OPTIMAL PARAMETERS FOR ArF LASER MICROMACHING OF SiC AND PZT

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ABSTRACT

The ablation process has been characterized for a number of laser sources in silicon (Si) micromachining. However, very few results can be found in the literature for excimer laser technology at 193 nm on Si and even fewer for other materials. Moreover, most of the work has previously been reported for quasi-static conditions, not taking into account the movement of the sample relative to the laser beam. In order to globally consider the relative velocity of the sample with respect to the laser beam, a metric called N_{ppd} (number of laser pulses deposited per beam diameter) is first defined in this work. Experimental results are presented to evaluate the micromachining performance of the excimer laser for three different materials (Si, PZT and Pyrex). Optimal parameters are obtained and then used to micromachine silicon carbide (SiC), in addition to the previous materials.

INTRODUCTION

Laser micromachining is currently being used to complement photolithography techniques in the prototyping of a number of MEMS devices [1]. In particular, the 193 nm ArF excimer laser allows to micromachine materials by ablation with minimal thermal effect thanks to a short pulse width (<20 ns). The photon energy at 193 nm (6.4 eV) is in fact higher than that at higher wavelengths (5 eV with a KrF laser at 248 nm). This allows to more easily destroy the intermolecular bonds within the material. However, the power delivered by the ArF laser tends to be slightly less than that of 248 nm lasers so that the overall micromachining efficiency is reduced. Details in the order of a few microns can be fabricated using laser micromachining. New generations of MEMS integrating a number of thick layers (>5 μm) made of different materials such as glass, silicon (Si), silicon carbide (SiC) and piezoceramics (PZT) could benefit from laser micromachining techniques. These materials do not find widespread applications due to limitations in fabrication processes. Moreover, laser micromachining offers the flexibility to fabricate 3D structures [2, 3, 4].

Very few quantitative results can be found in the literature on the interaction of the different parameters involved in excimer laser micromachining for workpiece dragging. Most of the references concentrate on static processes (e.g. hole drilling, mask patterning). Li [4] has however shown that experiment design methods can be used to optimize the parameters for Si. It appears that since considerable effort is devoted for the calibration of the parameters, very limited data is available on this. Glass (Pyrex, fused silica) and polymers are the most common materials micromachined using lasers [2, 6, 7, 8, 9, 10]. Ink jet printer nozzles are an example of devices manufactured by excimer laser micromachining.

It is the purpose of this work to present an experimental parametric study of ArF excimer laser micromachining of Si, PZT, Pyrex and SiC at 193 nm, taking into account the displacement of the sample. The results will help define optimal parameters for the micromachining of SiC, Pyrex and PZT which are becoming common components of MEMS.

THEORY

A. Laser-matter interaction

Two phenomena are involved in the ablation process using a laser beam: i) direct photochemical bond breaking by the absorption of photons and ii) melting of the material by thermal conduction in the material structure (photothermal process). Part of the beam energy is reflected at the surface of the sample. Following the ionisation of the material surface (photochemical process), a plasma creates an increase of the local pressure which helps vaporize solid or melted debris (Figure 1).

Figure 1. Laser-matter interaction of a pulsed laser beam.

The debris are then deposited in various shapes around the work zone. The material usability is dependent upon their optical and mechanical properties such as reflectivity, thermal conduction, optical absorption, melting temperature,... However, laser ablation allows to micromachine any material, as opposed to standard photolithographic microfabrication techniques, even if Si and metallic materials are poor candidates. For Si, wet etching techniques or plasma techniques (DRIE) are to be preferred.

B. Parameters for pulsed laser ablation process

There are many important geometrical relations between machining parameters when using laser ablation with the workpiece dragging technique. The main following parameters are to be considered:

- linear machining velocity [V] ($\mu\text{m/s}$);
- laser repetition rate [f] (Hz);
- beam size : diameter [D] (μm);
- energy distribution over the beam area : Gaussian or uniform following homogenization;
- fluence [F] (J/cm^2);
- number of passages [N];
- beam focalization angle (3°).

From these parameters, relations can be extracted to predict the resulting micromachined geometries. (Figure 2).

