Evaluation of molten area in micro-welding of monocrystalline silicon and glass

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Abstract. Characteristics of the molten area in micro-welding of monocrystalline silicon and glass are described. In this study, 4 types of laser beam, which are nanosecond pulsed laser and picosecond pulsed laser of 532 nm and 1064 nm in wavelength were used for joining monocrystalline silicon and glass. Influence of wavelength and pulse duration on micro-welding of monocrystalline silicon and glass was experimentally investigated under the same spot diameter, and the molten area of monocrystalline silicon and glass was characterized. A splash area of molten silicon with 532 nm wavelength was wider than that with 1064 nm in a nanosecond pulse laser. However, its splash area of molten silicon with 1064 nm changed drastically at certain pulse energy of 11 μJ in a nanosecond pulse laser. On the other hand, 12.5 ps pulsed laser still kept a stable molten area appearance even at pulse energy of 11 μJ. A splash area of molten silicon around the weld bead line was obvious in the nanosecond pulsed laser. On the other hand, there was no remarkable molten splash around the weld bead line in the picosecond pulsed laser. It is concluded that the combination of picosecond pulse duration and infrared wavelength leads to a stable molten area appearance of the weld bead.

1. Introduction
Micro electro mechanical systems (MEMS) devices are miniaturized components that may have mechanical or chemical features and microelectronic circuitry for sensor and actuator applications. In many of these devices, monocrystalline silicon and glass have been widely used as the material combination. For instance, glass has been used to cover silicon base sensor as a protection in MEMS packaging applications. Moreover, MEMS sensor devices require the environment to be maintained at a specific pressure to preserve the damping characteristics of the seismic mass. For this purpose, a proper and good quality sealing between silicon and glass has become an important issue in MEMS packaging technology.

In microfabrication technology, anodic bonding has become the most commonly used technique for joining of silicon and glass because of its high geometric accuracy and low bonding temperature [3-4]. However, some limitations such as longer processing time and requirement for wide flat surface have become restrictions of this method. Furthermore, high electrical field produced during the process might lead to a damage of microelectronics.

On the other hand, a micro-joining method such as the use of laser processing method has been proposed to overcome these limitations [5-7]. Laser micro-welding with its unique characteristic of space selective joining method has the ability of localized heating on materials. Reducing the
microstructural damage due to heat and thermos-mechanical stress is useful to perform the minimization of micro-products. Laser processing has not been practically used as the joining method of monocrystalline silicon and glass in MEMS fabrications, but the possibility to implement this micro-joining technique has been successfully reported. Several attempts by utilizing a nanosecond pulsed laser have been done, but the selective laser welding performances of silicon and glass were behind those of anodic bonding [8]. Moreover, recently, an ultrashort pulsed laser with high pulse repetition rate could provide a new technique for a fusion welding of glass and glass [9-10], and this fusion welding technique can also be applied for joining of glass and silicon. Studies on micro-joining of silicon and glass by using a femtosecond laser pulses have been published [11], and it is reported that filament occurs inside the glass plate corresponding to the high intensity femtosecond pulsed laser has become the reason for the lack of energy absorption in the silicon substrate. Picosecond pulsed laser which the laser intensity is below the threshold of multiphoton ionization (MPI) of glass [12], thus permitted more energy to be absorbed at the silicon substrate under slightly weak focusing conditions were introduced to overcome this problem. It has been reported the welding performance of picosecond pulsed laser particularly on the joint strength was higher than the one in anodic bonding method [13]. However, all these reports on micro welding of monocrystalline silicon and glass discussed the laser-matter interaction insufficiently.

In this study, 4 types of laser beam, which are nanosecond pulsed laser and picosecond pulsed laser with 532 nm and 1064 nm in wavelength were used for joining monocrystalline silicon and glass. Influence of the processing parameters on micro-welding of monocrystalline silicon and glass was experimentally investigated, and characteristics of the molten area were observed.

2. Experimental methods

A laser beam was focused to the specimens by a f-theta lens of 100 mm in focal length. Laser scanning was carried out by a Galvano scanner to achieve the high-speed laser scanning. The spot diameter was approximately 19 µm. Laser irradiation experiment was carried out for two specimen setup conditions. The specimen in first setup condition involved only the monocrystalline silicon, and the second setup condition was for monocrystalline silicon and glass as shown in Fig. 1. In the second setup condition, surfaces of silicon and glass were carefully cleaned to provide optical contact, and both monocrystalline silicon and glass were set in tight contact to avoid clearance. A laser beam was irradiated on the optical contact area from the glass plate side under various processing conditions, and the weld bead was created. The top surfaces of the weld regions were observed using scanning electron microscope (SEM), and its characteristics were discussed. Table 1 shows the material properties of the specimens. P-type monocrystalline silicon (100) with 0.675 mm thickness and its counterpart glass material with 1.1 mm thickness of borosilicate glass (Schott, D263) were used as the joint specimens.

![Figure 1. Laser irradiation experiment for two setup conditions of specimen](image-url)
3. Results and discussion

3.1 Laser irradiation on monocrystalline silicon

The band gap of transparent material such as glass is typically several times higher than the incident photon energy. Therefore, any absorption in the glass plate only occurs, when the intensity is high enough through multiphoton ionization. It is assumed that the laser intensity of picosecond laser is below the threshold of multiphoton ionization of glass under this experimental setup, and thereby the laser energy was firstly absorbed on the monocrystalline silicon substrate in micro-welding of silicon and glass. For this reason, it is important to have a better understanding of the characteristic of laser irradiated monocrystalline silicon. In this section, effect of wavelength on the molten area appearance of monocrystalline silicon will be discussed, and the glass plate was not used.

