Fast fabrication of silicon based microstructures using 355 nm UV laser

C. T. Pan*1, Y. M. Hwang1 and C. W. Hsieh1

In this study, a 355 nm UV Nd:YAG laser is used to process silicon wafers. In order to obtain microstructures with high aspect ratio, a dual prism optical system is set up to control the cutting linewidth of the UV laser beam. During the laser beam propagation through the prisms, the two prisms are rotated with the same angular velocity, which results in the focal spot of the laser beam moving in a circular path on the silicon substrates. When the laser beam moves relative to the holder (workstation), a laser cutting process can be carried out. With this laser system, the cutting linewidth is controllable ranging from 10 μm to 1 mm by adjusting the initial phase difference in the two prisms. The experimental results show that arbitrary shaped silicon based microstructures with high aspect ratio can be fabricated by this 355 nm UV laser system, and the aspect ratio over 10 can be obtained.

Keywords: Prism, UV, Laser, Silicon, High aspect ratio, Microstructures

Introduction

Micromanufacturing technology includes the silicon based, LIGA based and precision micromachining process. In the microelectronics and microelectromechanical systems (MEMS), silicon based and LIGA (from the German for lithography/electroforming/moulding) based technology are widely applied to fabricate microstructures with high aspect ratio through photolithography, etching process and thin film deposition, etc.

Silicon based process can be divided into two categories, i.e. surface micromachining and bulk micromachining. The former method is used to process silicon wafers by lithography and etching process. Lüdtke et al.1 applied the dry etching process to obtain microstructures with feature size of 4 μm and aspect ratio of 25 in 2000. Berte et al.2 utilised anisotropic dry etching process with CF gas passivation to protect the sidewall of the kerf, and aspect ratio of 25 was demonstrated in 2002. Although microstructures with high aspect ratio can also be manufactured by the wet etching process, most of the etchants are toxic. The (111) crystal orientation plane of silicon wafers is more closely packed than the (100) plane and, therefore, for any given etchants, the etching rate is expected to be slower. Because of the different etching rates, therefore, complicated arbitrary shaped microstructures cannot be made. The dry etching process can avoid the crystal issue, but it is too expensive and time consuming. Therefore, laser direct writing method can be a solution to the above problems.

Laser micromachining is a useful and versatile tool for rapid prototyping, small scale production and preform manufacturing. A laser pulse with short time duration and high pulse repetition rate is suitable for accurate and fast processes. The excimer laser was used to produce the ink jet nozzle.3 Reduction in the diameter of the ink jet nozzle holes from 60 to 20 μm by laser drilling was reported.4 Because of the increasing requirement for improved printing resolution, ink jet holes with high aspect ratio are needed. There are several types of UV lasers suitable for micromachining such as the excimer laser and the frequency tripled Q-switched Nd:YAG laser. The excimer laser is well known for its ability to machine microscale features. Its process is dependent on the material property, laser absorption rate, laser fluence and pulse number. Usually the high magnifying lens system for 248 nm UV light is too expensive and vulnerable to high laser fluence. Therefore, most of its applications were limited to processing polymeric materials.5 Arnold et al.6 processed AZ4620 and PMMA with an ArF excimer laser to fabricate microstructures with aspect ratios up to 10. On the other hand, Lawes et al.7 used a KrF excimer laser for the laser-LIGA process. In addition, the excimer laser has been applied to process non-polymeric IC materials. Pfleging et al.8 used a KrF excimer laser to machine poly-membrane of Fe0.6Co0.4/SiO2, Tb0.4Fe0.6Fe0.5Co0.5 and SiNx. They found that the key point to the process was determined by the surface properties of the materials. Fabrication of diffractive optical elements (DOEs) using an ArF excimer laser direct ablation of aluminium silicate and soda lime glass was reported by Winfield et al.9 In 2000, Govorkov et al.10 drilled holes on steel sheets using a Nd:YAG laser. The average power and pulse energy of the laser are about 3–5 W.

