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Micro-drilling of silicon wafer by industrial CO_2 laser

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Abstract

Background: Laser micromachining is currently used in the MEMS production to replace the traditional etching process which consumes longer time to complete. The objective of this study is to investigate the drilling capability of industrial CO_2 laser in processing of silicon wafer.

Methods: In this work, the holes were drilled on P-type silicon wafer with thickness of 525 μm. Geometrical characteristic of holes produce, which is diameter entrance that depends on laser parameter were investigated and analyzed. Analysis of Variance (ANOVA) was used to analyze the result and generated an appropriate model for the laser drilling processing.

Results: The laser parameters involved were laser power, pulse frequency and duty cycle. The experimental results showed the entrance diameter of drilling holes was increase when the laser power and duty cycle increased.

Conclusion: The entrance diameter of drilling hole decreases when the pulse frequency increases.

Keywords: MEMS; CO_2 laser; Silicon wafer; ANOVA

Background

Microelectromechanical system (MEMS) is a process technology applied to produce smaller devices or systems that combine together the electrical and mechanical components (Ku et al. 2011). Silicon wafer is the main material for MEMS, photonics, and semiconductor manufacturing industries (Ku et al. 2011; Wadhwa and Kumar 2014; Chen 2006). Nowadays, laser micromachining is used in the MEMS production to replace the traditional method such as the etching process which takes a longer time to finish the process. As a micromachining process, laser drilling is used to create through holes by using a laser beam where the principle of thermal removal of material occurred. There are many laser drilling techniques such as percussion drilling, single-pulse drilling, helical drilling, and trepanning drilling (Nayak et al. 2014). Nd:YAG laser becomes one of the most popular types of laser used in laser micromachining. The diameter used is the smallest value of laser wavelength (1.06 μm), which makes the Nd:YAG laser beam to be adsorbed by silicon wafer, but the initial cost is expensive. Compared with CO_2 laser, the processing cost for this type of laser is economical, but due to the high wavelength value (10.64 μm), silicon wafer cannot absorb the CO_2 laser beam. Silicon wafer will reflect more CO_2 laser beam than absorb it. This phenomenon becomes a constraint in applying laser drilling process on silicon wafer by using CO_2 laser.

A variety of lasers has been successfully used for silicon micromachining on experimental scale (Chung and Lin 2010; Vilhena et al. 2009), and these laser types have shorter wavelengths and shorter pulse lasers with high peak power. These lasers are not realistic for practical mass production due to being unstable, dangerous to the operator, and very high costs. Jiao et al. (2014) studied the effects of the hole geometry and the spatter which are around the drilled hole by femtosecond laser deep drilling with various temperatures and found 56% increasing drilling efficiency when temperature was raised from 27°C to 600°C. Recently, CO_2 and Nd:YAG lasers were tried out for micromachining of metals and glass and gained success to certain extent (Jiao et al. 2013). This intended to carry out silicon micromachining with CO_2 laser which is also relatively economical with better material removal rate. Chung and Wu (2007) discuss about silicon micromachining by using CO_2 laser by placing a silicon wafer on the Pyrex glass. The

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morphology view and cross-sectional profile were studied using an optical microscope. As a result, the depth of silicon etching was increased when the pass number and laser power increase. Besides, the hole diameters produced also increase when the pass number, laser power, and scanning speed were increased. Jiao et al. (2009) investigated the integrated effect of several laser parameters (focus position, laser power, focus lens, and number of pulses) on the results, including micro-hole geometry and spatter characteristics of the laser micro-drilling process. In the proposed research, Clark-MXR fs laser (Clark-MXR, Inc., San Jose, CA, USA) was used, and its wavelength was 1.03 μm with a nominal frequency of 1 kHz. By using a DUV microscope (Olympus Corporation, Tokyo, Japan), the average value of the diameter in the two directions was taken as the hole diameter. The experimental results showed that the increase of laser power and the number of pulses caused the hole entrance diameters and hole exit diameter to also increase. Yan et al. (2012) use CO_2 laser to conduct laser percussion drilling of thick-section alumina. The five controlled parameters of laser processing which are the pulse repetition rate, pulse duty cycle, laser peak power, pulse duration, and pulse energy were applied in the research. Spatter deposition and hole diameter (exit diameter and entrance diameter) of the drilled holes were investigated. Spatter deposition and hole diameter increase with increasing laser peak power and duty cycle. Wee et al. (2011) discussed four controlled parameters that affected the laser processing of silicon wafer in air and under water. The controlled parameters consist of scan velocity, laser pulse frequency, power level, and focal plane position that affect the laser spatter deposition (in air), irradiated areas (under water), and taper formation. The drilled hole on silicon wafer is observed with scanning electron microscopy (SEM).

