Profile control of a borosilicate-glass groove formed by deep reactive ion etching

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Abstract

We investigated the deep reactive ion etching (DRIE) of borosilicate glass and profile control of an etched groove. We carried out DRIE using an anodically bonded silicon wafer as an etching mask. We controlled the glass-groove profile, namely improving its sidewall angle, by removing an excessive polymer film produced by carbon-fluoride etching gases during DRIE. We experimentally compared two fabrication processes for effective removal of the polymer film: (1) DRIE with the addition of argon (Ar) to the etching gases and (2) a novel combined process in which DRIE and subsequent ultrasonic cleaning in DI water were alternately carried out. Both processes improved the sidewall angle, reaching 85° independent of the mask-opening width. The results showed that the processes remove the excessive polymer film on sidewalls. Accordingly, the processes are an effective way to control the groove profile of borosilicate glass.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Borosilicate glass, e.g. Coring 7740 Pyrex®, Hoya SD-2® and Asahi Techno Glass SW-3®, is a common material for micro-electro-mechanical system (MEMS) devices. It is typically used for fluidic devices and wafer-level packaging (WLP) of an inertial sensor as a cap wafer with a cavity, in which the sensor is hermetically sealed. The borosilicate-glass cap wafer used for WLP also has a through-hole for feedthrough, which is conventionally formed by ultrasonic drilling or sandblasting. However, these technologies do not provide fabrication techniques that are as precise as chemical etching because they are based on machining.

Li et al [1] first presented their research on the deep reactive ion etching (DRIE) of Pyrex®, but not many studies have successfully used anisotropic deep dry etching of borosilicate glass, in contrast with silicon [2–4] and silica [5, 6]. The reason for this difference is largely due to the quite low selectivity of the etching mask used for borosilicate glass. The conventional etching masks are resist, chromium, tungsten silicide, nickel and poly-silicon. The highest selectivity of a mask, e.g. tungsten silicide and poly-silicon, is around 20. This means that the necessary thickness of the mask film is calculated as 15 μm when a 300 μm deep glass groove is formed. However, other problems of internal and residual stress of the mask film will occur if a quite thick mask film is formed. That is why the stress has to be strictly controlled to successfully deposit a 15 μm thick mask film. Furthermore, the mask needs to be precisely etched. It is quite difficult to successfully fabricate precisely patterned stress-free masks. These are the reasons why a borosilicate glass cap wafer with a deep cavity and a through-hole fabricated by anisotropic etching has not been used for WLP.

The aforementioned low selectivity of an etching mask for the DRIE of borosilicate glass limits the groove depth. A novel fabrication process, which uses an anodically bonded silicon wafer as an etching mask, reportedly overcomes the low selectivity problem and achieves a much deeper etching [7]. Additionally, the process provides the advantage that stress control is unnecessary because the anodically bonded silicon wafer does not have residual stress inside. We used carbon-fluoride gases, i.e. C₄F₈ and CHF₃, as etching gases. However, the drawbacks of this process were that the sidewall...
angle of the etched groove did not reach more than \(80^\circ\), and that it depended on the mask-opening width. This was due to a thick polymer film produced by carbon-fluoride plasma during DRIE. The film was thickly deposited on the sidewalls and protected them against the plasma. DRIE needs to remove the excess polymer film as well as etch to control the etched profile and to improve the sidewall angle.

We investigated two fabrication processes for controlling the etching profile, namely for effectively removing the excess polymer film. The obtained experimental results are compared with previous ones [7].

2. Etching equipment and conditions

We used NE500 made by ULVAC Inc. as the dry-etching equipment for the experiment. A schematic of the equipment is shown in figure 1, and the DRIE conditions are listed in table 1. The equipment consists of a setting room, where a 4 inch wafer is placed, and an etching chamber, where inductively coupled plasma is generated. An electrostatic chuck fixed the etching wafer. An electrostatic chuck fixed the etching wafer. We introduced \(\text{C}_4\text{F}_8\), \(\text{CHF}_3\) and argon (Ar) gases into the chamber for the etching. Oxygen \((\text{O}_2)\) gas was used for plasma ashing for cleaning and helium \((\text{He})\) gas was used to cool the wafer. The variable valve automatically controlled the pressure inside the etching chamber during the DRIE of borosilicate glass, meaning that the valve kept the etching pressure constant. The maximum antenna power was 1 kW and the maximum bias power was 0.5 kW. In the experiment, the bias and antenna power were fixed at 400 and 600 W, respectively. In addition, the substrate temperature during DRIE was kept as low as \(-20^\circ\text{C}\) by a chiller unit.

