PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Studies on laser material processing with nanosecond and sub-nanosecond and picosecond and sub-picosecond pulses

Jie Zhang, Sha Tao, Brian Wang, Jay Zhao

Studies on laser material processing with nanosecond & sub-nanosecond and picosecond & sub-picosecond pulses

Jie Zhang[1,2*], Sha Tao[1,2], Brian Wang[1], and Jay Zhao[1,2]

[1]Advanced Optowave Corporation (AOC)
105 Comac Street, Ronkonkoma, NY 11779, USA

[2]ShenZhen Inno-Laser Technology Co.,Ltd.
Shenzhen, Guang Dong, China

ABSTRACT

In this paper, laser ablation of widely used metal (Al, Cu. stainless-steel), semiconductor (Si), transparent material (glass, sapphire), ceramic (Al_2O_3, AlN) and polymer (PI, PMMA) in industry were systematically studied with pulse width from nanosecond (5-100ns), picosecond (6-10ps) to sub-picosecond (0.8-0.95ps). A critical damage zone (CDZ) of up to 100um with ns laser, ≤50um with ps laser, and ≤20um with sub-ps laser, respectively was observed as a criteria of selecting the laser pulse width. The effects of laser processing parameters on speed and efficiency were also investigated. This is to explore how to provide industry users the best laser solution for device micro-fabrication with best price. Our studies of cutting and drilling with ns, ps, and sub-ps lasers indicate that it is feasible to achieve user accepted quality and speed with cost-effective and reliable laser by optimizing processing conditions.

Keywords: metal, transparent materials, semiconductor, polymer, nanosecond, sub-nanosecond, picosecond, sub-picosecond, fs laser, material processing

1. INTRODUCTION

Laser as an important & practical processing tool has been significantly changed in people's eyes and has been used almost in every area of material micro-processing and device micro-fabrication in particular consumer electronic, solar and light devices [1-3]. For material processing, the quality and throughput are the most critical factors for lasers to compete with traditional processing tools [4-5]. Thus, how to rightly choose laser source to meet the quality and throughput is a never-end investigation. From an academic point of view, laser material processing with short & ultrashort pulses, including nanosecond (ns), picosecond (ps) and sub-picosecond & femtosecond (fs) has been well-understood [6-9]. There are very clear processing solutions, such as using what type of laser for what type of materials to achieve the best quality; however, for the applications within manufacturing, it is not so simple because of their impact on throughput & cost. Quality is no longer the most important request. Instead, throughput and cost have become more critical. Good processing solutions have to meet not only quality & throughput, but also cost targets simultaneously. According to laser market value, the shorter the laser pulse width and laser wavelength, higher the laser price. Thus, as the solution provider, our principle is to provide the most suitable and affordable solution to users by choosing the right laser sources (wavelength, pulse width) based on the properties of the material to be processed, which is called Fit-User-Needs (FUN).

For this purpose, two classic processes of cutting and drilling of typical industry-needed materials of metal (Al, Cu, stainless-steel), semiconductor (Si), glass, ceramic (Al_2O_3, AlN) and polymer (PI and PMMA) have been systematically studied using different lasers including ns, ps and sub-ps (fs) pulses. The processing quality and speed are based on the industrial user's requirements. The studies include both theoretical modeling and experiments.

*jzhang@a-optowave.com; Phone: 631-750-6035; Fax: 631-803-4445

Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XXI, edited by
Beat Neuenschwander, Stephan Roth, Costas P. Grigoropoulos, Tetsuya Makimura, Proc. of SPIE
Vol. 9735, 973514 · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2220264

A two-temperature model was employed to simulate ps and fs laser ablation process to understand the underlying physical mechanism [10-11].

In addition, a 1D model was also employed to simulate ns laser ablation as comparison [12]. In the experiments, a full scope of laser ablation-based cutting and drilling of different materials with different pulse widths were carried out. Our studies show that with the optimized processing conditions, the appropriate beam delivery system and the right laser source, it is feasible to achieve the good quality and high throughput by using affordable lasers.

2. EXPERIMENTAL PROCEDURE

A successful laser processing solution has to meet four criteria simultaneously, as summarized in Figure 1.

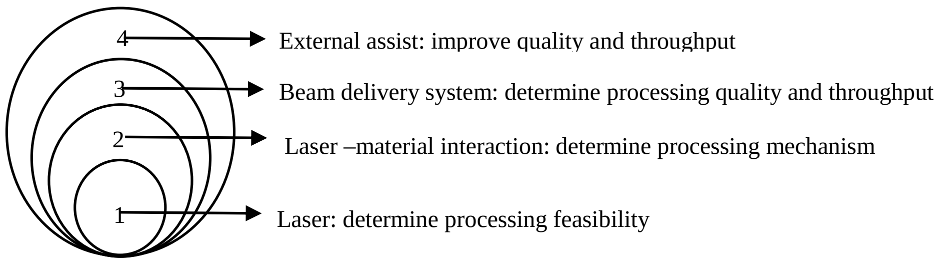


Figure 1. Summary of four criteria of a successful laser solution

Among the above four criteria, laser is the core of the whole solution, and laser-material interaction is the key factor of developing the processing methods.

Thus, in this study, the standard beam delivery system & optics and external assistance (gas-nozzle) are used to investigate the laser-material interaction effects on processing. Two basic processing, drilling and cutting on flat substrate, are conducted using two typical optics modules of the Galvo scanner/F-theta lens and the cutting-head (focusing lens embedded in co-axial gas-nozzle).

