Effect of repetition rate and peak fluence on ablation depth with ultrashort pulse laser irradiation in silicon

Shalini Singh, S. Niketh, G. L. Samuel*

Indian Institute of Technology Madras, Chennai, India

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ABSTRACT

KEYWORDS

Ultrashort Pulse Laser,
Micromachining,
Silicon,
Repetition Rate,
Peak Fluence.

The demand for high-depth micro features in silicon are highly desired for micro-electromechanical systems (MEMS) applications. Silicon, which is brittle, has low toughness characteristics and possesses high reflectivity, makes it highly challenging to fabricate high-depth micro features. In the present work, we explore the ablation mechanism for low (0.28 J/cm^2) and high peak (6.36 J/cm^2) fluence at various repetition rates (100-500 kHz) to create high-depth microchannels in silicon. The maximum depth of 6.64 and 107.73 µm are obtained at low and high peak fluence and repetition rate of 500 kHz. The higher deposition of fine particles is observed at a high peak fluence of 6.36 J/cm^2. Higher peak fluence can be more effective in creating high-depth microchannels with the deposition of fine particles at the edge of the microchannels. Present work will be highly beneficial where high-depth micro features in silicon are desired, which is highly challenging to fabricate.

1. Introduction

Miniaturization is now in demand ("Small is beautiful") as is employed extensively in the electronics, optical, automotive, aerospace, and biomedical fields. Since they are smaller and more sensitive than macro-components, micro-components often use less material and electricity.

With the advent of ultraprecision machining, the manufacturing industry is currently seeing a paradigm shift in the machining process. Regardless of the substrate material, it is now possible to produce micro/nanoscale features with any complex geometry. Micro/nanoscale structuring is a sort of ultra-precision machining in which the materials' surfaces are modified by the addition of minute features to provide a certain attribute (Zhang et al, 2019). Depending on the spectrum of applications, these characteristics shape may change.

1.1. Micro/nano micromachining challenges

Silicon is difficult to machine due to its high brittleness, low fracture toughness, and high reflectivity. Several researches have been conducted to address these issues and alternate machining techniques for providing the requisite structures. Micro-grinding, single-point diamond cutting, micro-turning, and micro-milling are among the most popular non-conventional techniques for creating small features in silicon surfaces. The main short comings of these methods are the formation of burr, material distortion, and restricted depth, which have an impact on the product's quality and lifespan in real-world use. In order to create micro/nanoscale features, this results in the use of an advanced processing technique as "ultrashort pulse laser (USPL) machining". USPL machining produces minimal and highly localized laser energy deposition on the workpiece, delivering a less thermal load and debris deposition (Cheng & Chen, 2017). Among the USPL parameters, the most important factor affecting heat accumulation and ablation depth is repetition rate.

1.2. Laser material interaction

The primary determinants for feature depth are pulse energy, duration, and average power (Chien & Gupta, 2005). When choosing the ideal parameters to produce higher-quality micro features, understanding the fundamentals of thermal ablation when ultrashort pulses interact with silicon material is essential. Numerous theoretical explanations for the mechanism of

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*Corresponding author E-mail: samuelgl@iitm.ac.in

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ultrafast melting when ultrashort laser pulses interact with silicon have been presented by numerous researchers. Avalanche ionization was observed as the primary means of removing material when interaction with silicon in the femtosecond regime by Pronko et al, (1998). Further research into the ultrafast melting in the femtosecond range was conducted by Rethfeld et al, (2004). In addition, they supported the generation of ultrafast thermal melting with experimental evidence obtained by polarization microscopy. Time-resolved optical microscopy was used to conduct research on the space-time dynamics of the thermal melting at the femtosecond regime by Ionin et al. (2013). Various studies have been conducted to develop high-depth microchannels that can be achieve with high fluence and repetition rates.

1.3. Heat accumulation

With an increase in pulse repetition rate for higher depth formation, the material removal rate can be increased. The specific removal rate saturates to its maximum when the pulse length shortens. The repetition rate controls the average power at fixed pulse energy. Typically, ultrashort pulse laser produces pulses with a maximum pulse energy of µJ at a repetition rate of kHz. A single high energy beam can be split into several parallel beams using the phenomenon of multiple beam processing, and the beam diameter can be altered in the split beams at a lower energy for each pulse to achieve the highest removal rate. As the pulse repetition rate increases the interval between succeeding pulses decreases, and the time for the heat diffusion from the previous laser pulse decreases.