Three controlled parameters involved in laser drilling of ceramic alumina are pulse frequency, laser power, and scanning speed (Bharatish et al. 2013). The processing performance, such as hole entrance diameter, hole exit diameter, hole taper, and hole circularity, was investigated. The laser parameters and response were correlated using response surface methodology (RSM) (Sivarao et al. 2013a). The laser parameters were feasible in the fabrication of MEMS structures on silicon. Nd:YAG laser (JK300HPS) was used with three controlled parameters which are width, pulse energy, and height of the laser power. The processing performance, such as the spot diameter produced, was investigated using the analysis of variance (ANOVA) method, and the model produced was discussed (Sivarao et al. 2013b). The experimental studies of the micro-laser drilling of silicon wafers by using CO_2 laser are also highlighted. Laser parameters such as pulse frequency, laser power, and duty cycle will be set up to drill holes on 525-μm thickness of silicon wafers. The entrance diameter of drilling holes will be analyzed.

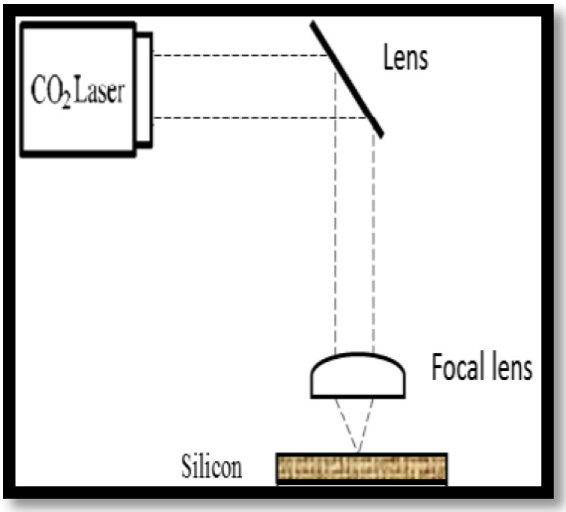

Figure 1 Laser drilling schematic diagram.

Methods

Basically, an experiment was conducted based on the schematic diagram in Figure 1. The main components involve in this diagram are CO_2 laser source, reflective mirror, focal lens, and silicon wafer. In this research, the (111) P-type silicon wafer with a 525-μm thickness was used. From the schematic diagram in Figure 1, when the CO_2 laser source starts to produce laser beam, the lens will reflect the laser beam toward the focal lens and the desired size of focus spot will be produced. From the focal lens, the laser beam continues to move to the silicon wafer and the laser drilling process will start.

Laser drilling processing was conducted by using Helius 2513 laser cutting machine manufactured by LVD Company (Gullegem, Belgium) with the maximum laser power of 3,000 W. The complete specification for Helius 2513 laser cutting machine is shown in Table 1. The small size of the nozzle diameter was used to develop micro-holes on silicon wafers with 0.4-mm diameter. Nitrogen gas was applied in the laser drilling process to control heat

Table 1 Complete specification of the Helius CO_2 laser machine

Specification	Description
Model	Helius 2513 laser cutting machine
Controller	FANUC Series 160 i-L
Maximum capacity	3 kW
Laser beam wavelength	10.6 μm
Laser source	CO_2 gas with the real ingredient mixture of N_2 (55%), He (40%), CO_2 (5%) with purity of 99.995%
Lense size	5 to 7.5 in.
Compressed air	5 to 6 bar

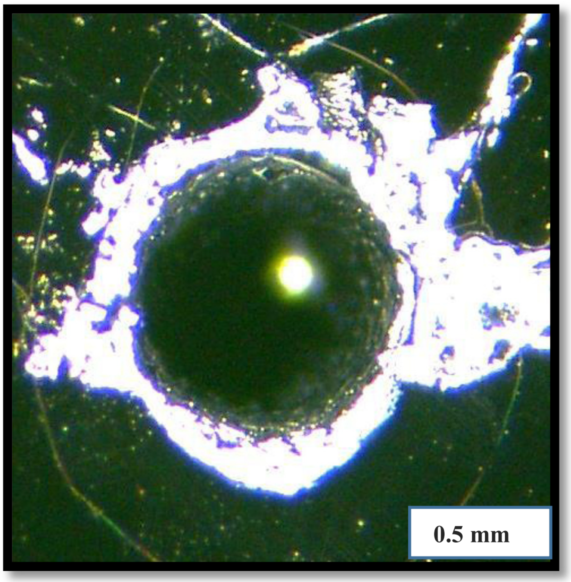

Figure 2 Entrance hole of the laser drilling setup.