Figure 2 shows a schematic drawing of two processing modules. It has been proved that the processing quality and speed depends on what kind of focusing module applied and what kind of sample motion. Table 1 shows the main advantages of these two drilling modules from our understanding

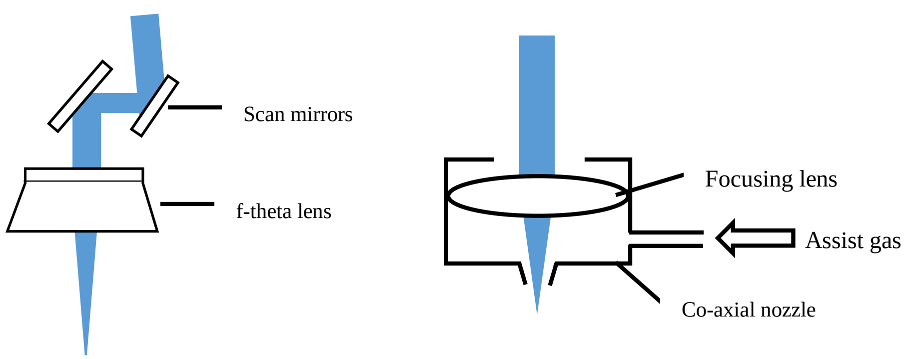


Figure 2. Schematic drawing of the two processing modules of the Galvo/F-theta lens and the co-axis nozzle/focal lens

In addition, all selected materials are qualified by customers, since slight difference of material properties may affect the processing results. Table 2 shows those customer-qualified materials used in this study. These materials are basically divided into thermal-sensitive (TS) and non-thermal sensitive (NTS).

Table 1. Brief description of Galvo/F-theta lens and On-axis nozzle/shorter focal lens

Drilling module	Process	Advantage
Galvo + F-theta lens	High speed beam motion by Galvo –mirror scanning	• Various sized hole/hole-array drilling, • High-speed scan & multiple-passes cutting, in particular for thermal sensitive materials • Thin materials (<100um)
Cutting head	Focused beam co-axis with gas stream	• <Tiny hole (<50um in dia) hole drilling • High efficient and large-area cutting • Thick materials (>100um)

Table 2. Brief description of materials in our studies

No#	Material	Type	Melting point (K)	Remarks
1	Al	6000s & 7000s series	933.5	TS
2	Cu	100s series	1358	TS
3	Stainless steel	304 & 316 series	1712	TS
4	Silicon	Single-crystal	1687	TS
5	Glass	Chemical strengthen	1670 ~ 1870	TS
6	Sapphire	Crystal	2310	NTS
7	Al_2O_3 & AlN	High-grade ceramic	Al_2O_3 : 2340 AlN: 2790	NTS
8	PI and PMMA	High-grade polymer	PI: none PMMA: 433	TS

3. RESULTS AND DISCUSSION

3.1. Modeling of pulse width dependence of laser ablation.

It is well-known that the thermal effect is the main course of the degradation of the processing quality in most material micro-processing. "Cold-processing" (minimized heat impact on surrounding zone) with the ultrashort pulse (ps and fs) becomes a symbol of high quality processing. However, for industrial applications, it is important to know the pulse width effects on material removal. For this purpose, a simulation of laser ablation of copper was carried out first.

Fig.3 shows the mechanism of ultrafast laser interaction with materials. When a ps/fs laser pulse is incident onto the target, the photon energy is first absorbed by the electrons through photon-electron interaction. As the electron temperature rises, the energetic electrons then transfer energy to the lattice through electron-phonon interaction until the thermal equilibrium between the electron and the lattice is established, and this characteristic time is called the thermalization time [10]. The whole process can be simulated by the two-temperature model [10, 11].

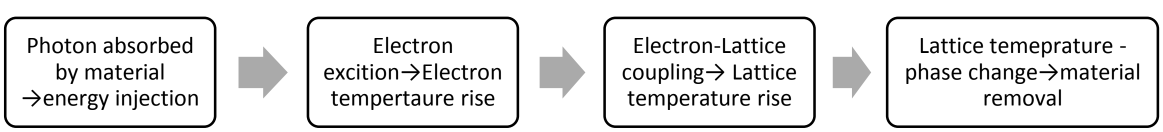


Figure 3. Description of ultrafast laser material removal process

Figure 4 shows the two-temperature model (a) and the simulated results at the pulse width of 400fs, 900fs and 6ps, respectively (b). The results indicate (i) shorter the pulse width, higher the peak-electron temperature (Te); (ii) lattice temperature (Ti) rises with decay of Te; (iii) the lattice temperature rises to the peak in a time scale of ~ ps, suggesting the material removal starts quite early (compared with ns laser below).