Increased fluence, the number of pulses, or geometric pulse-to-pulse overlap all affect the ablation threshold and incubation coefficient in response to the observed rise in heat accumulation (Mustafa et al, 2020; Benocci et al, 2019). The production of various micro-features in the crater rim formation around the crater, and the heat-affected zone (HAZ) and all instances of how heat accumulation invariably influences the morphology of the irradiated area (Di Niso et al, 2014; Bashir et al, 2021; Hu et al, 2022).

In the current work, the effect of peak fluences of 0.28 and 6.36 J/cm^2 are investigated to create microchannels in silicon at repetition rates from 100 to 500 kHz with constant pulse energy. Heat accumulation is the most significant factor affecting the ablation depth during femtosecond laser irradiation.

2. Experimental Details

An air-cooled ultrashort pulse laser micromachining equipment was used in the current work (Model: Satsuma HP2 from Amplitude systems). It is a diode-pumped, ultrashort fibre amplifier device that can produce pulses with 40 J of energy in less than 500 fs. Ytterbium-doped fibres act as diode-pumped photonic crystals that can create pulse energy up to several microjoules. It is a single-mode fibre, and the output beam is stable at constant power across the operational frequency range with a gaussian propagation factor of M2 ≤1.2. The ultrashort pulse laser specifications are listed in Table 1. A Field Emission Scanning Electron Microscopy (FESEM) and 3D optical profilometer (Wyko NT 1100) were used to analyse the laser-processed silicon quantitatively and qualitatively for ablation depth (FESEM).

The experimental setup of ultrashort pulse laser micromachining is shown in Fig.1, and it consists

Table 1

Specification of the ultrashort pulse laser.

Sl. No.	Laser parameters	Settings
1	Wavelength (nm)	1030
2	Pulse energy (µJ)	18 and 40
3	Pulse duration	300 fs
4	Repetition rate (kHz)	100, 200, 333, 400, 500
5	M^2	<1.2

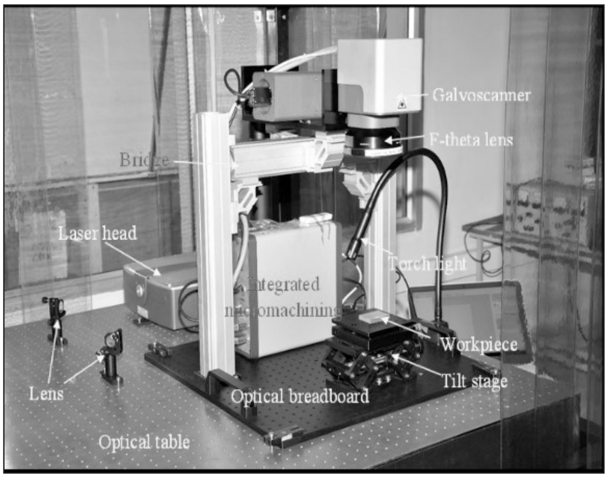


Fig. 1. Ultrashort pulse laser.

of a laser head, controller unit, scanner, and computer system. It includes a mode-locked laser oscillator, a high-power pump diode, and a digital motherboard to generate synchronized signals. The pump diode is connected to the laser head with multimode fiber. The compressor is used to reduce pulses up to 300 fs, and then a mechanical shutter is used to block the laser.

3. Results and Discussion

The following section discusses the microchannels depth formation at low and high peak fluence at various repetition rates. The peak fluence is evaluated using Eq. (1) as:

$$F_p = 2 \times E_p/(\pi \times r^2) \quad \text{................(1)}$$

where, F_p is peak fluence, E_p is pulse energy, and r is the spot radius. The average power increases with the increase in repetition rate as shown in Table 2. The obtained depth of the microchannels at various repetition rates are shown in Table 3.

