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Ultrashort pulse laser drilling and characterization of micro holes in silicon and coated silicon

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Abstract

Fabricating micro/nanoscale through holes in silicon is challenging for manufacturing industries like optics and electronic industries due to its higher reflectivity. Recently, the ultrashort pulse laser technique has gained wider acceptance in the manufacturing industries owing to its unique capability of processing any materials with higher geometric accuracy. In the present paper, we report the challenges confronted to create qualitative micro and nano through holes in silicon and coated silicon while performing percussion drilling using ultrashort pulse laser. The experiments were performed at fluence above the threshold fluence of the silicon. From the experimental investigation, it was noted that after a certain depth 3.224 µm of the micro hole in silicon, further removal of material was not observed even with the increase in number of pulses. This is due to the occurrence of ablated surface temperature near to saturation. Furthermore, an analytical modelling has also been incorporated in the present work for justifying the concept of occurrence of saturation temperature at various repetition rates. As the present work investigates the interaction of laser parameters with silicon at femtosecond regime, the findings from the research work can be a reference in creating qualitative micro holes on the silicon surfaces at various laser parameters. This is of higher importance in the electronic industries, as silicon has a wide range of applicability due to its excellent electrical properties.

Keywords: Ultrashort pulse laser, micromachining, silicon, silicon nitride, saturation temperature.

1. Introduction

Silicon is the most investigated material in electronics industries, MEMS, photonics etc. for fabricating higher quality micro/nano scale features. There are many conventional and non-conventional processes such as micro EDM, micro milling, etc. to create high-quality micro features. Among them, ultrashort pulse laser micromachining has come up as a new emerging technology in the recent years to fabricate highly complex intricate shapes in the silicon. This was reported by Zhao et al., i.e., the suppression of the thermal diffusion to the bulk silicon by avoiding melting of the bulk in ultrashort pulse laser irradiation [1].

1.1 Interaction of ultrashort pulse laser on silicon and silicon nitride

Usually, in ultrashort pulse lasers with femtosecond pulse durations the thermal effects (heat affected zone) is smaller due to the occurrence of interaction time lesser than the electron relaxation time. The threshold energy required to ablate silicon is 0.2 J/cm^2 [2] and for Silicon nitride (Si_3N_4) is 0.6 J/cm^2 [3]. Many researchers studied the formation of micro features from pulse-to-pulse irradiation at high repetition rates. In ultrashort pulse laser, the high repetition rate is the most significant parameter to create high depth microchannels with high quality in silicon materials. Mishchik et al., have reported the high ablation rate of 2.5 mm^3/min/W in silicon using the GHz repetition rate with pulse energy 400 µJ [4]. In another work, Wang et al., has reported the high depth micro features using THz repetition rates in silicon using direct ultrashort pulse laser writing [5]. Tran et al., investigated about the below and above threshold fluence at various number of pulses where low fluence used to produce different morphologies and high used for ablation in silicon [6]. Recently, Guk et al., has studied heat accumulation effect on the silicon at low repetition rate on the dynamics of surface temperature. [7]. Sobierajski et al., has studied the effect of heat accumulation in phase transition for surface modification in silicon at 1 MHz repetition rate with 400 nm wavelength femtosecond pulse laser [8].

1.2 Percussion drilling of silicon material

Putzer et al., has investigated on percussion drilling using ultrashort pulse laser. The transition of conical hole to the cylindrical hole tends to occur with the increase in number of pulses. [9]. Matsumura et al., has investigated effect of fluence and number of pulses on hole depth in silicon using 200 µJ pulse energy, 500 Hz repetition rate, 790 nm wavelength with 130 fs pulse duration. They observed that the hole depth increases with increase in fluence (14.5 to 59.4 J/cm^2) and number of pulses [10]. Laakso et al., mentioned the increment in depth with increase in number of pulses by 1 kHz repetition rate and 790 nm wavelength femtosecond pulse laser irradiation [11]. Wang et al., has investigated the fluence (50 J/cm^2) and number of pulses on the drilling hole in silicon. The hole diameter and depth also increase with increase in number of pulses [12]. Zahrani et al., has performed experiments on silicon nitride to crate hole using ultrashort pulse laser with 400 kHz repetition rate, 10 picosecond pulse duration, 125 µJ pulse energy. The maximum hole depth as 92 µm was obtained [13]. Nasrollahi et al., has investigated percussion drilling in silicon nitride using ultrashort pulse laser irradiation. The hole depth was increasing with increase in depth of focus and fluence [14]. From the literature survey it has been observed that the ablation mechanism eventually influences several aspects of the hole diameter, depth and surface roughness. Heat accumulation in various types of materials were reported with the interaction of short pulse laser irradiation on metals, dielectric, semiconductors and biological tissues (e.g., bone tissues). Numerous simulation studies were also reported by the researchers, showing the effect of increase in surface temperature with the increase in repetition rates. This was mainly explained in terms of the occurrence of heat accumulation with the increase in number of pulses per spot.