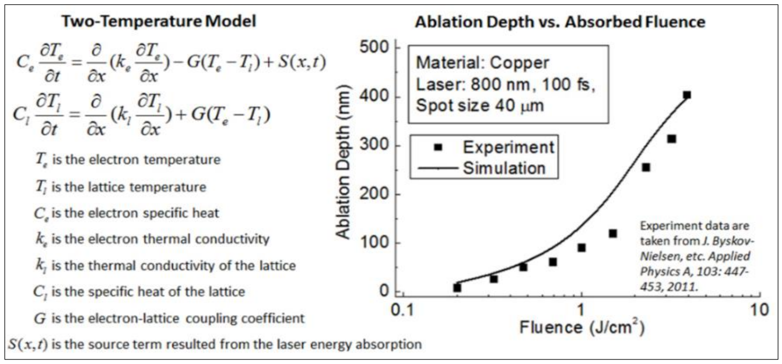


Figure 4a. Two-temperature model with fs laser ablation

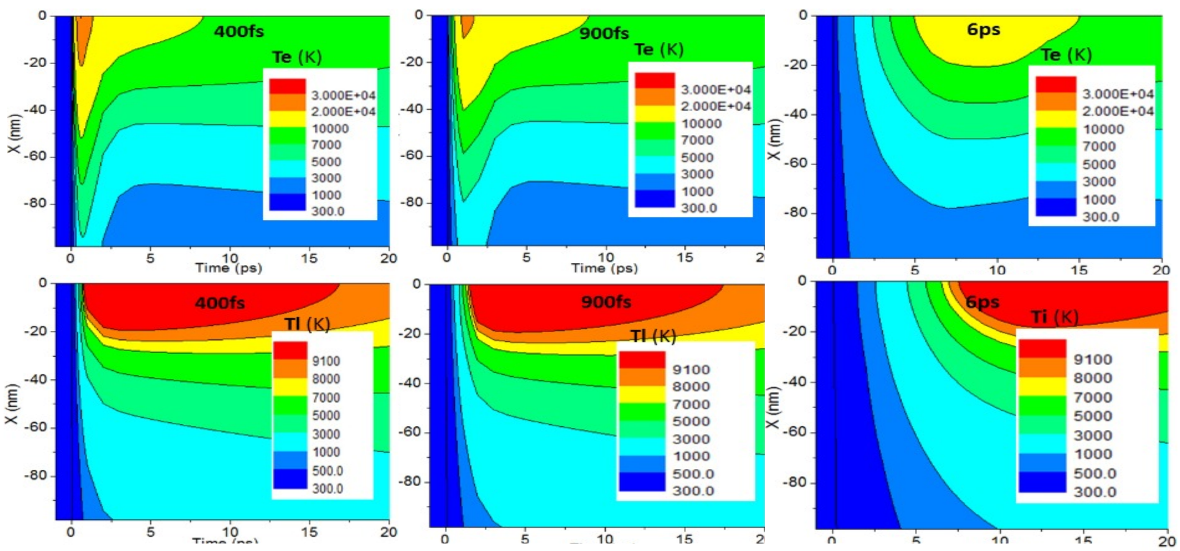


Figure 4b. Temperature evolution induced by fs and ps laser (Cu, 800nm, 0.2J/cm^2).

For ns laser material interaction, the pulse width is so long that the thermal equilibrium between the electron and the lattice has been well established and the two-temperature model is reduced to the one temperature model [12] for the simulation.

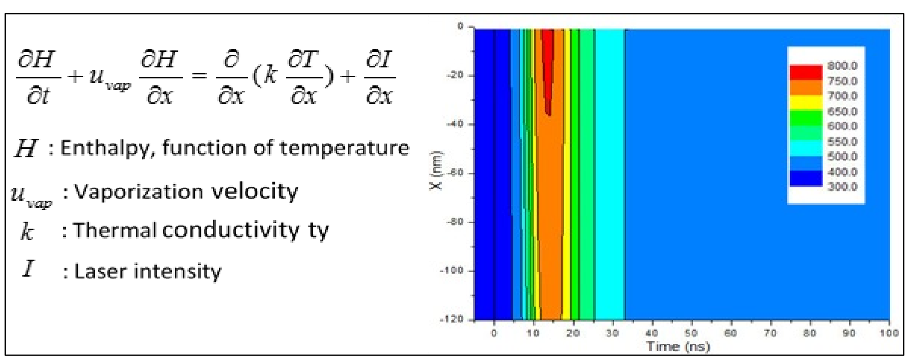


Figure 5. Temperature evolution induced by ns laser (Cu, 800nm, 0.2J/cm^2)

Figure 5 shows the model and the simulated results at the pulse width of 10ns with the same laser fluence as used in Fig. 4.

The results indicate that the material temperature rises to the peak of ~800k in tens of ns. Compared with ultrafast laser results shown in Fig.4, (i) the peak temperature is much lower (actually it is even lower than the copper melting temperature, 1358K) , suggesting much less material is removed; (ii) the material removal occurs much later, suggesting more heat will be dissipated inside the material.

The simulation results of ns, ps and fs laser ablation shows that:

- For ns lasers, the material removal requires a higher fluence and takes place in a longer period, and hence the thermal effect may be obvious; For ps & fs lasers, the material removal requires a lower fluence and takes place in a shorter period, and hence the thermal effect is limited;
- For sub ps lasers, little processing difference between 400fs and 900fs is observed (Fig. 4b), suggesting the pulse width of 900 fs is short enough for the simulated process. This is big benefits and makes laser lower cost and easier to manufacture.

3.2. Selection of laser processing conditions.

As a laser solution provider, the most important is to meet the FUN (fit user needs) principles. For this purpose, it is very important to know how to meet the processing quality and speed simultaneously. It is well-known, in laser processing, there is counterbalance of the processing quality and speed, in particular for ns lasers.

Figure 6 shows the schematic of the well-accepted model of the processing quality and speed vs fluence for ns, ps and fs lasers, respectively.