The microchannels depth formation at low peak fluence of 0.28 J/cm^2 with various repetition rates from 100 to 500 kHz are discussed as follows:

3.1. Low peak fluence

Each subsequent heat accumulation tends to gradually raise the surface temperature (Weber et al., 2014). The surface will absorb more pulse energy in the subsequent pulse, suggesting a lower ablation threshold energy. Between 100 and 500 kHz, the repetition rate tends to increase along with the average surface temperature. With an increase in repetition rate from 100 to 500 kHz, the ablation depth was seen to increase from 0.65 to 6.64 µm, indicating that an increase in surface temperature directly contributes to an increase in microchannels depth. Fig. 2 displays the SEM images at repetition rates ranging from 200 to 500 kHz. Temporal pulse separation is measured in terms of 10 to 2 µs at repetition rates of 100 to 500 kHz. From 10 to 2 µs temporal separation observed as a significant for heat accumulation, a substantial range of heat accumulation. High-depth microchannels are created as a result of the cumulative increase in beam intensity and concurrent increase in heat accumulation (caused by the reduction in diffusivity and increase in beam intensity) (Bauer et al., 2015). The microchannels depth at increasing repetition rates is depicted by Fig. 3.

Table 2
Average power at various repetition rates.

Sl. No.	Repetition rate (kHz)	Average power (W) (at 18 µJ)	Average power (W) (at 40 µJ)
1	100	1.8	4.0
2	200	3.6	8.0
3	333	6.0	13.3
4	400	7.2	16.0
5	500	9.0	20.0

Table 3
Microchannels depth at various repetition rates.

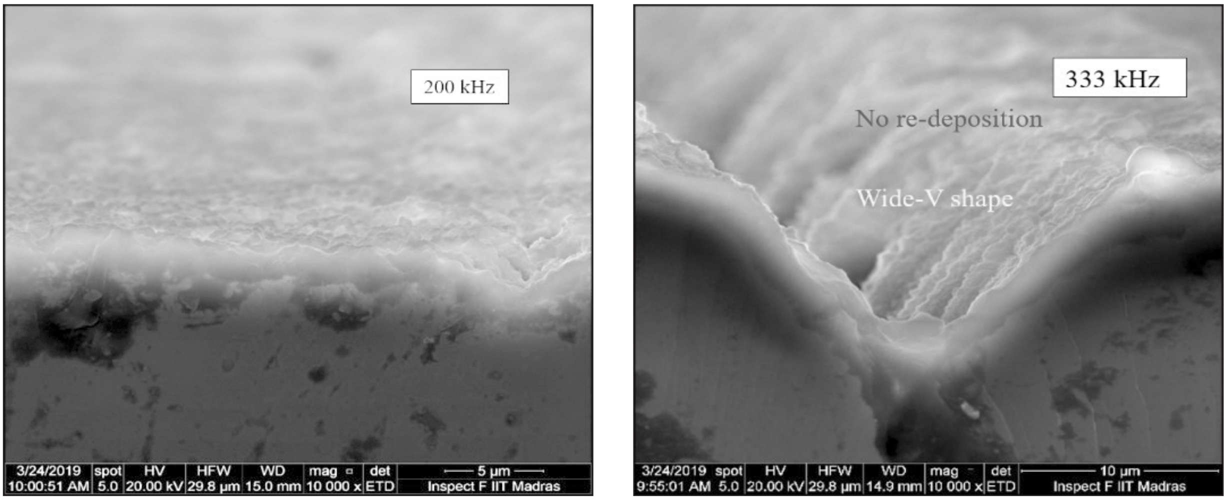
Sl. No.	Repetition rate (kHz)	Ablation depth (µm) at 0.28 J/cm^2	Ablation depth (µm) at 6.36 J/cm^2
1	100	0.65	6.30
2	200	0.60	28.16
3	333	4.10	85.73
4	400	5.90	94.50
5	500	6.64	107.73

The microchannels depth formation at a high peak fluence of 6.36 J/cm^2 and various repetition rates from 100 to 500 kHz are discussed as follows:

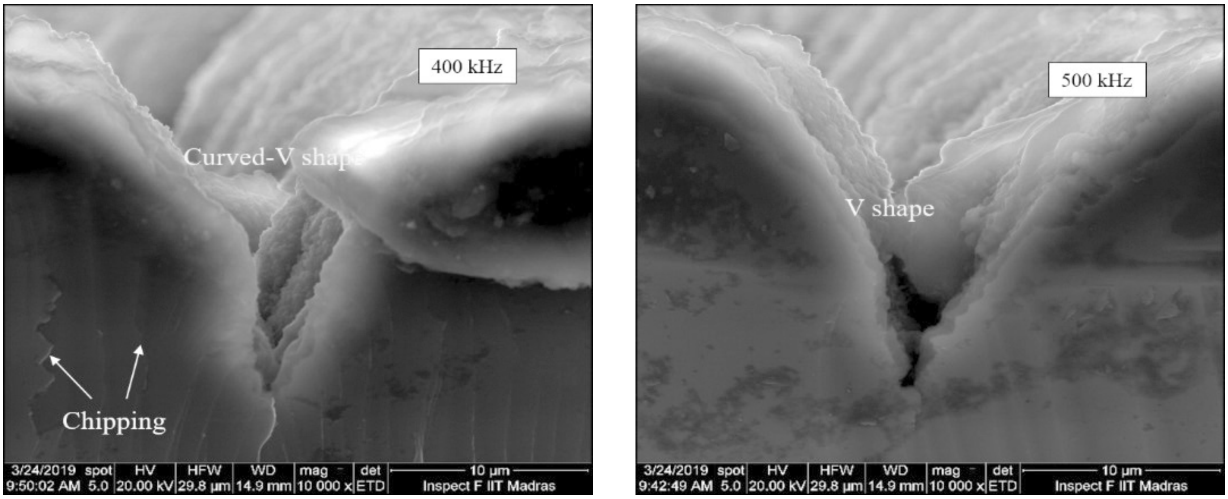
3.2. High peak fluence

The peak fluence of 6.36 J/cm^2 is higher than silicon ablation threshold. As the repetition rate increases from 10 to 500 kHz, the laser energy density of the beam increases from 254.71 to 12738.5J/mm^2. With the increase in repetition rate at constant pulse energy, the laser energy density increases, as shown in Fig. 5. The increase in excited electrons increases the absorption of the photons and thus increasing the electron density. The creation of electron-hole plasma rises with an increase in intensity and contributes to higher material removal. This removal depends upon the intensity of the laser beam. As the beam intensity increases, the direct laser ablation process becomes dominant.

In silicon, microchannel depth varies from 1 to 6.3 µm at repetition rates between 100 to 500 kHz, as shown in Fig. 3. These low-depth microchannels form possibly due to low average laser energy density, where the creation of direct intense electron-hole plasma does not occur. As the repetition rate increases from 200 to 500



(a) 200 kHz (b) 333 kHz



(c) 400 kHz (d) 500 kHz

Fig. 2. Silicon microchannels machined at peak fluence of 0.28 J/cm^2.

