prevent contaminants leaking into the laser from the outside environment, the laser head interior is kept under a slight overpressure of recirculation clean air. The fiber amplifier is pumped by high brightness, hermetically sealed diodes with extreme long lifetime. This arrangement allows for an easy disconnect of the laser head from the power supply as there are no fiber connections.

A number of application tests were recently conducted which demonstrated the value and advantages of this new high power UV laser tool for micro-processing applications. In one such test, using the Pantera™ laser mounted in the experimental set-up as shown in Fig. 1 (including AOM) a complex pattern was cut out of polyimide with a thickness of 75 µm. A high, 95% laser focus overlap was utilized to achieve high cut quality as one shown in Fig. 4. This pattern was produced with a very high processing speed of 1m/s. Even at such a high speed, the quality of the processed edges was found to be excellent with virtually no observable heat affected zones. The sample shown in Fig. 4 was not post-processed in any manner to clean debris from the surface. This demonstrates that the highly localized energy deposition process expected at these short pulse durations persists even at these high power levels.

Fig. 4: Polyimide cutting 75um with 1m/s

At still higher speed of 10 m/s, 9 µm deep and 25 µm wide grooves could be readily scribed in polyimide films, as shown in Fig. 5. Inspection of the groove with a surface profilometer shows remarkably smooth walls and constant depth.

Fig. 5: 9 µm deep and 25 µm wide groove machined in polyimide

Results of recent preliminary tests with the Pantera™ laser on a variety of other target samples confirm the dramatic increase in processing speed expected at higher power levels. Fig. 6 shows the cutting speed as a function of material thickness in polyimide, using the same experimental set-up described earlier. With 12 W average power output available at 355 nm, the power incident upon the work piece was measured to be 10.5 W. The trend shown in Fig. 6 is consistent with expectations from the data obtained in the previous study discussed above using the lower power Vanguard™ laser and again indicates increased cutting speed the thinner the material. However, the speeds achievable are much higher in this case. For example, the data of Fig. 6 indicate that a 10 µm thick film can be cut at a very high speed - just slightly less than 10 m/s. These are much higher processing speeds than demonstrated with any previously available lasers.

