Surface characterization of laser-induced molten area in micro-grooving of silicon by ultraviolet (UV) laser

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Abstract The objective of this research is to understand the fundamental mechanisms that govern the formation of laser-induced molten area during the micro-grooved fabrication on silicon material. In this research work, micro grooves were fabricated on silicon wafer by using ultraviolet (UV) laser of 248nm wavelength. Influence of lasing parameters such as pulse duration, laser pulse energy and scanning speed on the surface of micro-grooved was characterized. It is found that, the width of the micro grooves become wider with increasing laser pulse energy when ultraviolet laser was irradiated on silicon material. On the other hand, heat affected zone (HAZ) can be found at the surface of micro groove line at high pulse energy, high pulse repetition rate and lower scanning speed irradiation condition. This is considered due to the excessive heat input of the laser irradiation condition. It is concluded that proper selection of laser processing parameters of pulse energy, $E$, pulse repetition rate, $R_p$, and scanning speed is necessary to achieve high quality micro-grooves.

Keywords: laser microfabrication, silicon, molten area

1. Introduction
Silicon is a semiconductors material that has been widely used in electronic components such as photonic devices, sensors and microcontroller [1]. The brittleness of silicon material makes it vulnerable to crack. Thus, fabrication process for this material using conventional technique become challenging since most of the method required mechanical contacts between tools and surface of the material. Precision control of the load applied in conventional machining process is necessary to avoid excessive load that might damage the material. In addition, fabrication of micro scale features such as micro-grooves are important for achieving specific properties of the material such as adhesion reduction in sensor packaging and boiling improvement in heat exchange applications [2].
On the other hand, a micro-grooving technique such as the use of laser processing method has been proposed to overcome this limitation. Laser irradiation process is a thermal energy-based process and there is no direct tool-to-work piece contact. It uses a highly focused photon energy absorbed at the surface and caused it to melt. Figure 1 shows the illustration interaction between silicon and laser. High intensity of focused laser beam enables non-linear absorption on silicon surface through multiphoton ionization. Then, laser beams penetrate inside the material. Heat was accumulated in upwards direction of laser irradiation axis. After laser irradiation process, a thin molten layer forms at surface of silicon material at room temperature [3]. It is well known that amount of absorbed energy during the irradiation process influence the molten area formation and the surface quality of the work piece [4]. This accumulated energy or heat input can be controlled by proper selection of the lasing parameters.

Many works have been done to investigate the influence of lasing parameters on surface of laser-irradiated area. Jiangmin et al. studied that the melt spatter phenomenon of the polysilicon surface is caused by melting from the heat generated when the material absorbs high-energy laser photons under various laser processing parameters. [5]. Cheng et al. conducted an experiment to study on rapid development the ultrafast laser micromachining undergoes at the present time [6]. It goes through the results of several key parameters in ultrafast laser micromachining studies, such as laser pulse length, pulse energies, and spot diameter, as well as the techniques used to achieve high machining precision and throughput. Landowski, M. is one of example of researcher that studies on influence of laser welding parameters on weld geometry of buttwelded joints by using different material than silicon material, which is Duplex stainless steel, it proves that laser welding through extremely fast heat dissipation increases the ferrite content in the welded joint, reducing the corrosion resistance of the weld [7].

Numerous laser beam machining works as described previous are focusing on the laser wavelength of visible and near infrared range. In this paper, we report the fabrication of micro-grooves on silicon material by using nanosecond pulsed laser with ultraviolet (UV) laser wavelength of 248nm. Influence of laser processing parameters such as laser pulses energies, scanning speed and pulse repetition rate on the micro grooves quality were discussed. Characteristics of the surface around the micro grooves and its relation to molten area formation were analysed.

Figure 1. Schematic illustration on laser-silicon interaction
2. Experimental details

2.1. Laser irradiation experimental setup

Figure 2 shows a rapid X250 laser microfabrication equipment used in this experiment. Laser irradiation wavelength of 248nm and pulse repetition rate of 100Hz to 300Hz were used. Spot diameter was set 30µm by adjusting the focal length. This experiment was carried out to investigate the influence of laser pulse energies, laser wavelength and scanning speed on the laser-induced molten area on silicon material. Figure 3 shows the schematic illustration of laser irradiation experimental setup. The laser beam was delivered from the laser source by collimator and bending mirror before being focused on the specimen by using focusing lens. To avoid the back reflection of incident laser beam, the head of the lens was adjusted 10° to the perpendicular axis of the stage. The x-y-z stage was used for controlling the scanning speed.

Figure 2. Rapid X250 laser machine

Figure 3. Schematic illustration of laser irradiation experimental setup.