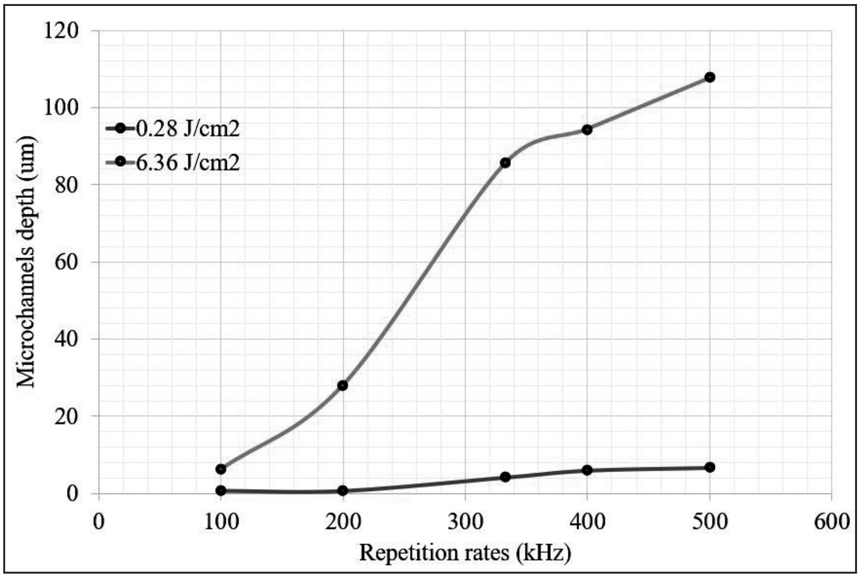
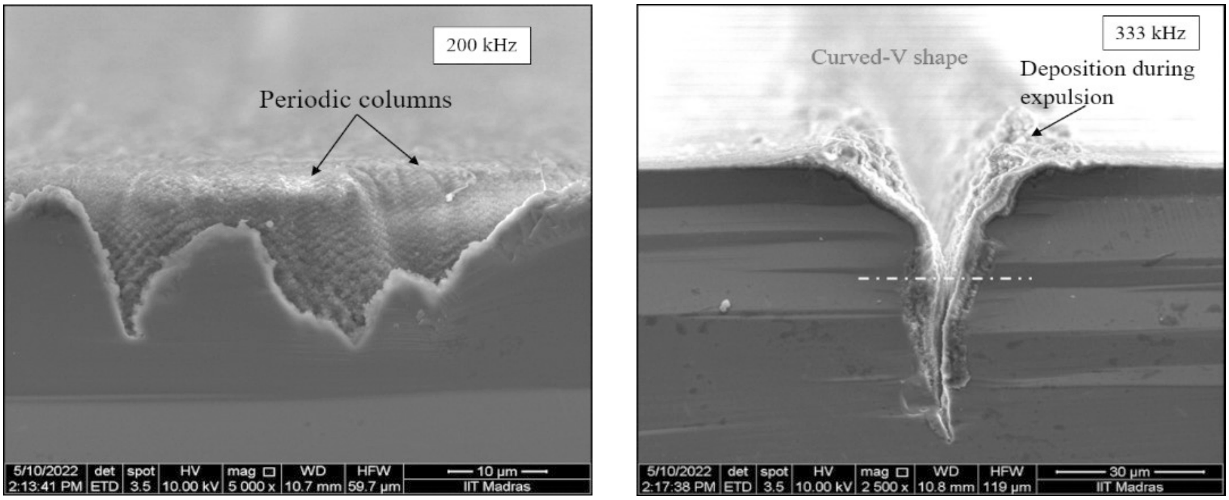
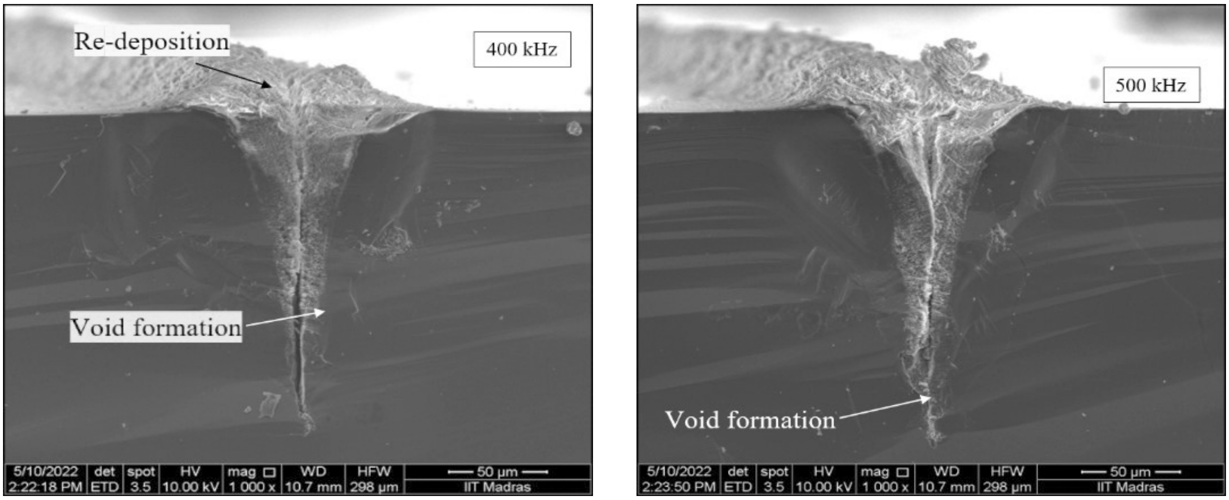


Fig. 3. Microchannels depth at low and high peak fluence at various repetition rates.