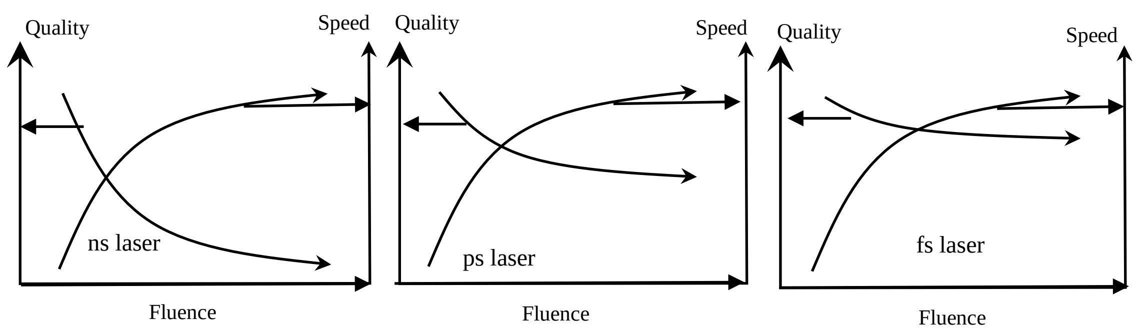


Figure 6. Quality and Speed vs fluence for ns, ps and fs laser.

Basically, higher the fluence, higher the speed and worse the quality. Thus, using ps and fs lasers can mitigate the quality degradation and achieve well-balance of the quality and speed. In reality, however, the selection of laser source is based on not only the pulse width, but also the damage tolerance, and the material thermal & mechanical properties.

Table 3 shows preferred lasers for processing those 5 typically materials used in industry of metal, semiconductor, glass, polymer and ceramics, respectively.

- Because of high material ductility high thermal conduction and high melting point, metals usually are processed by either ps & fs laser or ns laser as well, even though the thermalization time is shorter. In ns laser case, the fluence has to be low to minimize the thermal effects.
- Because of high fragility, low thermal conduction and/or low melting/soft point, semiconductor, glass and polymer are usually processed by ps & or fs lasers. , even the thermalization time is longer.
- Because of high material hardness, high thermal conduction and high melting point, ceramic is usually processed by ns laser.

Those principles have been successfully applied to our service jobs to customers. As shown below are some examples of using right laser source for right materials to achieve the cost-effective and high-efficient processing.

All processing experiments were carried out using AOC ns, ps and fs lasers, respectively. Table 4 lists lasers used for experiments.

Table 3. Preferred lasers for processing metal, semiconductor, glass, polymer and ceramics

Material	Ductility	Thermal conduction	Melting/soft-temperature	Thermalization Time [2]	Laser suitability
Metal	*High*	*High*	*High*	*1-10s ps*	*ns &ps & fs laser*
Semiconductor	*Low*	*High*	*High*	*10s – a few 10s ps*	*ps &fs laser*
Glass	*Low*	*Low*	*High*		*ps & fs laser*
Polymer	*High*	*Low*	*Low*	*10s -100s ps*	*ps&fs laser*
Ceramics	*Low*	*High*	*High*		*ns&ps*

Table 4. Applied ns, ps, and sub-ps AOC lasers in the studies

Laser model	Performance	Picture
1. ns, 532nm, 355nm	• 40W/50kHz/<30ns@532nm • 20W/30khz/<15ns@355nm	
2. ps, 1064nm, 532nm	• 10W/100kHz/<7ps@1064nm • 5W/100khz/<7ps@532nm	
3. Sub-ps (fs) 1030nm, 515nm	• 10W/100kHz/~900fs@1030nm • 5W/100khz/~900fs@515nm	

3.3. Various samples processed by fs, ps, and ns laser.

(1). Metal.

Metal processing using lasers is the most important part of laser applications due to naturally matching each other from laser-matter interaction point of view. The beauty is that this perfect matching enables engineers to predict the experimental result, which save cost and minimize mistakes. Our studies shows that both ns, ps and sub-ps (fs) can be used for metal processing and the quality depends on not only the pulse width but also the thickness and the material thermal properties.

Table 5 summarizes our studies on Al, Cu and stainless steel (SUS) processing with ns, ps and sub-ps (fs) lasers, respectively. The processing difficulty is in the order of SUS ≥ Cu > Al, which is mainly due to the product of the density and the vaporization heat: lower the product, lower the laser energy required to remove the same volume of materials.

Table 5. Summarizes of cutting Al, Cu and SUS

	Al		Cu		SUS	
Thickness	<100um	>150um	<100um	>150um	<100um	>150um
Laser	ps & fs	ns & ps & fs	ps & fs	ps & fs	ps & fs	ps & fs
Density (kg/m^3)	2700		8960		8030	
Vaporization heat (J/kg)	1.05×10^7		4.7×10^6		6.5×10^6	
Volcano/Burrs/burn/color change	<10um	<10um	<10um	<10um	<10um	<10um
Speed	<20mm/s	<10mm/s	<10mm/s	<5mm/s	<10mm/s	<5mm/s

Figure 7 shows optical microscope image of front & back surface and cross-section of cutting 0.4mm thick Al with ns-532nm (a) and sub-ps-515nm (b) laser, respectively. There is no damage zone observed on both samples. However, clear heating effect (color change) was observed on the sample cross-section cut by ns-532nm laser.