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Published by Maney on behalf of the Institute
Received 27 October 2004; accepted 30 March 2005
DOI 10.1179/174328405X46141
and 0.3–0.8 mJ, respectively. A diameter of 100 μm was reported to have been achieved. They found this method fast and accurate. Using a Q-switched Nd:YAG laser to micromachine conductor patterns on an insulating substrates was realised by Kripesh et al.,11 which serve as a passive component in many microelectronic applications.

Although lasers have been widely applied to process a variety of metallic materials, little research has been reported on processing silicon wafers for applications to IC and MEMS devices. Silicon wafer is a brittle material with a crystal structure and a high vapourisation temperature. However, these features do not cause a problem in laser micromachining. In 1996, Müllenborn et al.12 studied laser micromachining of silicon for microsystems. A process based on an argon laser, which can induce melting of silicon in a chlorine atmosphere was presented to directly fabricate arbitrary shaped microstructures on silicon substrates. However, the argon laser is not suitable for industrial purposes as a result of its low power limitation. SYNOVA Corporation in Switzerland developed a coaxial laser water jet system to cut silicon in order to reduce the thermal damage caused by conventional photothermal lasers. A system for drilling or cutting holes was presented by Leighton13 for an optical laser. It provides an independent control of the beam angle and displacement from the system axis by adjusting the distance of the pair of rotating prisms.

In this study, a 355 nm UV Nd:YAG laser is used to process silicon wafers directly. The cutting linewidth of the laser beam is controllable by adjusting dual prism optical systems, which causes the laser beam to move in a circular path on the silicon substrate. When the silicon substrate moves with respect to a laser beam, the cutting process can be carried out. The cutting linewidth ranges from 10 μm to 1 mm. In the case of a huge material removal rate being required, the cutting linewidth can be set at 1 mm to reduce the processing time. On the other hand, when high resolution and accurate patterns are needed, the cutting linewidth can be adjusted to 10 μm. With this UV laser system, arbitrary shaped silicon based microstructures with high aspect ratio can be obtained.

**Fabrication process**

**Laser system set-up**

The UV laser system for the experiment consists of a 355 nm Nd:YAG laser, a Q-switched controller, a 4 in holder for the workpiece made of a porous ceramic vacuum chuck, a cooler and a programmable computer. The laser beam mode is TEM_{00} with M^{2} < 1. The average power and pulse energy are 8 W and 0.8 mJ at 10 kHz, respectively. The travel distance and resolution of the holder are X (105 mm ± 1 μm), Y (200 mm ± 1 μm), Z (40 mm ± 2.5 μm), and θ (360° ± 0.005°), respectively. The system layout is 900 × 960 × 1800 mm in volume. The tool contour of the laser beam can be designed using AutoCad software to carry out the three-dimensional fabrication process.

In this study, processing parameters include laser power, repetition rate, holder moving velocity and prism rotating angular velocity as listed in Table 1, i.e. the power ranges from 2.5 to 5.5 W, the repetition rate ranges from 10 to 20 kHz, the holder moving velocity ranges from 1.5 to 5.0 mm s⁻¹ and the prism rotating angular velocity ranges from 1000 to 1500 rev min⁻¹, respectively.

**Dual prism optical system**

In this study, a dual prism optical system was set up as schematically shown in Fig. 1. The two prisms, with a difference in phase angles, rotate at the same angular velocity ω during cutting process. When prism 2 rotates from 0° to 180° relative to prism 1 (see Fig. 1), the propagation of the laser beam can be refracted to the opposite position. Therefore, when the two prisms rotate at a constant angular velocity, the optical path of the laser beam will move in a circular path on the substrate.