produced when the drilling process is performed. The hole drawing was transferred to CADMAN software provide by the LVD Company, which was used to generate the G code for the drilling process. Three types of laser parameters are involved in this experiment. They are laser power controlled at 30 to 50 W, pulse frequency at 100 to 300 Hz, and the duty cycle about 60% to 80%. Trepanning method was applied in the laser drilling process to create 15 circular holes on the silicon wafer. Although percussion drilling offers fast material removal rates, trepanning was selected as this method provides better hole roundness and accuracy. A lot of spatter deposits that form around the drilling hole will affect the entrance diameter measurement process. Solvent cleaning process was conducted to clean the silicon surface from spatter deposition that can interfere the hole diameter measurement process. Solvent can clean oils and organic residues that appear on glass surface. Unfortunately, solvents by themselves (especially acetone) leave their own residues. This is the main reason the two-solvent method is chosen here. Acetone and methanol were added separately into a glass container by heating only the acetone container onto a hot plate to warm up (not exceeding 55°C). The silicon wafer was placed in warm acetone bath for 10 min. Then, it was kept in methanol for 2 to 5 min which yields better cleaning. Meiji Techno microscope (Meiji Techno, San Jose, CA, USA) with × 30 magnification was used to measure the entrance diameter of the drilling holes. The value of the hole entrance diameter was entered into the Design Expert software and analyzed using ANOVA.

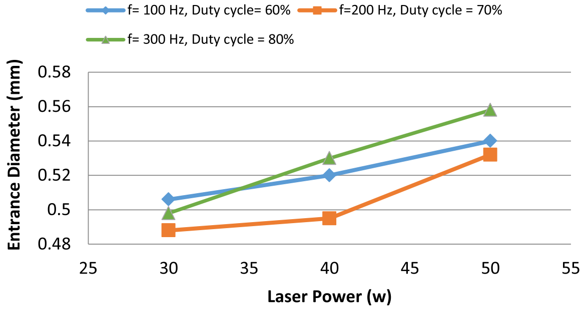

Figure 3 Entrance diameter values as a function of laser power.

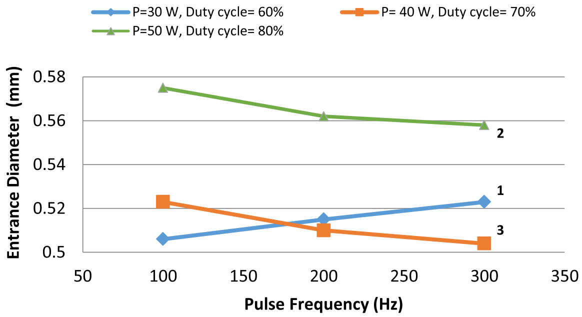

Figure 4 Entrance diameter values as a function of pulse frequency.

Results and discussion

After finishing the laser drilling process, all of the hole entrance diameters were measured using a metallographic microscope and analyzed using ANOVA. Figure 2 shows the entrance of the drilling hole with laser power of 40 W, pulse frequency of 200 Hz, and duty cycle of 70%. There was some form of spatter deposition at the hole entrance, which is caused by the material repelled when the laser drilling process was performed.

From ANOVA, the relationship between the controlled laser parameters and the hole entrance diameter can be made based on the graph generated. The plot of Figure 3 evidenced that the entire data of the entrance diameter of the drilling holes increase due to the increase of laser power up to 50 W. Generally, the laser power serves as

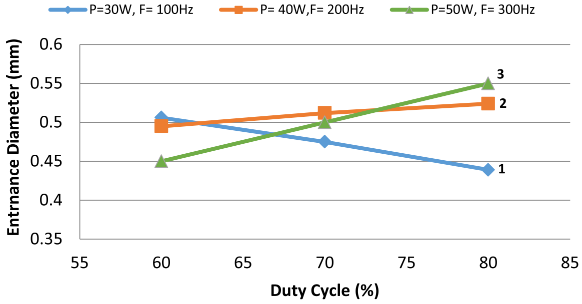

Figure 5 Entrance diameter values as a function of duty cycle.