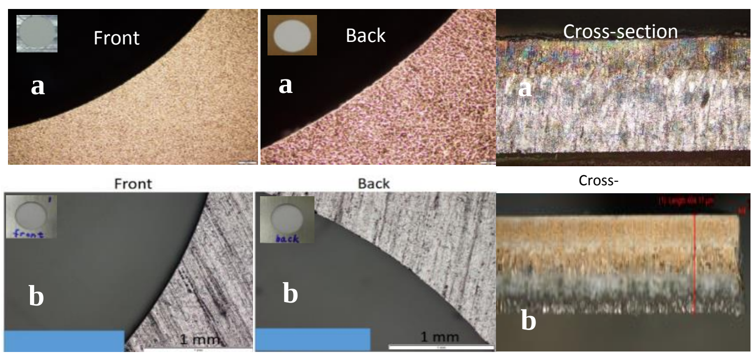


Figure 7. Optical microscope image of front & back surface and cross-section of cutting 0.4mm thick Al with 30ns-532nm (a) and 900fs-515nm (b) laser.

Figure 8 shows optical microscope image of front & back surface of cutting 0.12mm thick Cu with sub-ps-515nm laser (a) and 0.06mm thick Cu with ns-355nm (b) laser, respectively.

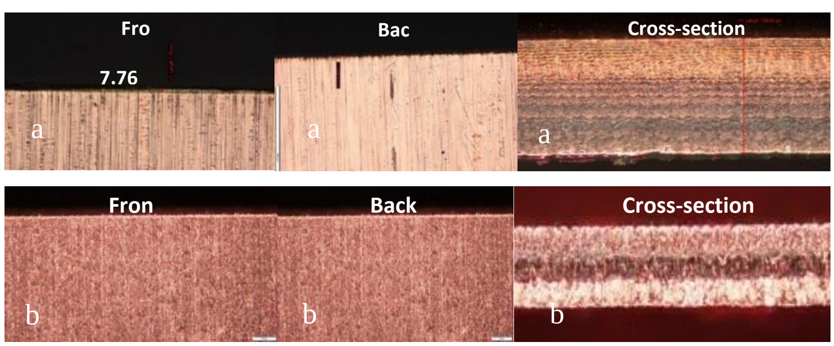


Figure 8. Optical microscope image of front & back surface of cutting 0.12mm thick Cu with 900fs-515nm laser (a) and 0.06mm thick Cu with 20ns-355nm (b) laser.

Both sub-ps-515nm and ns-355nm lasers are able to make clean cutting and no clear damage zone (burn/burrs/color change) is observed. However, melting and rough side-wall were clearly observed on cross-section with ns-355nm laser cutting, indicating the thermal effects exist.

Figure 9 shows optical microscope image of front & back surface of cutting 0.4mm thick SUS with sub-ps-515nm laser (a) and 0.12mm thick SUS with ns-355nm (b) laser, respectively.

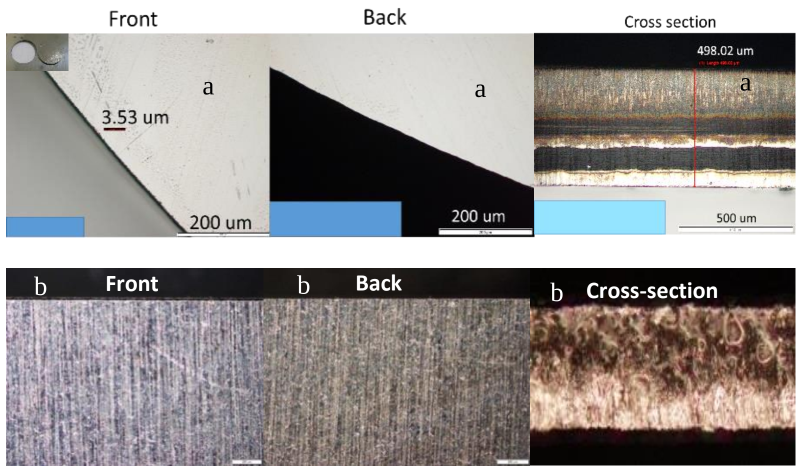


Figure 9. Optical microscope image of front & back surface and cross-section of cutting 0.4mm thick SUS with 900fs-515nm (a) and 20ns-355nm (b) laser.

Although clean achieved with both fs-532nm and ns-355nm laser. More severe melting and rough side-wall were observed on cross-section with ns-355nm laser cutting, indicating more pronounced thermal effects in SUS.

(2). Semiconductor.

For Si-based device processing, the quality is very critical. Due to the relatively high absorption of Si at visible and near-IR wavelength, Si can be processed by either fully laser cutting-through, which is usually applied to the thin wafer (<100um) or laser scribing followed by breaking, which is usually applied to the thick wafer (>150um).

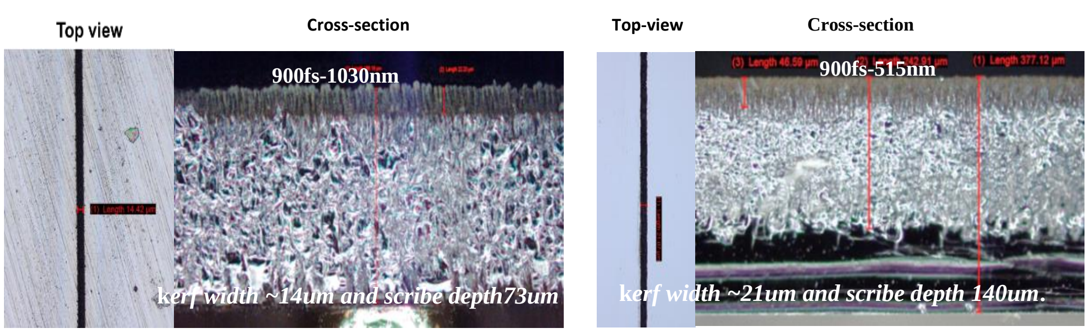


Figure 10. Optical microscope images top-view and cross-section of scribed Si with sub-ps-1030nm laser.

