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# Micromachining of Silicon using Excimer laser for MEMS applications

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**Abstract**

In this work an attempt is made to study the use of excimer laser ($\lambda$=248nm) on fabrication of micro fluidic devices on silicon wafers. A parametric study for silicon ablation depth is carried for various fluence (2.5-6.5 J/cm$^2$), number of pulses (200-600) and frequency (10-40 Hz). It has been observed that laser fluence is the most dominant factor for controlling the depth of machining followed by number of pulses whereas frequency change has very low significance. On choosing the best parameters (fluence of 5.9 J/cm$^2$ and 500 pulses) fabrication of micro mixtures are carried out under two different environments (air and water). It has been observed that while machining under water, heat affected zone is reduced drastically i.e. by 97%.

## 1. INTRODUCTION

Lab-on-a-chip have attracted considerable attentions in the past decade. They are not only capable of performing multiple procedures e.g. single handling, pretreatment, separation and mixing but also offer several advantage, such as having smaller reagent volumes, higher selectivity and yield, shorter reaction times, fewer byproducts, possibility of parallel operations and automation. One of the most difficult tasks these microfluidic devices face is rapid mixing of two or more fluid species [1-4].

In Micromixture, passive mixers are those where mixing completely relies on diffusion and chaotic advection, whereas external perturbation is introduced in active micro mixers to enhance mixing. Further, below millimeter length scale, flow is not only laminar but viscosity dominated, which makes the design for this devices very challenging. There has been great effort for developing numerous micromixture devices based on various mechanisms for improving performance [1] As fabrication of these micromixture has been carried on silicon which is a material suitable for MEMS application, is used as workpiece for the current study.

Silicon is a natural semi-metal element which is extremely versatile in its application which includes electronics equipment, microfluidics, optical devices, alloys, biomedical applications [5] etc. Silicon has revolutionized the concept of miniaturization of mechanical devices [6]. Its properties like high melting temperature, high temperature stability, age resistant and minimal mechanical hysteresis makes it first choice as a base material for miniaturized industry. However, its brittle nature makes it difficult to machine by conventional processes [7]. In literature, researchers have used various methods for machining of silicon like ductile regime machining using single point diamond cutting tool [8-9], photolithography and wet chemical etching [10-13], microlithography and reactive ion etching [14] and mechanical techniques [15] . All these techniques have their own limitation like ductile regime machining is a very complicated process whereas etching techniques have limitation dependence upon crystallographic orientation, non-uniform material removal, requirement of hazardous chemical etchant and long processing time. Mechanical machining has the disadvantage of non-uniform material removal and also produce micro cracks on the surface.

Laser has been widely used in micromachining processes due to their ability to deliver high energy associate with the photon to the material in a very confined space. They are used in various machining process like drilling, marking, grooving, scribing and cutting. Energy that is associated with the photons is high enough that there is no limit to range of possible materials like metals, ceramics, composite, biological tissues and polymer that can be processed with lasers. When laser light interacts with the material the energy contained by them is transferred to the substrate surface. If the energy is high enough to break the bonds this leads to photo ablation at the substrate surface otherwise it elevates its temperature by means of diffusional transport which eventually vaporize the material[16] i.e. by thermal ablation. It should be noted that incident energy and the time scale of laser interaction dictate the behavior of laser matter interaction.

Excimer laser ($\lambda$=248 nm, E ~ 5 eV) high pressure gas UV laser which removes material by combination of thermal ablation and photo ablation [16-17]. Though for metals, the main mechanism for ablation seems to be thermal whereas very rare photochemical bond-breaking occurs. At higher fluence thermal ablation becomes more dominant and also leads to greater thermal degradation [18-19]. Few researchers have demonstrated the use of Excimer laser for machining on Silicon [20-22].

Another important aspect associated with Laser micromachining is the heat affected zone (HAZ). This thermal damage (HAZ) is an unavoidable outcome but it can be reduced to a large extent by machining the sample under water. Choo et al.[14] in their study concluded that the thermal degradation on substrate (through HAZ) while machining under water is very less as compared while machining under air.
In this paper, initially parametric study of silicon micromachining under air is presented, then by using these experimental and above mention results (for machining under water), fabrication of micro mixer on silicon is demonstrated. Machining of silicon for above mentioned application is done under air as well as water.

## 2. Experimental Setup

The KrF Excimer laser (Cohernt Variolas Complex Pro 205F) used in these experiments has the following specifications: wavelength: 248 nm, maximum pulse energy: 750 mJ, pulse width 20ns and maximum frequency: 50Hz. Energy of the pulses can be varied either by changing discharge energy or by manually adjusting the attenuator. Setup for laser machining using mask projection is shown in Fig. 1. For homogenous illumination at the mask plane, a pair of 8 X 8 fixed array of insect eye lenses are utilized to create a square field of 20 mm X 20 mm with a homogenous top hat beam profile at the mask plane. The beam transmitted across the mask is imaged on the workspace using an imaging lens with a typical demagnification of 10X. Energy meter (Coherent Field Max II) is used to



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measure the intensity of the laser pulse at the mask plane. Machined surface was initially characterized by using a microscope (Olympus BX51) and optical profilometer (Bruker ContourGT-K).