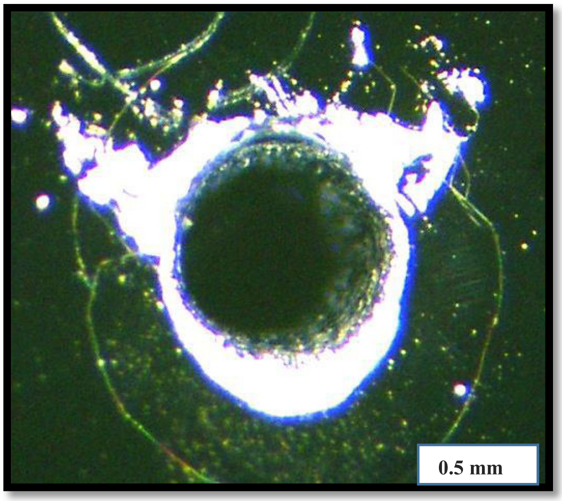

Figure 6 Entrance hole with large spatter deposition area.

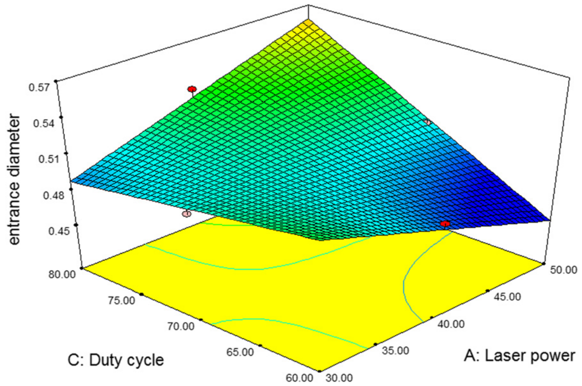

Figure 8 Response surface plot of hole entrance diameter with laser power and duty cycle.

the energy supplier to the laser beam to melt the drilled material. The increase of laser power caused more energy to spread on the silicon wafer and melts the silicon wafer surface rapidly. The molten material increases, and the escaping vapor produces a very high recoil pressure on the molten material at the bottom of the hole. The molten material repelled sideways, then vertically up the sides of the hole, and finally out of the hole. The results of greater material removal rate will produce larger entrance hole (Jiao et al. 2009).

The entrance diameter of the drilling holes in the graph of Figure 4 increases in curve 1, where the laser power is 30 W, duty cycle is 60%, and pulse frequency is up to 300 Hz. These results were actually affected by increasing the other type of laser parameters which are laser power and duty cycle. However, in curves 1 and 3, the entrance diameter of the drilling holes decreases due to the increase of pulse frequency up to 300 Hz. This phenomenon occurs by the high material removal that resulted in the faster rate of vapor pressure buildup inside the drilling hole in the higher laser power condition. The increasing material removal of silicon wafer caused the larger drilling holes produced by decreasing the pulse frequency (Wee et al. 2011).

The entrance diameter of the drilling holes in the graph of Figure 5 is decreased in curve 1, where the laser power is 30 W, pulse frequency is 100 Hz, and duty cycle is up to 300 Hz. This result may be due to the systematic error that happens when the hole entrance diameter was measured. However, in curves 2 and 3, the entrance diameter of the drilling holes increases due to the increase of duty cycle up to 80%. The high application of pulse duty cycle in the laser drilling process caused the high melt ejection velocity produced before the drilling hole. The melt ejection of material caused the spatter to deposit with large area around the drilling holes. The size of the melt front is also larger and produced a larger hole entrance diameter throughout the silicon thickness (Chung and Wu 2007). Figure 6 shows a large spatter deposition area produced around the entrance hole with applied 80% duty cycle.

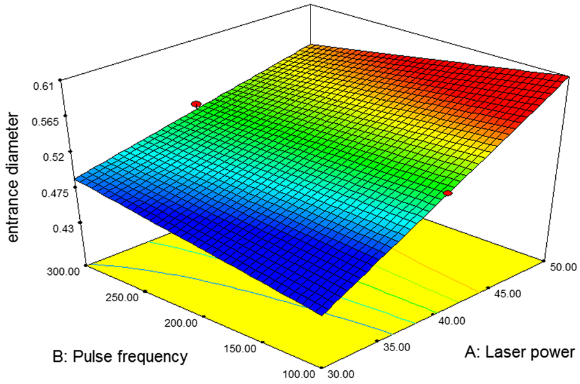

Figure 7 Response surface plot of hole entrance diameter with laser power and pulse frequency.