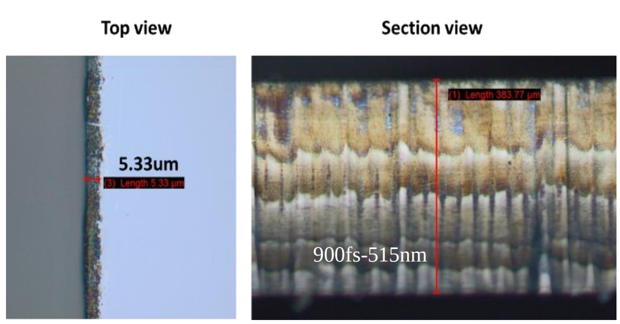


Figure 11. Optical microscope images top-view and cross-section of full cut Si with 900fs-515nm laser

Figure 10 shows optical microscope image of top-view and cross-section of scribed Si with sub-ps-515nm and 1030nm, respectively. Clean cut was achieved with both sub-ps-515nm and 1030nm laser, respectively. The scribed side-wall appears a grinding surface.

Some Si devices need very high quality cutting, and no defect allowed. In this case, fully cutting through needed. Figure 11 shows the top-view and cross-section image of cut Si by layer-by-layer ablation with 900fs-515nm laser. The side-wall quality is significantly improved. The disadvantage is the lower cutting speed (<10mm/s)

(3). Glass processing.

For application in the touch-panel display, glass needs to be chemically strengthened, which is called CS-glass (DOL~20-40um). Usually, glass can be processed by laser either before the CS-process or after the CS process. For both cases, ps & fs lasers are always considered first due to material low ductility and very low linear absorption to 515-532nm and 1030-1064nm lasers. Table 6 summarizes two methods of laser processing glass, and feasibility of the device fabrication (outline and via-hole).

Table 6. Summary of two methods of laser processing glass for feasibility test of fabrication (outline and via-hole)

Method	Cutting-through by ablation		Scribing followed by breaking	
Glass	Non-CS	CS	Non-CS	CS
Laser	ps or fs		ps or fs	
CDZ(Chipping)	<50um		<10um	
Effective speed	<30mm/s		>100mm/s	
Device-1: large curvature outline cutting & via-hole drilling	Yes	No	No	No
Device-2 small curvature outline cutting	Yes	Yes	Yes	Yes

So far, laser cutting small curvature outline in both CS and non-CS glass is very successful. The biggest challenge is the large curve line cutting and hole-drilling in CS glass. Figure 12 shows the optical microscope images of straight (a) and small curvature (b) outline-cutting in CS glass by sub-ps laser with scribing method. Clean cut was achieved and no chipping or cracking was observed on the edge. The effective cutting speed is >100mm/s.

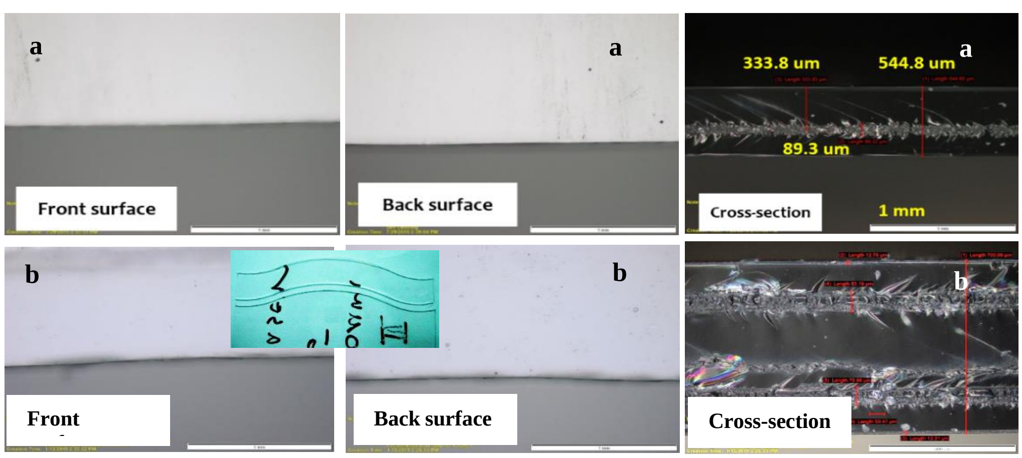


Figure 12. Optical microscope images of (a) straight, and (b) small curvature outline-cutting in CS glass by 900fs-1030nm laser with scribing method.

Figure 13 shows the optical microscope images of large-curvature cutting (Disk with 5mm in dia.) in 0.7mm thick non-CS glass and micro-hole drilling (30um in dia.) in 0.03mm thick non-CS glass, respectively by ps-532nm laser ablation. For 5mm in dia. disk cutting, the cut piece falls off automatically from base with a clean cut and ~40um chipping. The effective cutting speed is ~1-10mm/s. For micro-hole drilling, clean edge with little chipping was achieved. The drilling speed is ~2hole/s.