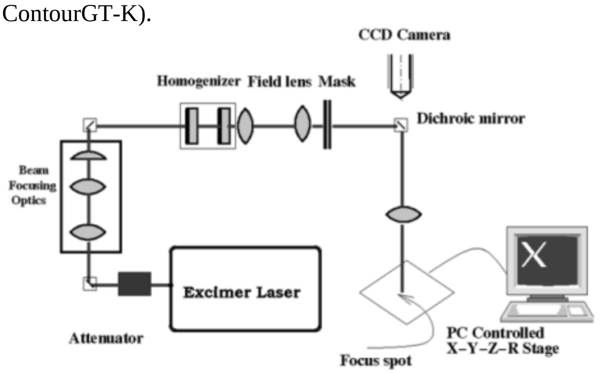


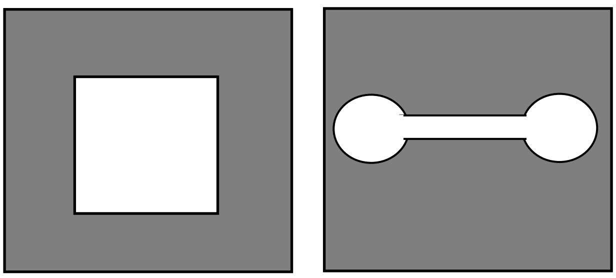

Fig. 1 Schematic of Excimer laser

### 3. Experimental Procedure

### 3.1 Mask Preparation

Square mask of 50 mm is prepared on kapton® (Polymide, manufactured by Dupont) of thickness 12 µm using Excimer laser. Schematic of the initial mask used for parametric study is shown in Fig. 2(a). After preparation mask is coated with Aluminum using PVD. This Al coated mask is used for parametric study on Silicon. Before machining, silicon is cleaned ultrasonically in ethanol and deionized water which removes dirt and contamination from the surface.

Fig. 2(b) shows the schematic of the mask used for the fabrication of Micro mixer. Masks were prepared on kapton® (Polymide, manufactured by Dupont) by trepanning with Excimer laser. Masks were trepanned to get better edge quality as any edge roughness on the mask will lead to deterioration of the edges of the final feature.



(a) (b)

Fig. 2 Schematic of mask used in this experiment (a) parametric study (b) fabrication of micromixture

### 3.2 Parametric Study:

The experiments are designed using response surface methodology[24]. Three machining parameters are considered as input parameters during machining, namely the fluence, frequeny and number of pulses. Using the central composite design [24], 16 sets of experiments are carried out using the values of α = 1.682 for a rotable design. The machined features are analyzed for machining depth.

Table1. shows the different parameters (fluence, number of pulses and frequency) at different levels used for this study along with the ablation depth obtained for respective set of parameters. Best possible parameters are used for fabrication of micro mixture of required dimensions.

Table1. Depth obtained for different levels of parameters

| S.No. | Fluence ($J/cm^2$) | Frequency (Hz) | Number of Pulses | Depth (um) |
|---|---|---|---|---|
| 1 | 3.15 | 20 | 300 | 1 |
| 2 | 5.93 | 20 | 300 | 11.2 |
| 3 | 3.15 | 40 | 400 | 1.52 |
| 4 | 5.93 | 40 | 300 | 11.2 |
| 5 | 3.15 | 20 | 500 | 1.9 |
| 6 | 5.93 | 20 | 400 | 17 |
| 7 | 3.15 | 40 | 500 | 1.75 |
| 8 | 5.93 | 40 | 500 | 21 |
| 9 | 2.51 | 30 | 400 | 0.5 |
| 10 | 6.55 | 30 | 400 | 26 |
| 11 | 4.61 | 10 | 400 | 2.5 |
| 12 | 4.61 | 50 | 400 | 2.6 |
| 13 | 4.61 | 30 | 200 | 1.75 |
| 14 | 5.93 | 30 | 300 | 11.15 |
| 15 | 4.61 | 30 | 400 | 2.5 |
| 16 | 4.61 | 30 | 600 | 3.2 |

### 4. Results and discussion:

### 4.1 Mathematical Model for Machining Depth

The quadratic models were proposed for the response variable i.e. machining depth, was evaluated by the F-test of ANOVA. Low p value (less than .0001) and high F value are obtained for the fitted model. This suggests high dependence of the measured output on design parameters. The equation fitted to model the machining depth is given below. The equation are presented in terms of actual factors , where *A*, *B*, and *C* denotes the input parameter *fluence*, *number of pulses* and *frequency* respectively