Figure 2 shows the microphotographs of molten area appearance in an individual irradiation spot of laser irradiated monocrystalline silicon for various pulse energies with 532 nm and 1064 nm wavelength. Nanosecond pulse lasers were used for the comparison of the wavelength. As can be seen from the figure, the molten area becomes wider with increasing the pulse energy. Moreover, molten splash could be observed at low pulse energy of 5 μJ in the case of 532 nm wavelength, while for 1064 nm wavelength molten splash was observed at high pulse energy of 16 μJ. This phenomenon indicates that temperature increased above the melting point of monocrystalline silicon at low pulse energy in the case of 532 nm wavelength, while 1064 nm wavelength required a high pulse energy. When the laser beam with low pulse energy was focused on the monocrystalline silicon, high absorption rate of 532 nm wavelength resulted in more energy absorption in monocrystalline silicon compared with that in the case of 1064 nm wavelength.

### Table 1 Properties of monocrystalline silicon and borosilicate glass D263

| Properties                  | Silicon | D263 |
|-----------------------------|---------|------|
| Density ρ [g/cm³]           | 2.30    | 2.51 |
| Specific heat c[J/(kg · K)]  | 680     | 820  |
| Melting temperature θ_m [K] | 1970    | 1324 |
| Coefficient of thermal expansion CTE [1/K] | $3.2 \times 10^{-6}$ | $7.2 \times 10^{-6}$ |

Figure 2 Effect of wavelength on molten area appearance of monocrystalline silicon in nanosecond laser

(a) λ = 532 nm
(b) λ = 1064 nm
3.2 Laser irradiation on monocrystalline silicon and glass

Figure 3 shows the microphotographs of molten area appearance at the interface of monocrystalline silicon and glass in an individual irradiation spot observed from the glass plate side. Nanosecond and picosecond pulse lasers with 1064 nm wavelength were used for the comparison. Laser beams with pulse energies of 9 μJ and 10 μJ were irradiated to the interface of monocrystalline silicon and glass from the glass plate side. Effect of pulse duration on the molten area appearance in different pulse energies is discussed. It can be seen from the figure that molten area increases with the increasing pulse energy. Stable molten area appearance was observed in laser irradiated specimen by picosecond laser. On the other hand, recast layer of silicon material could be observed at the outer region around the irradiated area in the case of nanosecond laser, and melting and resolidification processes were occurred.

Figure 4 shows microphotographs of the molten area, when the pulse energy increased up to 11 μJ. Laser wavelength of 532 nm and 1064 nm were used for the comparison. Molten area appearance in nanosecond pulse laser for both wavelength condition changed drastically at pulse energy of 11 μJ, where splash area of the molten silicon was remarkable around the irradiated area. This phenomenon indicates that temperature rose above the melting point of monocrystalline silicon at least. On the other hand, picosecond laser still kept a stable molten area appearance even at pulse energy of 11 μJ.
Therefore, it is considered that the silicon substrate was heated mildly by a picosecond laser.

Figure 5 shows microphotographs of the molten area appearance for effect of wavelength in nanosecond laser. A splash area of molten silicon with 532 nm wavelengths is wider than that with 1064 nm wavelength. It is assumed that the shallow absorption area has contributed to increasing size of the molten area. Moreover, molten area appearance was kept stable at 532 nm wavelength even at higher pulse energy of 10 μJ. This condition was different from the molten area appearance characteristics by laser irradiation for only on monocrystalline silicon (see Fig. 2), where molten splash could be observed at lower pulse energy. It is considered that glass plate on the top of silicon substrate has influence on the generation of the molten splash. When glass plate was placed to cover silicon substrate with tight contact, compressive force between the joint specimens acts to increase the pressure at the interface of monocrystalline silicon and glass. Hence, the molten area appearance was kept stable even at high pulse energy.

Figure 6 shows the weld beads created at high overlap rate. It can be observed that molten splash around the weld bead line was obvious in the case of nanosecond laser. On the other hand, no remarkable molten splash was found around the weld bead line in the case of picosecond laser, which indicates that the substrate was heated mildly. It is considered that the shorter pulse length of picosecond pulse duration resulted in higher power densities, which lead to rapid heating and earlier evaporation of the monocrystalline silicon compared with that in nanosecond pulse laser. This explains the amount of the molten splash reduced after the end of the laser pulses by picosecond laser.

![Figure 5](image)

**Figure 5** Effect of wavelength on molten area appearance of monocrystalline silicon and glass in nanosecond laser

![Figure 6](image)

**Figure 6** Weld bead created at high overlap rate
Stable molten area appearance might lead to higher joint strength between monocrystalline silicon and glass. In contrast, formation of the molten splash might generate the gap between the interfaces of joint material, which will reduce the joint strength. Therefore, proper selection of processing parameters, such as the combination of picosecond laser and near infrared wavelength was necessary in order to obtain good quality of the joint material. In addition, the advantages of the technique such as no need for pre- and post- heating, high joining rate and capability for space selective welding have made it unique for future development of high efficiency and reliable technique of micro joining of silicon and glass.

4. Conclusions
Micro-welding of monocrystalline silicon and glass was experimentally investigated, and effects of the wavelength and pulse duration were clarified. The main conclusions obtained from this study are as follows:
(1) Area of molten splash with 532 nm wavelength was wider than that with 1064 nm in nanosecond pulsed laser.
(2) Moten splash appeared suddenly at more than a boundary pulse energy in nanosecond pulsed laser. On the other hand, picosecond pulse laser still kept a stable molten area appearance even at the same boundary pulse energy, and a stable molten behaviour could be obtained even at high overlap rate condition.
(3) The combination of picosecond and infrared wavelength showed stable molten area appearance in the micro-welding of monocrystalline silicon and glass.

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