Though there are many research work in the area of ultra-short pulse machining of silicon, limited works are reported so far in exploring the physics of micro ablation and their influence on surface quality. Hence the major objective of the work was to understand the effect of various lasing parameters in generating qualitative micro features with lesser surface defects.

2. Experimental details

Direct ultrashort pulse laser micromachining was used to accomplished experiments on silicon at 1030 nm. The ultrashort pulse laser scribing experiments were carried out on the silicon and silicon nitride (Si_3N_4) coated (coating thickness 0.8 µm) surface of a single crystal silicon wafer (n-type) of thickness 0.5 mm using Ytterbium-doped photonic crystal fiber laser delivering 40 µJ pulse energy. Silicon nitride is transparent material in the exposure to visible range wavelength (<500 nm) but present work accomplished by considering wavelength 1030 nm [15]. The schematic diagram of the laser micromachining setup has been shown in Fig. 1. The ultrashort pulse laser with pulse duration 300 femtosecond, average power 20 W, scanning speed at 1 mm/s and repetition rate from 100 kHz to 500 kHz. The peak fluence used was 6.364 J/cm^2 and calculated using Eq. (1).

$$F_0 = \left(2 \times E_p\right)/\left(\pi \times r^2\right) \qquad (1)$$

where, F_0 is the peak fluence, E_p is the pulse energy, r is the spot radius. The number of pulses per spot was calculated using the Eq. (2).

$$n = \sqrt{\frac{\pi}{2}}\left(\frac{f \times d}{v}\right) \qquad (2)$$

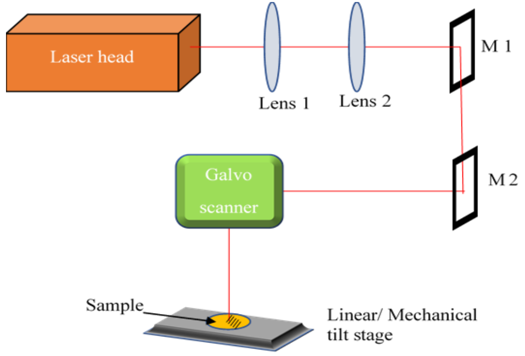


Fig. 1. Schematic diagram of the laser micromachining setup; M1- Adjustable Mirror 1 and M 2- Adjustable Mirror 2

3. Results and Discussion

The present work focused on the effects of high fluency at different lasing conditions on hole depth and its morphology in silicon and coated silicon. All the experiments were performed at room temperature without any assisted gas. The laser processed silicon specimens were analyzed quantitatively and qualitatively using 3D optical profilometer (Fig. 3) and scanning electron microscopy (SEM). The hole depths at repetition rates from 100 kHz to 500 kHz in silicon and coated silicon are shown in Table 1.

Table 1
Depth of hole at various repetition rates

Sl. No.	Repetition rate (kHz)	Depth (µm)	
		Silicon	Coated Silicon
1	100	1.678	0.827
2	200	1.782	1.135
3	333	2.815	2.739
4	400	3.399	2.969
5	500	3.224	3.078

3.1 Hole Depth obtained at various repetition rates

Hole depth was investigated as a function of heat accumulation at repetition rates from 100 kHz to 500 kHz. The hole depth increases from 1.678 µm to 3.224 µm in silicon at 100 kHz to 500 kHz repetition rates as shown in Fig. 2. The increase in hole depth was due to the heat accumulation with the increase in number of pulses. The repetition rate increases at constant pulse energy which tends to increase the average power of the pulse. The peak fluence was 6.364 J/cm^2 which is above the threshold fluence of the silicon and silicon nitride. The time required to cool down the elevated temperature during previous pulse in silicon and silicon nitride is in the range of 10 µs. From 100 kHz to 500 kHz repetition rates, the temporal separation between pulses was in the range of 10 µs to 2 µs. This range of temporal separation between pulses were not enough to cool down the elevated temperature caused by the previous pulse. Due to heat accumulation the energy required to ablate material by the next pulses get reduced. The heat accumulated during successive pulses increases the surface temperature of the ablated region from 100 kHz to 500 kHz repetition rates. The high absorption of the laser light occurs at high temperature ablated surface which further increases the depth formation in silicon and coated silicon. In the present work, it was noted that for silicon and coated silicon 40 µs was taken to reach maximum depth at 500 kHz.