The diameter D of the circular path is used as the cutting linewidth during the laser process. The cutting linewidth can be changed by adjusting the initial phase of the dual prism optical systems. According to Snell’s Law, light is refracted when it passes through a prism to the air. So the diameter of the circular path is changed, by which the cutting linewidth can be changed. Figure 1 also shows that θ_1 > θ_2 > θ_3 > θ_4 > θ_5 and D_1 > D_2 > D_3 > D_4 > D_5 can be controlled by adjusting the phase difference in the prisms. As a result, the largest diameter

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**Table 1** Processing parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser beam power, W</td>
<td>3.0, 4.5, 5.5</td>
</tr>
<tr>
<td>Repetition rate, kHz</td>
<td>10, 15, 20</td>
</tr>
<tr>
<td>Holder moving velocity, mm s⁻¹</td>
<td>1.5, 2.0, 3.5, 5.0</td>
</tr>
<tr>
<td>Prism angular velocity, rev min⁻¹</td>
<td>1000, 1500</td>
</tr>
<tr>
<td>Wafer thickness, μm</td>
<td>50, 90, 140, 190, 525</td>
</tr>
</tbody>
</table>
of laser path used as the cutting linewidth can be achieved in the case of Fig. 1a and the smallest one in the case of Fig. 1c.

**Silicon materials**

Four-inch silicon wafers with a variety of thicknesses were used for 355 nm UV laser process. In the study, a wafer of 250 µm in thickness was thinned down to 50 µm, 90 µm, 140 µm, 190 µm, respectively, by KOH anisotropic wet etching. The wafers were then cleaned in ethanol and acetone to remove surface residue particles because surface contaminants can affect the accuracy of the process. 

Besides, prior to the laser cutting process, two wafers with and without polymeric material coating were prepared, respectively. Later, the effect of polymeric materials on cleaning laser debris formation was discussed.

**Results and discussion**

In this study, processing parameters include laser power, repetition rate, holder moving velocity and prism rotating angular velocity. Normally the laser power is adjusted based on the spacing of the microstructure pattern to avoid serious formation of debris and redeposition in the denser microstructure area. The repetition rate also should be adjusted properly to obtain a smooth profile. The holder moving velocity will affect the morphology of the kerf directly. Besides, in order to avoid the inaccuracy caused by vibration from mechanism of laser system, the prism rotating angular velocity is set at a certain constant value that does not induce the resonance with the laser system.

The propagating direction of the laser beam does not move along the straight line as illustrated in Fig. 1. When the laser beam moves relative to the wafer holder, the spot of the focal laser beam on the substrate can be guided in a circular motion as shown in Fig. 2. After laser processing, the kerf with columnar ripples can be observed. The motion relationship between the laser beam and the holder can be expressed as follows

\[
S = \begin{cases} 
  x = r \cos(\omega t) + vt \\
  y = r \sin(\omega t) 
\end{cases} \tag{1}
\]

where \( S \) is the path of the focal laser spot on the substrate, expressed as \( x \) and \( y \) direction, \( r \) is the radius of the circular path of the laser spot and \( \omega \) is the holder moving velocity.

From equation (1), the cutting path can be predicted. The simulation results are shown in Fig. 2b and c. Figure 2b has a slower holder moving velocity than Fig. 2c. It is worth noticing that when the holder moves more slowly, the kerf edge becomes smoother. The formation of the columnar ripple is less obvious. On the other hand, when the holder moves at a faster velocity, more columnar ripples can be observed clearly in the kerf.

Prior to the laser cutting, an appropriate initial phase difference in two prisms was set up. During the laser process, the dual prism system rotates at a constant angular speed. After laser processing the silicon wafers, the silicon based microstructures were examined using a scanning electron microscope (SEM).

Figure 3 shows a comparison between the pattern designed by AutoCAD software and experimental results. The black line in Fig. 3a with the variable linewidth will be ablated away efficiently by adjusting the cutting linewidth of the laser beam. Later, the cutting linewidths ranging from 1 mm to 10 µm were tuned properly to process silicon wafers. The experimental result is shown in Fig. 3b.