From Figure 2, for a laser beam with a diameter of 15 μm pulsed at a rate of 3 Hz and travelling at 15 $\mu\text{m/s}$ with respect to the sample, the depth of the micromachined trench can be predicted. Assuming an ablation rate of 5 $\mu\text{m/pulse}$, a trench of 15 μm depth is micromachined with an angle of 45° .

Figure 2. Geometrical parameters for material ablation using pulsed focalized excimer laser.

In order to globally consider the relative velocity of the sample with respect to the laser beam, it is thus possible to define a metric called *Nppd* (number of laser pulses deposited per beam diameter):

$$Nppd = N * f * D / V \quad [shots] \quad (1)$$

By encompassing *N*, *f*, *D* and *V*, the *Nppd* parameter provides a global parameter taking into account the coupling between these parameters. The *etch rate* (μm/shot) can be determined from the *Nppd* given that one is able to measure the final depth of cut after *N* passages for constant process parameters:

$$Etch \ rate = h / Nppd \quad [\mu m / shot] \quad (2)$$

Finally, the shape of the beam area and its energy distribution will also influence the cutting profile. For example, with a circular beam and workpiece dragging technique, the pulse overlap will be more important in the center of the trajectory. The cutting profile would then be a semi-elliptic shape. The beam focalization angle also affects slightly the cutting profile since the fluence decreases as beam area increases.

EXPERIMENTAL SETUP

A. Laser micromachining system

The four-axis (XYZR) laser micromachining system is shown in Figure 3. The system uses an X-imer 300 ArF excimer laser (MPB Communications Inc.) which generates pulses with 5 ns width. The maximum energy is around 6.5 mJ and the highest repetition rate is 300 Hz.

Figure 3. Four-axis laser micromachining system.

The 4 mm x 4 mm Gaussian beam is conditioned with a circular mask of 3 mm diameter. The beam is then collimated and focused with appropriate lenses. A variable attenuator is used to modulate beam energy. The diverging portion of the beam is used

to ablate the material. By positioning adequately the sample with the Z axis, the machining tool diameter can be adjusted. Typical tool diameters can vary between 10 μm and 150 μm and the fluence used never exceed 100 J/cm².

B. Experimental procedure

In order to evaluate optimum parameters for laser ablation of some selected materials (Si, Pyrex, PZT and SiC), a series of seven experiments were realized, as shown in Table I.

Test	Parameter	Materials
1	Fluence, <i>F</i> (J/cm ²)	Si, Pyrex, PZT and SiC
2	Repetition rate, <i>f</i> (Hz)	Si, Pyrex, PZT
3	Velocity, <i>V</i> (μm/s)	Si, Pyrex, PZT
4	Number of passages, <i>N</i>	Si, Pyrex, PZT
5	Beam diameter, <i>D</i> (μm)	PZT
6	Focal spot displacement	Pyrex
7	Trajectory overlap for milling demonstration	Pyrex

Table I. List of conducted tests.

For each test and material, 16 cuts were made in order to limit the number of experimental measurements. Imaging of each laser cut is obtained using an optical microscope at 20x. Measurements for each cut are shown in Figure 4 and were estimated (±3 μm) from the image using National Instruments Vision Builder.

Figure 4. Typical measurements extracted from sample image.

Criteria for laser micromachining process optimization are:

- *ablation time* : a metric called *t* was define as the time to cut a 100 μm line with a depth of 50 μm at a particular speed (*V*) in reference with the measured ablation depth (*h*) :

$$t = 100 \mu m * 50 \mu m / (V * h) \quad [s] \quad (3)$$

- *acceptable edge quality and minimum recast materials*;
- *minimum taper angle A*;
- *high value of etch rate (μm/shot)*.

Each test is intended to help identify optimal values for each parameter to incrementally calibrate the process (from one test to another, cascading approach). Second order interaction between parameters was neglected. The parameters for Test 1 were fixed to known working values: *F*= 1-80 J/cm², *f*=50 Hz, *V*=25 μm/s, *N*=2, *D*=35 μm. Laser fluence threshold ranges from 0.5 J/cm² (for Pyrex) to 1 J/cm² (for SiC) according to preliminary observations. Pressurized air is used to clean the ablation zone.

RESULTS

Test 1 through Test 4 revealed that a proper choice of parameters can lead to better laser micromachining results (Figure 5). From these curves and visual observation of the cut profile, the optimal range identified for the process parameters are given below:

- **Fluence (*F*)** : *etch rate* rapidly increases for fluence range of 1 to 40 J/cm². It was observed (Figure 5a) that to avoid

thermal damage for Pyrex, fluence must be limited to 10 J/cm².