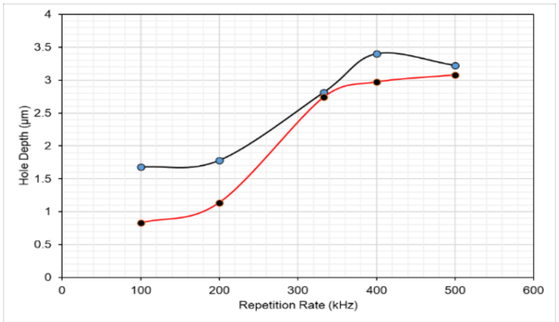


Fig. 2. Hole depth at various repetition rates

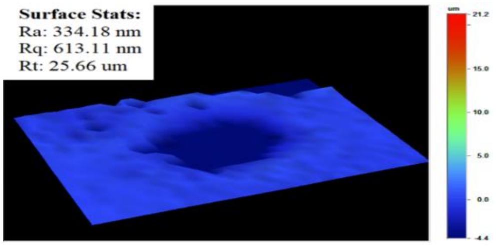
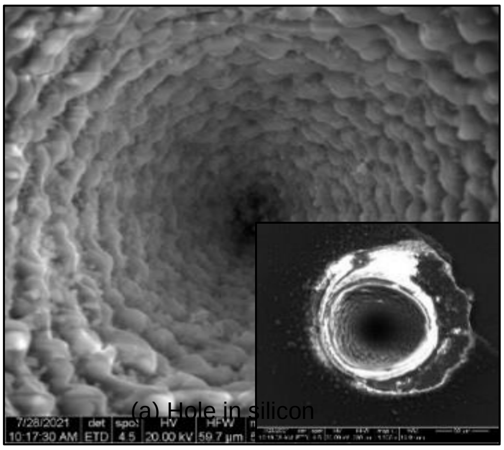


Fig. 3. 3D optical view of the hole

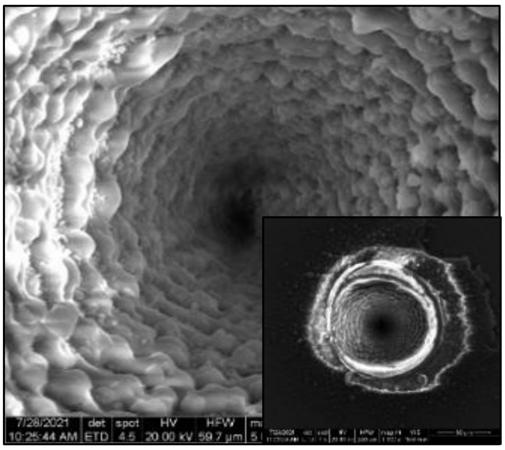
The effect of number of pulses becomes negligible when the ablated surface temperature reached to saturation temperature. This saturation temperature observed to the main cause which hinders to create through hole in the silicon. The predicted surface temperature shows that after certain number of pulses, the saturation temperature reached. It shows that after reaching saturation temperature, the effect of number of pulses becomes negligible irrespective of the material properties. Present study focuses at the high repetition rates (100 kHz to 500 kHz) where temporal separation between pulses is between 2 µs -10 µs. This range of temporal separation allows minimal heat diffusion to the bulk, which reduces heat affected zone to the ablated hole.

3.2 Hole morphology of silicon and coated silicon

The hole morphology was studied at repetition rate from 100 kHz to 500 kHz at fixed pulse energy 40 µJ. Conical shape hole was noticed at all the lasing conditions in both the materials. The conical shaped hole in silicon and coated silicon was shown in Fig. 4 (a, b). The debris formation was not observed in both the materials at all lasing conditions. The taper angle of the holes observed in the range of 67.865° to 82.768° and 61.561° to 75.864° in silicon and coated silicon respectively. The measurement of taper angle was evaluated as shown in Fig. 5.



(a) Hole in silicon



(b) Hole in coated silicon

Fig. 4. SEM images of hole at 500 kHz

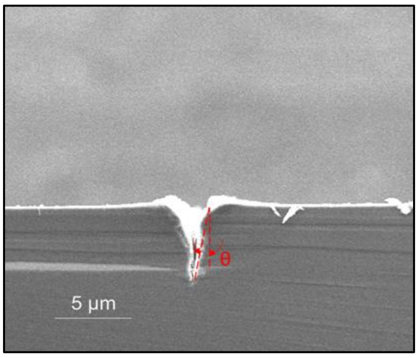


Fig. 5. SEM images for taper angle of hole

3.3 Prediction of surface temperature

From the analytical modelling we observed that the surface temperature increases with increase in the number of pulses and this effect is enhanced at higher repetition rates (333 kHz, 400 kHz and 500 kHz). As the repetition rate increases the temporal separation between pulses decreases. The surface temperature increases with increase in repetition rates is shown in Fig. 6. As the temporal separation between pulses decreases, the time required for heat diffusion decreases. Consequently, the surface temperature of the top surface of the ablated surface is increasing. The main cause of not attaining through hole is due to the saturation temperature reached after certain number of pulses. To predict the surface temperature (T), one dimensional heat conduction model (Eq. 3) was utilized [16]. Heat conduction model is valid for present study because the heat accumulation duration in microseconds (µs) which is higher than the 10 picoseconds (required for electron relaxation).