Depth =72.885.49- 25.49088*A- 0.12816*B-0.28450*C+

0.01304*AB+0.03165*AC+0.03165*BC (1)

Model P value = < 0.0001;$R^2 = 0.9849$;

adjusted $R^2 = 0.9712$

Out of all the design parameters fluence and number of pulses is the most significant factor with p value less than 0.0001. However p value for frequency is 0.4239 which shows it does not have any significant effect on machining depth. The response surfaces are plotted using commercial software: Design Expert® 10. Fig. 3(a,b,c) shows the inetration effect of fluence and number of pulses, fluence and frequency, number of pulses and frequency recpectively

### 4.2 Effect of Fluence

Fig. 3 (a,b) shows 3D interaction plot for the variation of depth with fluence and number of pulses as well as fluence and frequency respectively . As it can be clearly seen in both the graphs two distinct regimes is cleared observed from the experiments. At lower fluence < 4.5 $J/cm^2$ the hot electrons density is low and so energy transfer occurs only within the area characterized by skin depth while at higher fluences the contribution of carrier conduction becomes dominant and we see heat affected region. The heat affected region is defined by electrons driven heat penetration [23]

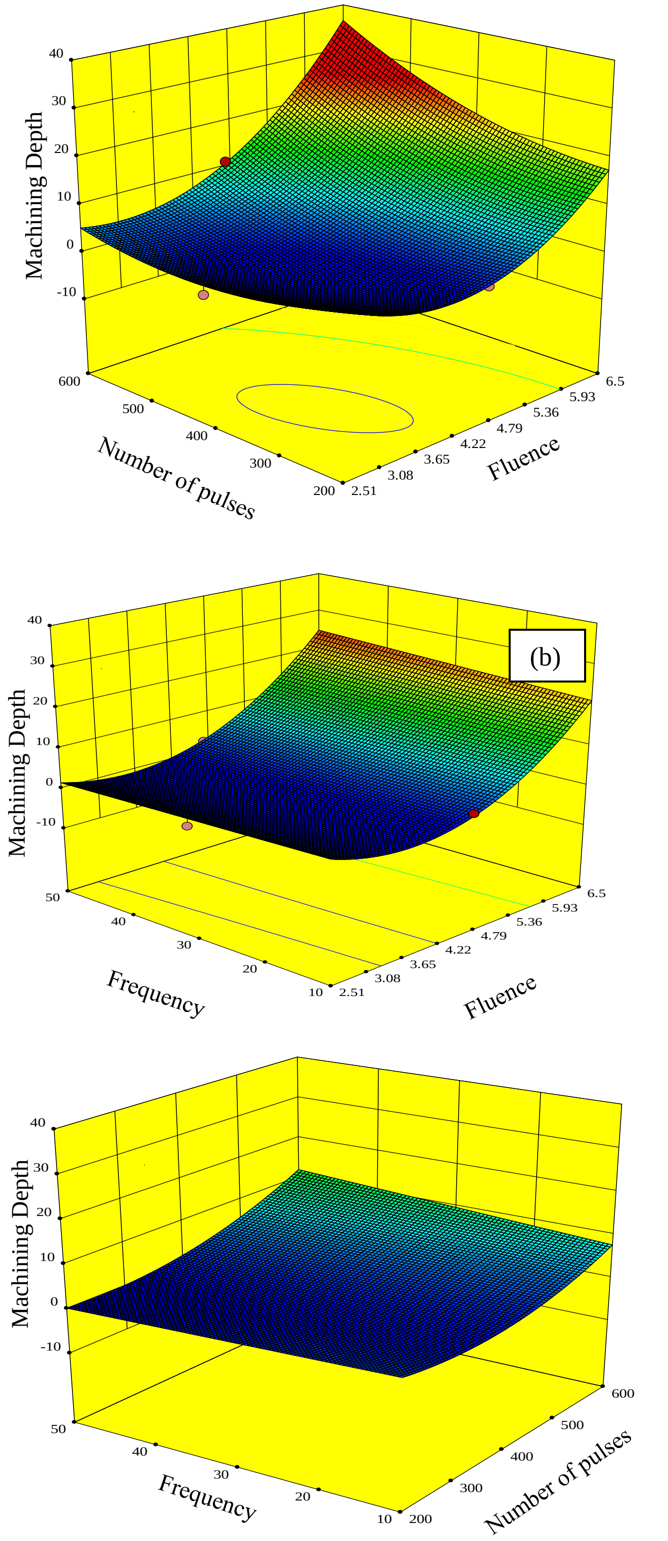



Fig. 3 3D surface plot showing interaction effect of (a.) fluence and number of pulses (b) fluence and frequency (c) number of pulses and frequency on machining depth

### 4.3 Effect of Number of Pulses

Experiments had been carried out at different number of pulses for various fluences as shown in Table 1. But due to the aforementioned reason a considerable increase in depth can only be seen above 4.61 J/cm$^2$. As it can be seen from Fig.3(a,c) a linear trend can be observed for machining depth with increase in number of pulses which is due to the increase in total energy delivered to the substrate increase with increase in number of pulses which further increases the electron driven heat penetration depth because of higher hot electron density.