2.2. Specimen preparation

P-type monocrystalline silicon with 0.5 mm thickness is used as the specimen. Figure 4 shows the illustration of silicon specimen that has been cut by using silicon diamond cutting machine into rectangular size of 20mm x 20mm. After cutting process, surface of the silicon was cleaned by using alcohol to remove dust and contamination.

Figure 4. Sample preparation
3. Result and discussion

3.1. Effect of pulse energy on surface of micro grooves

Figure 5 shows the optical microphotographs of the silicon surface after UV laser beam was irradiated on the work piece for various pulse energies with 200 Hz pulse repetition rates. Scanning speed, $v$ is fixed at 2.5mm/s. It was observed that laser-induced molten area start to become visible at pulse energy of 13 mJ. At this point, energy density or fluence value is 5.2 J/cm² which are consistent with the ablation threshold reported for silicon material [8]. On the other hand, micro grooves line can be clearly observed starting at pulse energy of 14 mJ. It is seen from the figure that the width of the groove line become wider with increasing pulse energy. Moreover, heat affected zone (HAZ) can be found at 15 mJ and it became obvious at higher pulse energies. This phenomenon indicates that higher pulse energies resulted in higher amount of absorbed laser energy at the focal area. This huge amount of energy could rise the temperature rapidly as heat was conducted in to the lattice, and excessive heat input might lead to larger HAZ area around the groove lines in width direction. Therefore, it is necessary to control the heat input precisely, because large HAZ area is not desirable because it might deteriorate microstructure around the groove.

3.2. Effect of pulse repetition rate on surface of micro grooves

It is well known that the number of laser shot influence accumulated energy at the irradiated area. If the number of laser shot was higher, the amount of energy absorbed around the focal area will become greater. Number of laser shot was varied by controlling the pulse repetition rate and scanning speed. In this section, effect of pulse repetition rate on the surface is discussed. Figure 6. shows the microphotographs of the laser-irradiated silicon surface for various pulse repetition rate with pulse laser energy and scanning speed of 15 mJ and 2.5 mm/s respectively. As can be seen from the figure, molten area appearance around the micro groove line was kept stable at 100 Hz than that at higher pulse repetition rate, where HAZ can be observed along the micro grooves line. Moreover, molten splash or spatter could be observed at 300 Hz. It is considered that large amount accumulated energy has increased the temperature above at least the melting point of silicon to cause molten splash. Therefore, proper selection of pulse repetition rate is necessary to control the heat input at the focal area.

![Figure 5. Effect of pulse energy at 200Hz](image)

![Figure 6. Effect of pulse repetition rate on surface of micro grooves](image)
Figure 6. Effect of pulse repetition rate

Figure 7. Effect of scanning speed

3.3. Effect of scanning speed on surface of micro grooves

As mention in the previous section, laser scanning speed influence the number of laser shot at focal area. Also, it is understand that the higher the number of laser shot, amount of energy absorbed will become greater. In this section, effect of scanning speed on the surface of micro-grooves will be observed. Figure 7. shows optical micrographs of silicon surface at various scanning speed. Laser pulse energy was kept constant at 16mJ. It is seen from the figure that HAZ formation can be noticed at slowest scanning speed condition of 2.5mm/s. At slower scanning speed, large amount of energy can be absorbed due to longer exposure time of laser irradiation and number of laser at the irradiated spot. Thus, more energy or heat diffuse out of the focal area to lattice and increase its temperature. Meanwhile, as the speed increase, physical appearance changes on the surfaces is not significantly observed except for the gap size between two laser spot become bigger.
Stable molten area appearance at the surface might lead high quality of micro grooves. In contrast, HAZ formation around the surfaces might deteriorate microstructure nearby, which is not desirable in microfabrication of silicon wafer. Reducing the microstructural damage due to heat and thermo-mechanical stress is useful in minimization of micro-products. Therefore, proper selection of the lasing parameters was necessary in order to obtain high quality micro grooves on silicon material by UV laser. In addition, the advantages of the technique such as no need for post processing and capability of space selective machining have made it unique for future development of high precision technique of microfabrication of silicon wafer.

4. Conclusion
Micro-grooving on silicon was experimentally investigated and the effects of lasing parameters such as pulse energy, repetition rate and scanning speed were determined. The main conclusion that can be made from this experiment are as follows:

a) The width of the micro grooves become wider with increasing laser pulse energy when ultraviolet laser was irradiated on silicon material.

b) Heat affected zone (HAZ) can be found at the surface of micro groove line at high pulse energy, high pulse repetition rate and lower scanning speed irradiation condition.

c) Proper selection of lasing parameters of pulse energy, pulse repetition rate and scanning speed is necessary in order to obtain high quality micro-grooves.

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