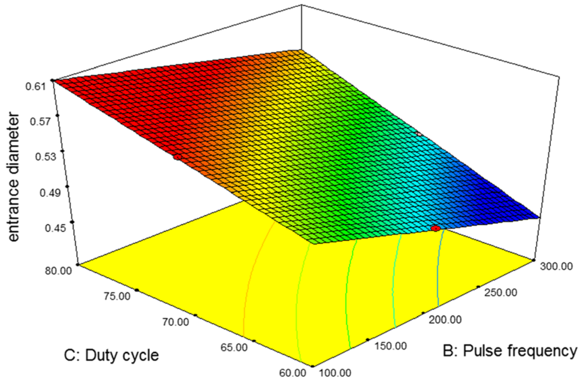

Figure 9 Response surface plot of hole entrance diameter with pulse frequency and duty cycle.

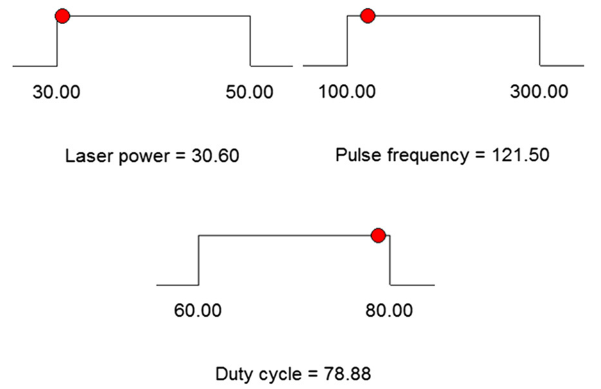

Figure 10 Optimized parameter value of the laser drilling process.

ANOVA generated a final equation in terms of the actual factors for the entrance diameter of the drilling hole. From the equation, the value of percentage error between the experimental and predicted values for hole entrance diameter can be obtained. The final equation is shown below:

Entrance diameter = 1.262 – (0.017 × laser power) + (2.938×10^{-4} × pulse frequency) – (0.015 × duty cycle) – (2.5×10^{-5} × laser power × pulse frequency) + (3.5×10^{-4} × laser power × duty cycle) + (8.75×10^{-6} × pulse frequency × duty cycle).

Figure 7 shows the effect of laser power and pulse frequency on hole entrance diameter by keeping duty cycle constant at 80%. The surface plot shows that the hole entrance diameter increases with the increase in laser power but decrease in pulse frequency. The minimum and maximum hole entrance diameters produced are 0.475 and 0.575 mm, respectively.

Figure 8 shows the effect of laser power and duty cycle on hole entrance diameter by keeping pulse frequency constant at 300 Hz. The surface plot shows that the hole entrance diameter increases with the increase in laser power and duty cycle. The minimum and maximum hole entrance diameters produced are 0.475 and 0.575 mm, respectively.

Figure 9 shows the effect of pulse frequency and duty cycle on hole entrance diameter by keeping the laser power constant at 50 W. The surface plot shows that the hole entrance diameter increases with the increase in duty cycle but decrease in pulse frequency. The minimum and maximum hole entrance diameters produced are 0.475 and 0.575 mm, respectively.

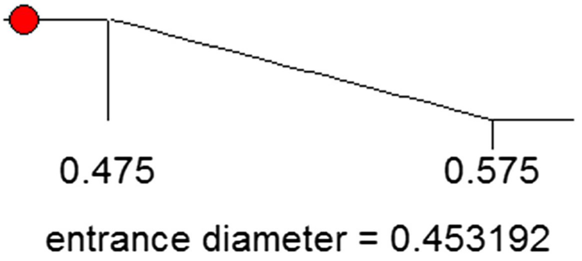

Figure 11 Predicted entrance diameter of the drilling hole.

The optimization process was conducted to find the best parameter values for minimizing the entrance diameter of the drilling holes. The optimized parameter values (Figure 10) consist of laser power (30.60 W), pulse frequency (121.50 Hz), and duty cycle (78.88%). The optimized parameter values of the laser drilling process were predicted to produce an entrance diameter of the drilling hole of 0.4531 mm (Figure 11).

Conclusions

The micro-holes were successfully generated on the silicon wafer using CO_2 laser and showed an overwhelming result. The experimental results showed that the increase of laser power and duty cycle in the laser drilling process significantly can increase the entrance diameter of the drilling hole. Otherwise, the increase of pulse frequency will reduce the entrance diameter of the drilling hole. The diameter of holes produced in this experiment (0.475 to 0.575 mm) is close to the diameter of the hole produced in the standard. A model was generated, and the percentage of error between the experimental data and predicted data was below 10% which is acceptable. The developed model was optimized by finding the best laser parameter to minimize the hole entrance diameter produced.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

SS is the main author who contributed and organized the entire research and confirmed the obtained results including the critical discussion. MSK, MAMA, RIRA are helped to analyse the partial data and TJSA helped to check the language and critical discussion. All authors read and approved the final manuscript.

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