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial z^2} \qquad (3)$$

where, D is the thermal diffusivity (cm^2/s), k is the thermal conductivity (W/mK), I_a is the absobed intensity (W/cm^2) and t_p is the pulse duration (fs). The surface temperature can be solved in terms of temporal seperation form as shown in Eq. (4).

$$T(z,t) = \frac{D^{1/2}}{k\pi^{1/2}}\int_0^{t_p}\frac{I_a(\tau)}{(t-\tau)^{1/2}}\exp\left(-\frac{x^2}{2D(t-\tau)}\right)dt \qquad (4)$$

where, I_a is the absorbed laser intensity during interaction and k is the thermal conductivity. The time dependence temperature during laser pulse ($t<t_p$) is written as Eq. (5) if tp< 1/tpp.

$$T(t) = T_m\left(\frac{t}{t_p}\right)^{1/2} \qquad (5)$$

T_m is the maximum surface temperature and t_p is the pulse duartion. The surface temperature at the end of the pulse evaluated by using Eq. (6).

$$T(0,t) = T(0,t_p)(\frac{t_p}{t})^{1/2} = \sqrt{\frac{2}{\pi}}\frac{I_a(Dt_p)^{1/2}}{k}(\frac{t_p}{t})^{1/2} \qquad (6)$$

The surface temperature after "n" number of pulses evaluated using Eq. 7.

$$\overline{T_n} = \frac{1}{n(t_p+t_{pp})}\int_0^{n(t_p+t_{pp})} T(0,t)dt = 2\alpha\frac{(1-\frac{2\alpha}{3})}{(1+\alpha^2)}\frac{1}{n}\sum_{i=1}^{n}\overline{T}_{\max,i}$$

(7)

where,

$$\sum_{i=1}^{n}\overline{T}_{\max,i} = T_m\left(1+\frac{1-\alpha^2}{1-\alpha}+.....+\frac{1-\alpha^n}{1-\alpha}\right)=\frac{T_m}{(1-\alpha)}\left(n+\frac{\alpha^n-\alpha}{1-\alpha}\right)$$

The surface temperature was observed maximum at the end of the pulse. Due to heat accumulation by the successive pulses, the surface temperature increases with increase in the number of pulses. After a certain number of pulses, the surface temperature becomes saturated. This saturation of surface temperature was observed in silicon at the repetition rates i.e., 100 kHz to 500 kHz. The saturation temperature of the ablated surface at 400 kHz and 500 kHz repetion rate are shown in Fig. 7 for silicon. Similar trend was also observed in the coated silicon.

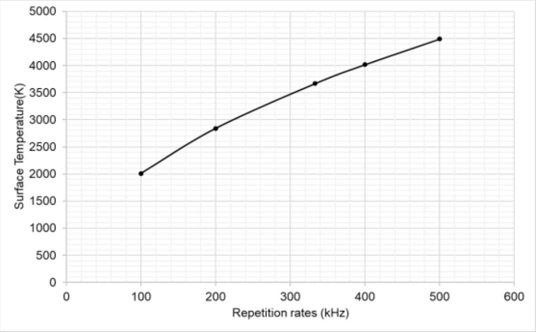


Fig. 6. Surface temperature vs repetition rates

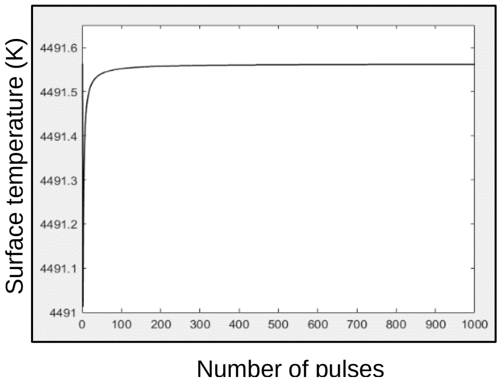


Fig. 7. Saturation temperature at 500 kHz

4. Conclusion

The present study focusses in exploring the fundamental physics effecting the surface integrity during laser material interaction while creating micro holes in silicon.

- The maximum hole depth 3.224 µm and 3.078 µm was obtained at 500 kHz in the silicon and coated silicon respectively.
- The underlying mechanism of not attaining through hole even at higher number of pulses was found to be due to the occurrence of saturation temperature.
- The maximum surface temperature was noted to be formed at the end of the pulse at repletion rates 100 kHz to 500 kHz. Wherein the maximum surface temperature obtained at 500 kHz.
- Further study can be done on ultrahigh repetition rates for understanding the effect of heat diffusion on creating through holes.

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