(a) 200 kHz

(b) 333 kHz



(c) 400 kHz

(d) 500 kHz

Fig. 4. Silicon microchannels machined at peak fluence of 6.36 J/cm^2.

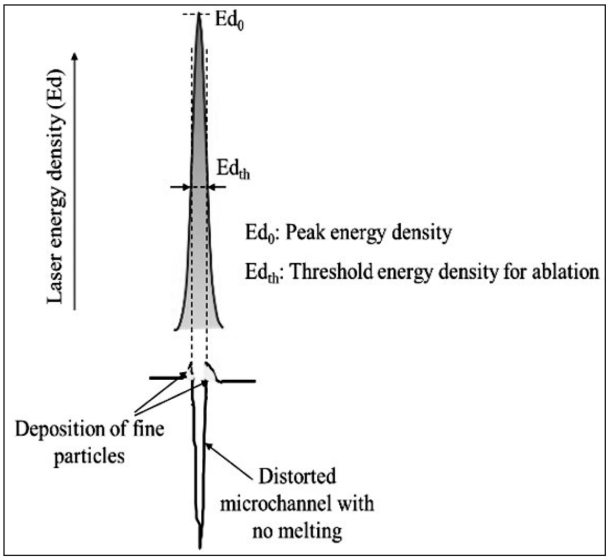


Fig. 5. Threshold energy density for ablation at fluence 6.36 J/cm^2.

kHz, the microchannel depth increases from 28.2 to 107 µm as shown in Fig. 4. This happens due to an increased tendency to form intense electron-hole plasma (especially at the centre of the ablated region). Plume shielding also does not restrict with high material removal at high intensities.

4. Conclusions

The achievement of high-depth microchannels in silicon are reported in this chapter by conducting experiments at various repetition rates with minimum pulse energy at two peak fluences. The laser low and high peak fluences of 0.28 and 6.36 J/cm^2 were used to investigate the effect of repetition rates and peak fluence on depth creation in an ambient environment. The high-depth microchannels were obtained by applying a high peak fluence of 6.36 J/cm^2

with an observation of fine particles. At high fluence and a repetition rate of 500 kHz, the highest microchannel depth obtained was 107.73 µm. At 6.36 J/cm^2, the depth formation was observed from 333 kHz. The repetition rate and laser energy density were found to be important factors influencing the geometrical properties of the microchannels in silicon. The formation of voids in silicon was also observed in high-depth microchannels obtained at high repetition rates at a peak fluence of 6.36 J/cm^2. The peak fluences and repetition rates have been found to control the depth formation in microchannels machined in the femtosecond regime.

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Shalini Singh has a Ph.D degree in Manufacturing Engineering from IIT Madras (2022) and has Master's degree in Production Engineering from NIT Rourkela. Her research interests include laser micromachining, and non-conventional manufacturing processes. She has published one journal, one book chapter, and five international conferences, in the field of laser micromanufacturing.
(E-mail: shalinisingh4190@gmail.com)

S. Niketh is currently working as a Post Doc Researcher in the proposed Centre of Excellence for Advanced Laser Material Processing in the Department of Mechanical Engineering, IIT Madras. He has completed his Ph.D from IIT Madras in the area of Laser Micro structuring, in 2019. Based on his research work, he has published five international Journal and participated in five international conferences. He has been awarded Institute Research Award (2018-2019) from the Department of Mechanical Engineering, IIT Madras in recognition of the exemplary research work done during the period of research at IIT Madras.
(E-mail: niketh30@gmail.com)

Prof. G. L. Samuel is currently working as Professor at IIT Madras in Department of Mechanical Engineering. He is Principal investigator of proposed centre of excellence on Advanced laser material processing. His areas of interest in research are CAD/CAM, Micro Machining, Metrology, and Non-Conventional and Conventional Manufacturing. He has 38 papers in international journals and more than 40 papers at national and international conferences are among his publications. He served as a Post-Doctoral Research Fellow at the Mechanical Engineering Department of Kyungpook National University in Daegu, South Korea.