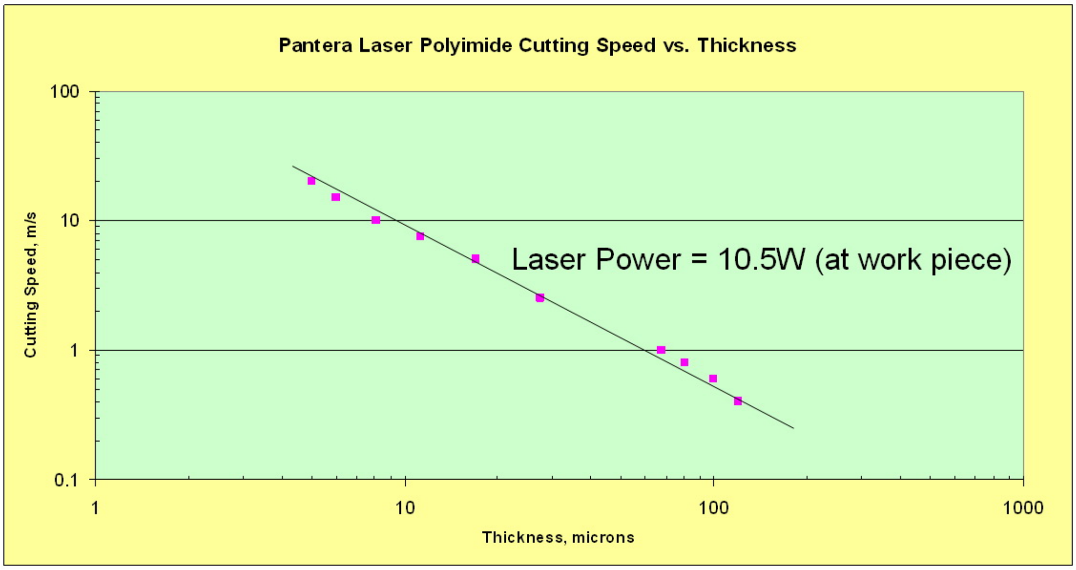

Fig. 6: Cutting speed vs. thickness in Polyimide using a Pantera™ laser

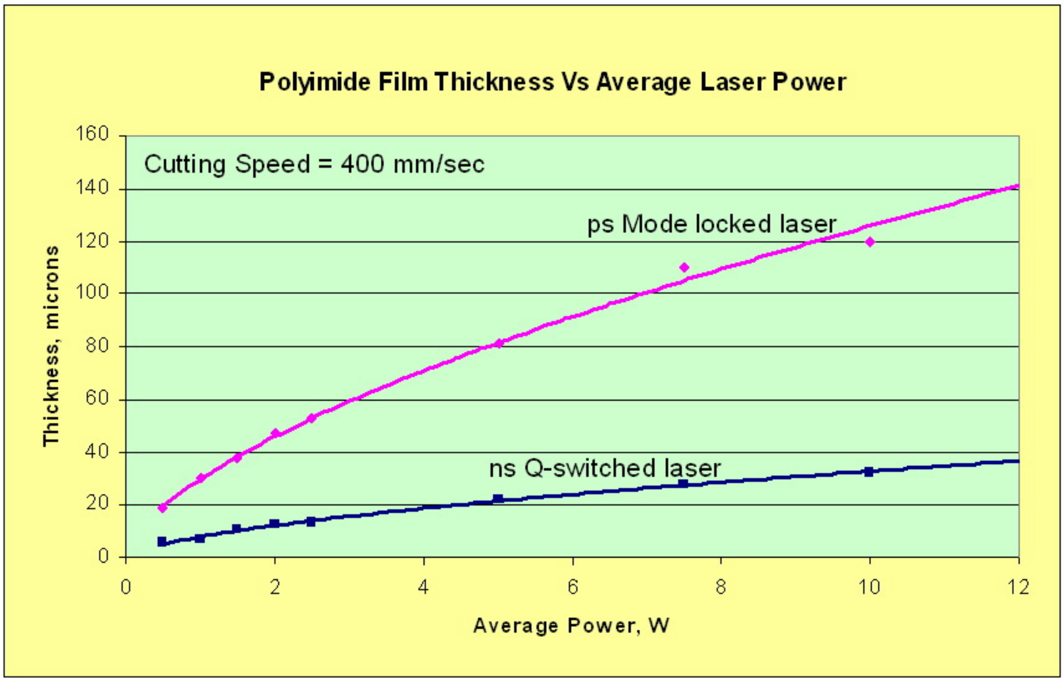

Fig. 7: Comparison of nanosecond and picosecond cutting of polyimide with laser

In another set of experiments, we compared the thickness of polyimide that can be cut at a speed of 400 mm/s using a nanosecond Pulseo^{TM} laser and the picosecond Pantera^{TM} laser. Fig. 7 shows the scribe thickness as a function of average power. These data indicate the striking advantage of the picosecond laser with its much higher repetition rate over that of a q-switched laser at all power levels. Thus, at 2 W power the picosecond laser can cut a 50 µm thick film as compared with only 10 µm for the nanosecond laser. This 40 µm advantage increases to a 90 µm spread at 10 W, clearly a major performance improvement.

The data in Fig. 7 proves that the efficiency advantage of the mode-locked picosecond laser increases with increasing average laser power. The data indicates that as average power increases, the mode-locked laser is able to cut much deeper than a q-switched nanosecond laser with the same average power. Thus, scaling up the power of a mode-locked UV laser should allow cutting through increasingly thicker material. In particular, based on the data shown in Fig. 7, we estimate that at a cutting speed of 400 mm/s, a picosecond mode-locked UV laser with an average power of 10 W is easily capable of cutting through polyimide film more than 100 µm thick, but a q-switched nanosecond laser at the same average power is only capable of cutting film about 30 µm thick at the same speed**.** Thus scaling up the UV powers should yield dividends in opening up new, hitherto unavailable, processing capabilities, with processing rates as high as tens of meters per second.

We believe that, in the not too distant future, a further increase in the average power output of mode-locked lasers is possible. In particular, the power output from a fiber amplifier configuration is scalable as higher power diodes become available. Thus, it is not inconceivable that UV picosecond lasers will become available in the next few years with powers exceeding 20 W. The higher powers would enable higher throughputs and may provide a path for greatly improving economics of industrial material processing plants.

5. CONCLUSIONS

Given the complexity and variety of existing and planned laser material processing applications, comparing ablation rates at different energy densities, peak power levels and experimental conditions, as many previous studies have done, is clearly of limited practical usefulness to an end customer. With high power UV lasers now available as nanosecond or picosecond laser, the selection of a laser technology to match specific requirements of industrial microprocessing applications clearly requires reliable guidelines backed by systematic comparative studies. We believe the analysis we have presented here provides a first step in that direction.

Not surprisingly, the choice of the laser type – for example a picosecond or nanosecond laser - is highly dependent upon the type and thickness of the material to be processed. In particular, we find that nanosecond lasers, with their higher pulse energies, continue to demonstrate an efficiency advantage when processing metals and thicker materials. On the other hand, picosecond lasers are preferable when material is thinner, higher processing speeds, and/or exceptionally high quality is required. This is especially true with the cutting, scribing, and structuring of dielectrics such as polyimide.

We find that mode-locked lasers offer better capability in terms of material removal efficiency in materials such as polyimide. Although, for a given average power level, there is a cross-over point of material thickness below which mode-locked laser show higher throughput and above which q-switched lasers show higher throughput for micromachining of polyimide film. The key advantage of the mode-locked picosecond laser is its higher repetition rate, since this is found to be the key limiting factor in achieving higher cutting speed using a q-switched nanosecond laser.

New laser developments using fiber amplifier architecture now allow raising the power of picosecond lasers up to 12W at 355nm. We believe that high power picosecond lasers such as the recently introduced Pantera™ are very well suited for micromachining at extremely high processing speeds, making them especially useful in scribing thin films and other material layers used in electronics, flat panel display and solar cell manufacturing. Preliminary experiments on dielectrics demonstrated record high speeds, exceeding 10 m/s and enabling far higher throughputs than were possible with their more common nanosecond laser counterparts. This translates into potentially dramatic reductions of part costs - a significant benefit for microelectronics manufacturing. We have also demonstrated that, even at higher power levels, the UV picosecond laser provides excellent cut quality with no visible heat affected zone and with only "cold debris" left on the surface of the work piece that can be wiped off with no residue or damage.

It is expected that the superior quality and increased processing speed made possible through power scaling, industrial mode-locked picosecond UV lasers will prove to be a versatile, cost effective tool for the microelectronics and other manufacturing industries. New higher laser performance enhancements are also likely to spur new material processing applications involving dicing, scribing, ablating, and patterning of thin films as well as contribute to improved economics and tooling innovations in industrial scale micromachining.

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