- **Repetition rate (f)** : f can be fixed to more than 100 Hz for Pyrex and PZT without *etch rate* reduction. The frequency is limited to 100 Hz by the laser performance which drops rapidly for higher values (Figure 5b).
- **Velocity of sample (V)** : velocity can be set higher than 150 μ m/s since *etch rate* reach a constant value from $V=50$ μ m/s as seen in Figure 5c.
- **Number of passages (N)** : up to 32 passages without significative reduction in *etch rate* for Pyrex and PZT (Figure 5d).

Figure 5. Ablation rate per laser pulse for Si, PZT and Pyrex, as a function of the fluence (a), the repetition rate (b), the velocity of the sample (c) and the number of passages (d).

Test 1 was conducted a second time with optimal parameters on all previous materials, in addition to a-SiC. As shown in Figure 6a, *etch rate* has not changed significantly after optimization even if sample velocity and repetition rate are increased. Even if *etch rate* values for SiC seem to be the lowest, the laser cut profile for amorphous SiC is clean and has a flat bottom (Figure 6c).

For an optimized process, thin layers of material are ablated at each passage. Typical ablation rate varying from 5 μ m to 10 μ m per passage can be achieved with fluence around 10 J/cm² and optimal parameters ($f=100$ Hz, $V=170$ μ m/s). Ablation time t is typically reduced by two for all materials after calibration (see Figure 6b for Pyrex) and less recast is observed in the ablation area. It is important to note that the diameter and wall angle measurements are slightly different for each material tested. Si cut wall are also less uniform than other materials tested and recast material can be clearly see under microscope or SEM images.

Other important results arise from the complementary tests:

- **Test 5, beam diameter:** the laser beam diameter can be easily adjusted via focal point displacements. The *etch rate* is velocity and diameter dependent by the *Nppd* metric defined previously. The *etch rate* decreases with an increase in the beam diameter but not linearly as expected. Further work would be required to understand why this is not observed for PZT (Figure 6d).
- **Test 6, focal spot displacement:** by moving the focal spot in order to follow depth penetration during ablation, no *etch rate* variation is observed for a single cut with multiple passages.
- **Test 7, trajectory overlap:** in order to verify if laser milling leads to good geometrical results, Test 7 consisted in two laser

cuts side by side with a varying overlap (0-80%). Results showed that with minimal overlap (<5%) and a circular laser beam, it is possible to ablate a cut profile with flat bottom on Pyrex. To ensure good interface between cuts, focal spot displacement was used. This result was extrapolated to laser milling of a rectangular cavity in Pyrex (Figure 7).

Figure 6. Results from optimization: ablation rate per pulse (a), ablation time for Pyrex for non-optimized and optimized processes (b), cut in a-SiC (c), ablation rate per pulse as a function of beam diameter for PZT (d).

Figure 7. Laser milling on Pyrex realized with optimal parameters and circular beam overlap strategy ($F=6$ J/cm², $f=100$ Hz, $V=170$ μ m/s, $N=40 \times 8$ for rectangular cavity, machining time: 3 hours).

DISCUSSION

The experimental optimization process shows that optimal parameters selection is independent of material properties, except for the laser energy level (fluence) needed to ablate adequately each material (see Figure 5). Recasts were observed for Si which seems to be ablated by melting and ejection of matter. This leads to poor machining results compare to Pyrex, PZT and even SiC. However, optimal machining parameters results in cleaner ablation wall for Si because less material is processed at each passage, at higher velocity and repetition rate with moderate fluence.

Less than half of initial machining time is now necessary to ablate all materials after the optimization of the process. Si cuts are generally wider at surface and wall taper is more important. This indicates that optical or mechanical properties influence the energy absorption and thermal dissipation during laser ablation process.

The mechanical and optical properties of tested materials are shown in Table II.