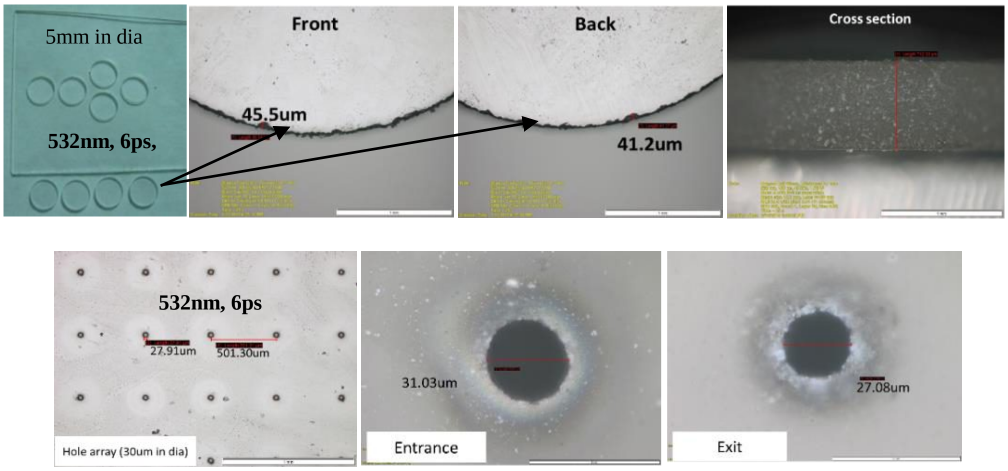


Figure 13. Optical microscope images of large-curvature cutting (Disk with 5mm in dia) in 0.7mm thick non-CS glass and micro-hole drilling (30um in dia.) in 0.03mm thick non-CS glass,

(4). Polymer.

For polymer-based device processing, due to material flexibility, cutting through is the only way. Also due to low melting/soft-temperature, ps or fs laser shows unique advantages for the high -end device processing.

Figure14 shows optical images of (a) top surface of sub-ps-1030nm laser cut polyimide (PI) foil, and (b) top-view & cross-section of ps-532nm laser cut Cu/PI devices. The cutting edge appears almost free of damage.

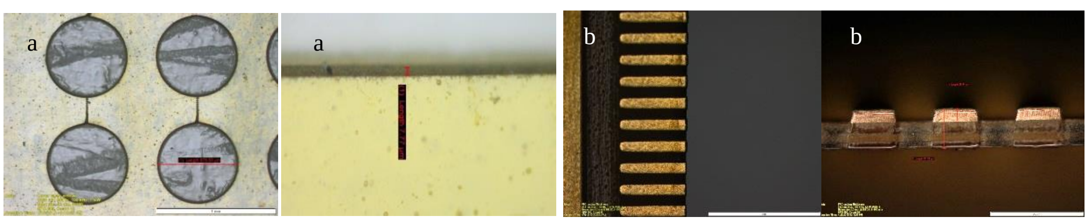


Figure14. Optical images of (a) top surface of sub-ps-1030nm laser cut polyimide (PI) foil, and (b) top-view & cross-section of ps-532nm laser cut Cu/PI devices.

Figure15 shows optical images of the cross-section of the engraved PMMA with sub-ps-515nm (a) and ps-355nm, respectively. This shows that better quality achieved with sub-ps-515nm laser that that with ps-355nm laser.

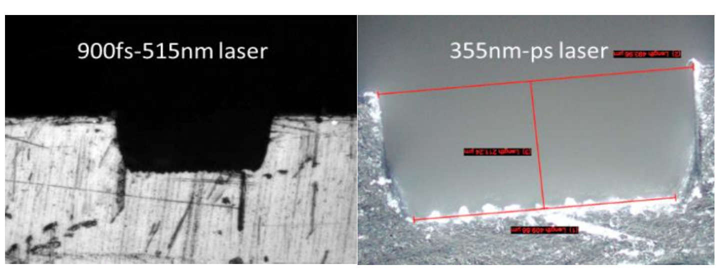
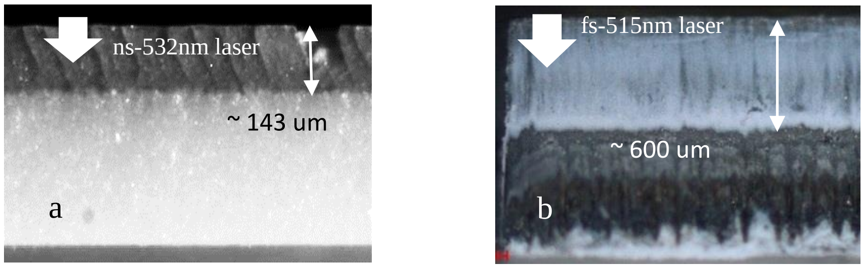


Figure15. Optical images of cross-section of engraved PMMA with fs-515nm (a) and ps-355nm (b).

(5). Ceramic processing.

As for ceramic processing, ns laser is always considered first. Figure 16 shows optical microscope image of the cross-section of Alumina (Al_2O_3) cut by ns-532nm (a) and fs-515nm laser (b) respectively. The cutting edge and cross-section by fs laser is smoother and cleaner than that by ns laser. But, there is no significant cracking, dross and burrs observed on the cutting edge and cross-section by ns laser. The processing speed with ns laser can easily reach >100 mm/s.



Wavelength: 532nm; Pulse width: ~230ns

Wavelength: 515nm; Pulse width: ~900fs

Figure 16. Optical microscope images of cross-section of cut Al2O3 with 230ns-532nm (a) and 900fs-515nm laser (b),.

Via-hole drilling in Al_2O_3 and AlN ceramics with ns 532nm laser was tested. Figure 17 shows optical microscope images of hole's entrance and exit, indicating ns-532nm laser suitable for processing. The processing speed reaches 100 holes/s.