Figure 4 shows the experimental results of the laser micromachining. Figure 4a illustrates that the diameter of the hole is 150 µm by laser cutting of 525 µm thick silicon wafers. The processing parameters include that laser power is 3.0 W, repetition rate is 10 kHz, holder moving velocity is 1.5 mm s\(^{-1}\), and prism rotating angular velocity is 1000 rev min\(^{-1}\), respectively. Figure 4b shows the result of laser cutting of 190 µm thick silicon wafers. The processing parameter of holder moving velocity changes to 3.0 mm s\(^{-1}\) from 1.5 mm s\(^{-1}\). Other parameters are all kept unchanged. It is worth noticing that when the holder moving velocity is increasing, the columnar ripple can be observed around the sidewall as shown in Fig. 4b.
Figure 5a shows the columnar ripple and debris formation on the cutting sidewall. The main processing parameters are: laser power, 4.5 W; repetition rate, 15 kHz; holder moving velocity, 5.0 mm s\(^{-1}\); and prism rotating angular velocity, 1500 rev min\(^{-1}\). By decreasing the holder moving velocity to 2 mm s\(^{-1}\) and keeping the other parameters the same, the columnar ripple can be improved effectively. The improved result is shown in Fig. 5b. There are many factors that cause these problems such as the laser beam power, the repetition rate, the holder moving velocity, the phase difference in prism and the angular velocity of the dual prism systems. When a better cutting quality is required, optimal processing parameters can be tuned out.

Figure 6a is a close-up view of Fig. 5a. It shows that there are many columnar ripple and debris microstructures around the cutting sidewall, which are redeposited and resolidified during the cutting process. In a pulsed beam laser process, a discontinuous laser beam was used to process silicon wafers. It results in irregular formations on the kerf sidewall surface. This is because the ablated particles or segments cause the issue of redeposition and resolidification on the silicon substrates, especially around the kerf. There is a need to explain this complicated problem.\(^1\) When the laser beam evaporates, the material leads to the formation of a shock wave and three-dimensional pressure distributions. This pressure gradient results in the ejection of the molten material and forms debris.

In this study, an effective method to reduce the debris deposition was presented. Prior to the laser processing, the wafer was coated with a polymeric thin film. During laser processing, the debris is deposited on the surface of polymeric thin film rather than on silicon wafers. When the process was finished, the polymeric thin film was etched off without damaging the underlying microstructures, by which method the debris can be washed away effectively. Figures 4b, 6b, c and 7 show the results using an efficient method to significantly improve the quality of the surface and sidewall.

In the experiment, wafers of various thicknesses ranging from 50 to 525 \(\mu\)m were prepared for the laser
cutting process. The result shows that the 50 mm thick wafer is more vulnerable to cracking. This is caused by the thermal stress induced by high energy thermal shock. Figure 7 shows the SEM photography of the experimental results of the laser processing of a 525 mm thick silicon wafer. The processing parameters include laser power of 5.5 W, a repetition rate of 20 kHz, holder moving velocity of 3.5 m ms⁻¹, and prism rotating angular velocity of 1500 rev min⁻¹. This result shows that the 355 nm UV laser systems can fabricate arbitrary shaped silicon based microstructures successfully with a size of less than 50 μm. Microstructures with a high aspect ratio of up to 10 can therefore be obtained. Although the silicon based microstructures with such a high aspect ratio has been fabricated successfully by the time consuming and expensive inductively coupled plasma (ICP) dry etching process, the are few reports on any UV laser processes in the literature. The preliminary result reveals that to fabricate arbitrary silicon based microstructures of high aspect ratio, 355 nm UV laser systems are a good choice.

Conclusion

In this study, a 355 nm UV Nd:YAG laser was used to process silicon wafers. To obtain microstructures of high aspect ratio and better cutting quality, laser processing parameters were realised. In the study, the cutting linewidth ranging from 10 μm to 1 mm was used to process silicon wafers. Laser micromachining of silicon wafers provides advantages such that it can be used regardless of the crystal orientation of silicon wafers and its fast fabrication for prototyping. The experimental results show that arbitrary shaped silicon based microstructures can be fabricated by the laser beam direct writing method. With these laser systems, an aspect ratio of over 10 can be achieved.

Acknowledgement

The authors would like to thank Dr Tung-Chuan Wu and Dr Min-Chan Chou at MIRL of ITRI in Taiwan for their guidance, and the National Science Council (NSC) for their financial support to the project (Grant Nos.: NSC93–2622–E–110–003–CC3, NSC93–2212–E–110–028 and NSC93–2212–E–110–029).

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