Properties	Materials				
	Si	SiC	Al	PZT	Pyrex
ρ (kg/m ³)	2300	3200	2700	7650	2230
S_y (MPa)	2000	2100	276	80 (static)	-
E (GPa)	160	448	70	64	62.75
k (W/m.K at 300 K)	156	490	236	~1.1	1
C_p (J/kg.K)	771	750	890	350	726
$\kappa=k/\rho \cdot C_p$ (cm ² /s)	0.88	2.04	0.98	0.0041	0.0062
$L_e=2(\kappa t)^{1/2}$ (μ m, $t=5$ ns)	3.25	4.95	3.43	0.22	0.27
CTE (10 ⁻⁶ /°C)	2.62	4.2	25	4-6	3.5
T_{melting} (°C)	1410	3100	660	1250	820
n_R (193 nm)	3.46	4.05	0.11	-	1.543
n_i (193 nm)	2.75	1.42	2.17	-	0.077
R	50%	41.1%	~85%	-	4.6%
α^{-1} (10 ³ cm ⁻¹)	1769	1000	3000	125	48.4
L_o or α^{-1} (μ m)	0.0057	0.01	0.0033	0.08 [11]	0.21
$Ke=L_o/L_e$	0.002	0.002	0.001	0.364	0.765
Behavior (193 nm)	Metallic $Ke<0.01$			Strong absorption $0.01<Ke<10$	

Table II: Physical properties of materials for laser micromachining at 193 nm [11, 12, 13].

A metric named Ke is defined as the ratio of the optical penetration length (L_o) and the thermal penetration length (L_e) [11] and gives an evaluation of the ablation behaviour of material for a given wavelength and pulse width. The Ke values in Table II indicate that Si, SiC and Al exhibit metallic behaviour at 193 nm ($Ke<0.01$). Si and Al ablation mechanism is mainly a photothermal process which means that they melt and dissipate laser energy by thermal conduction. This explains why Si gives poor geometric results. On the other hand, Pyrex and PZT have strong absorption at 193 nm ($0.01<Ke<10$) and ablation tends to be more a photochemical process. Their low thermal conductivity and high absorption combined to low melting point explain this behaviour. Absorbing energy and keeping it into the exposition zone helps elevating the local temperature to melt or vaporize material. Even if SiC requires high fluence compared to Pyrex and PZT, it appears to be a good candidate for laser micromachining at 193 nm. While Si melts under the energy corresponding to 193 nm, SiC directly vaporizes when it reaches the melting point (2400-3100 °C). This leads to a slow but clean ablation.

More uniform beam energy could lead to better results for Si since the high peak energy of the Gaussian beam results in non-uniform machining depth. This aspect does not appear to be a problem for other materials that show strong absorption at 193 nm and poor thermal conductivity which leads to local machining and better depth control over the beam area.

As depicted in experimental results, typical cut widths ranging from 10 μ m to 100 μ m can be achieved with all materials. This is limited by optical system and laser energy. Wall angles could be at best estimated to 5° and it seems possible to get deeper than 250 μ m (see Figure 4) with Pyrex, PZT and SiC. This allows high aspect ratio structures to be realized. The precision for cut width appears to be less than 5 μ m. Depth precision could be as low as 0.25 μ m for SiC or PZT with low fluence. The machining precision could be improved further with better and faster measurement tools.

The excimer laser machining system seems to be a good alternative for rapid machining of MEMS materials for which precision in the order of 1-5 μ m is acceptable. Laser machining is faster than wet etching and DRIE for SiC and allows Pyrex, PZT and polymers machining. Among MEMS applications which can benefit from laser micromachining, bioMEMS on glass and polymers, PZT sensors and SiC high temperature sensors are good candidates. Even 3D surfaces are to be expected from laser

micromachining in the next years with mask dragging techniques using excimer, high power DPSS and Copper vapor lasers [2, 3, 6].

CONCLUSIONS

The optimal parameters for excimer laser micromachining of Si, Pyrex, PZT and SiC were identified from experimental data. Optimal parameters show that high repetition rate combined with high velocity workpiece dragging technique and laser fluence less than 20 J/cm² allow clean laser ablation at 193 nm. Thin layer ablation of material is more efficient. Pyrex, PZT and SiC appear to be good candidates for excimer laser micromachining at 193 nm as opposed to Si for which material redeposition and melting make ablation difficult.

Various 3D geometries can now be ablated in order to complete conventional microfabrication techniques for MEMS prototyping. Further investigation of parameters interaction by the use the design of experiment method may be necessary to get better machining results.

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