### 4.4 Effect of Frequency

As it can be observed from Fig. 3 (b,c) the frequency range we had used for this experiment shows very low significant on machining depth. This can be explained as the range of frequency used is very low which might not be enough to study the effect of frequency.

### 4.5 Fabrication of Micromixtures

Aforementioned results are used for fabrication of micromixtures. A mask as shown in Fig. 2(b) is used for fabrication of micromixtures. The dimension of mask is ten times the actual required dimensions which are; length of channel: 1500 µm, width of channel: 50 µm , diameter of circle: 250 µm, machining depth: 20 µm. Further fabrication of micromixture is carried out under air as well as water for comparison of HAZ. Water used in this experiment is stationary with overall height of water above substrate is 2mm. Table 2 show the HAZ absorbed under air and water for different fluences and number of pulses. It has been observed that while machining under water, heat affected zone (HAZ) is reduced drastically i.e. more than 97%. Fig. 4 shows the optical microscope images of fabricated micromixtures (a) under air (b) under water

Table 2. Comparison of HAZ under air and water

| S.No. | Fluence (J/cm$^2$) | Number of pulses | HAZ in air (µm) | HAZ water (µm) |
|---|---|---|---|---|
| 1 | 3.15 | 300 | 103.4 | 2.5 |
| 2 | 3.15 | 400 | 111.6 | 2.61 |
| 3 | 3.15 | 500 | 117.11 | 2.78 |
| 4 | 4.61 | 300 | 121.41 | 3.7 |
| 5 | 4.61 | 400 | 122.27 | 3.69 |
| 6 | 4.61 | 500 | 159.55 | 3.87 |
| 7 | 5.93 | 300 | 178 | 3.9 |
| 8 | 5.93 | 400 | 200.62 | 4.64 |
| 9 | 5.93 | 500 | 212.5 | 5.53 |

Final parameters are chosen on the basis of required machining depth for fabrication.The final machining is done in water at 5 J/cm$^2$ fluence, 500 numbers of pulses and 30 Hz frequency so as to achieve the required depth. Fig.5 shows the optical profilometer image of fabricated micromixture.

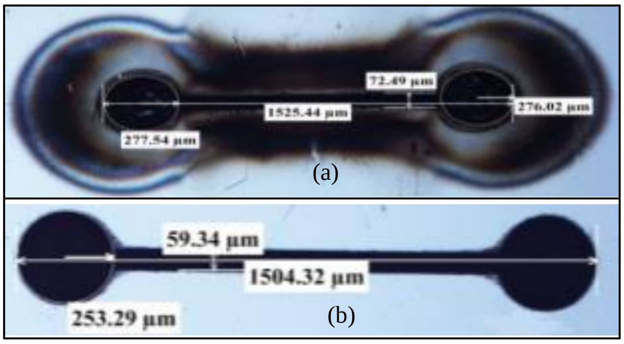



Fig. 4 Optical microscope images of silicon machining (a) in air (b) in water respectively

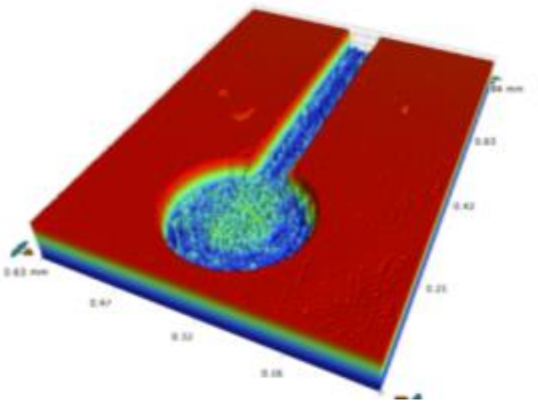


Fig.5 Optical profilometer images of micromixture

## 5. Conclusion

In this work, use of excimer laser ($\lambda$=248 nm) for machining of silicon wafer has been demonstrated. Firstly a parametric study is conducted by varying the fluence, number of pulses and frequency and it has been concluded that fluence is the most dominant factors among the aforementioned factors. Further using the results from this study micromixture is fabricated successfully on silicon wafer in water for minimizing HAZ. Though our study did not characterize the change in the mechanical properties of silicon wafer. Further crack formation in silicon wafer while machining can also be studied for better results

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