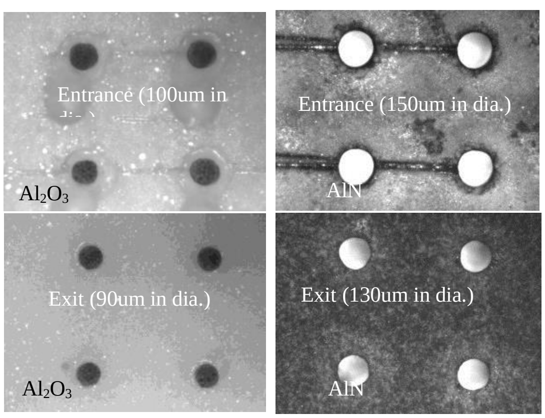


Figure 17. Optical microscope images of drilled via-holes in Al_2O_3 and AlN, by 230ns-532nm laser

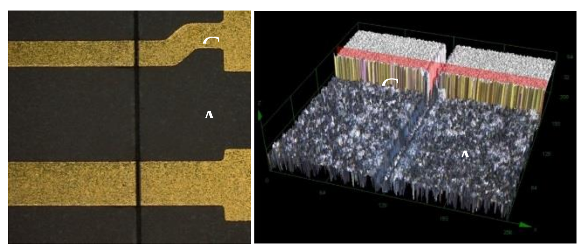


Figure 18. Optical microscope images of cut Cu/AlN devices with 900fs-515nm laser

However, it was observed that on the Al_2O_3 melt formed around holes (entrance) if the air-blow is not strong enough. This melt can be mechanically scraped away. This Al_2O_3 melt will not form in fs laser processing due to high material ionization and vaporization. Thus, for processing ceramic based electronic device, ps or fs laser is required to avoid damaging to devices. Figure 18 shows the 2D/3D image of sub-ps laser cutting a Cu/AlN chip. Clean cut without damage to Cu was achieved.

4. CONCLUSION

Cutting and drilling of metal (Al, Cu and SUS), semiconductor (Si), polymer (PI and PMMA) and ceramic were systematically investigated by ns, ps and sub-ps laser respectively. In order to provide affordable laser solution, it is required to choose right laser (pulse width and wavelength) using right processing methods based on (i) material properties/thickness, (ii) quality & speed requirements and (iii) device type. Thus, it is a multiple-factors process. In general for ductile materials, ns laser is 1st option. However, when material is very thin (<100um) or have device on it, ps orsub-ps (fs) laser needs to be considered. For brittle material, ps & sub-ps (fs) laser is always considered first.

ACKNOWLEDGMENTS

We would like to thank AOC and INNO-Laser engineering teams for their great support. Part of this work is sponsored by Guangdong “Peacock” Plan.

REFERENCES

[1] Lee, J., Jang, J. and Yoo, T., “Scribing blue LED wafer using laser induced plasma-assisted ablation with a q-switched Nd:YAG laser,” Proc. SPIE 3933, 237-244, (2000).
[2] Gower, M. C., “Industrial applications of laser micromachining,” Opt. Express, 7(2): 56-67, (2000).
[3] Colville, F., “Ultrafast laser-based tools enhance solar cell efficiencies”, Proc. SPIE 7589, 758913, (2010).
[4] Kurita, T., Komatsuzaki, K. and Hattori, M., “Advanced material processing with nano- and femto-second pulsed laser,” Int. J. of Mach. Tools Manu., 48, 220-227, (2008).
[5] Jiang, L., Liu, P., Yan, X., Leng, N., Xu, C., Xiao, H. and Lu, Y., “High-throughput rear-surface drilling of microchannels in glass based on electron dynamics control using femtosecond pulse trains,” Opt. Lett., 37(14), 2781-2783, (2012).
[6] Cheng, J., Liu, C., Shang, S., Liu, D., Perrie, W., Dearden, G. and Watkins, K., “A review of ultrafast laser materials micromachining,” Opt. & Laser Technol., 46, 88-102, (2013).
[7] Uteza, O., Bussiere, B., Canova, F., Chambaret, J. P., Delaporte, P., Itina, T. and Sentis, M., “Laser-induced damage threshold of sapphire in nanosecond, picosecond and femtosecond regimes,” Appl. Surf. Sci., 254, 799-803, (2007).
[8] Kononenko, T. V., Garnov, S. V., Klimentov, S. M., Konov, V. I., Loubnin, E. N., Dausinger, F., Raiber, A. and Taut, C., “Laser ablation of metals and ceramics in picosecond – nanosecond pulse width in the presence of different ambient atmospheres, ” Appl. Surf. Sci., 109/110, 48-51, (1997).
[9] Semerok, A., Chaleard, C., Detalle, V., Lacour, J. L., Mauchien, P., Meynadier, P., Nouvellon, C., Salle, B., Palianov, P., Perdrix, M. and Petite, G., “Experimental investigations of laser ablation efficiency of pure metals with femto, pico and nanosecond pulses,” Appl. Surf. Sci., 138-139, 311-314, (1999).
[10] Jiang, L. and Tsai, H., “Improved two-temperature model and its application in ultrashort laser heating of metal films,” J. of Heat Trans., 127, 1167-1173, (2005).
[11] Byskov-Nielsen, J., Savolainen, J., Christensen, M. S. and Balling, P., “Ultra-short pulse laser ablation of copper, silver and tungsten: experimental data and two-temperature model simulations,” Appl. Phys. A, 103, 447-453, (2011).
[12] Tao, S., Wu, B., Zhou, Y. and Gao, Y., “Themal modeling and experimental study of infrared nanosecond laser ablation of silicon,” J. of Appl. Phys., 106, 123507, (2009).