3. DRIE of borosilicate glass

Figure 2 illustrates the fabrication process for the DRIE of borosilicate glass [7]. The process involved using a 200 \(\mu\text{m}\) thick silicon wafer as an etching mask. The silicon wafer was anodically bonded to a borosilicate-glass wafer. In step (a), a 200 \(\mu\text{m}\) deep trench groove was formed on a 300 \(\mu\text{m}\) thick (1 0 0)-oriented silicon wafer. Aluminum and silicon-dioxide films were used as an etching mask for the DRIE of silicon. We used the A601E DRIE etcher made by Alcatel Vacuum Technology. In step (b), the DRIE mask was removed and the wafer was thermally oxidized. Subsequently, a silicon-dioxide film on the back surface was removed. In step (c), a silicon through-hole was formed by etching the wafer with a tetramethylammonium hydroxide (TMAH) solution. In step (d), the silicon wafer was anodically bonded to a borosilicate-glass wafer in the air. We used a Pyrex\textsuperscript{\textregistered} glass wafer as borosilicate glass. The bonding was carried out at 300 \(^\circ\text{C}\) and 300 \(\text{Vi}\text{na}\). In step (e), the DRIE of borosilicate glass was implemented using a bonded silicon mask. In step (f), the silicon mask was removed by a KOH solution.

We did not use the process in which a silicon wafer is first anodically bonded to the glass wafer and the DRIE of silicon is subsequently carried out for fabricating a silicon through-hole, because this process created micro-needles of Pyrex\textsuperscript{\textregistered} glass as shown in figure 3. To avoid these micro-needles, we used the process shown in figure 2.

4. Process for control of the groove profile

To control the glass groove profile, we implemented two fabrication processes in step (e) of figure 2. One was DRIE with Ar added to carbon-fluoride etching gases, i.e. \(\text{C}_4\text{F}_8\) and...
CHF₃ gases; the other was a novel combined process in which DRIE with a mixture of C₄F₈ and Ar gases and subsequent ultrasonic cleaning in DI water were alternately carried out. In the former process, the etching gas composition was changed compared with the previous conditions [7]. In the latter process, the wafer was cleaned by the ultrasonic cleaning bath of W-338 made by HONDA Electronics Co., Ltd after a 2.5 h DRIE. Subsequently, DRIE was carried out again after the ultrasonic cleaning. In other words, the ultrasonic cleaning was carried out every 45 µm deep etching, because the rate of DRIE was approximately 0.3 µm/min. The conditions for the ultrasonic cleaning were 300 W, 20 min and frequencies of 28, 45 and 100 kHz. These processes were repeated until the depth of the groove reached approximately 300 µm.

5. Results and discussion

Figure 4 shows a scanning electron microscope (SEM) image of a groove etched by using C₄F₈ plasma before the removal of the polymer film and the silicon mask. In addition, a typical cross-sectional profile after the removal of the silicon mask is shown in figure 5. A thick polymer film can be seen on the sidewalls of the groove in these figures, and the bottom of the etched groove was rounded. Due to heavy-ion bombardment, facet formation was observed on the silicon mask. This phenomenon can be typically observed under the DRIE conditions shown in table 1. The sidewall angle of the groove did not reach more than 80°. It was around 70° due to the polymer film produced by the C₄F₈ plasma protecting the sidewalls during DRIE.

Figure 6 shows the dependence of the measured sidewall angle on gas pressure. We carried out DRIE with etching gas composed of CHF₃, C₄F₈ and Ar. The gas-flow rates of CHF₃, C₄F₈ and Ar were 2.5, 10 and 10 sccm, respectively. The figure shows that low gas pressure is necessary for obtaining the vertical sidewall. Accordingly, we kept the pressure as low as possible during DRIE to increase the sidewall angle.

Figure 7 shows a photograph of a 4 inch borosilicate-glass wafer after DRIE. A silicon mask wafer is anodically bonded to the glass wafer. Mask openings with various widths are formed on the wafer. After the depth of the groove whose mask opening is 1.0 mm wide reached approximately 300 µm, we measured the groove profile.

Figure 8 shows the measured groove profile representing the depth and difference in width between a mask opening and an etched groove. The C₄F₈+Ar+CHF₃ data are of DRIE that was carried out with Ar gas added to C₄F₈ and CHF₃ carbon-fluoride etching gases. The C₄F₈+Ar data are the combined process. In the combined process, the DRIE gas was composed
Figure 7. Photograph of the borosilicate-glass wafer after DRIE with a bonded silicon mask.

Figure 8. Profiles of borosilicate-glass grooves etched using C4F8 plasma, C4F8+Ar+CHF3 plasma and combined process (C4F8 conditions: antenna/bias power: 600/400 W; gas pressure: 0.3 Pa; gas-flow rate: 15 sccm; C4F8+Ar+CHF3 conditions: antenna/bias power: 600/400 W; gas pressure: 0.28 Pa; gas-flow rate of C4F8, Ar and CHF3: 10, 10 and 2.5 sccm, respectively; the DRIE conditions in combined process: antenna/bias power: 600/400 W; gas pressure: 0.25 Pa; gas-flow rate of C4F8 and Ar: 10 and 10 sccm, respectively).

Figure 9. The measured sidewall angle of borosilicate-glass grooves etched using C4F8 plasma, C4F8+Ar+CHF3 plasma and combined process composed of DRIE with C4F8+Ar plasma and ultrasonic cleaning in DI water as a function of the width of the mask opening.

Figure 10. Cross-sectional SEM image of a borosilicate-glass groove etched using mixed gas composed of C4F8, Ar and CHF3 gases before the removal of the silicon mask (opening size: 1.0 mm²; depth: 300 µm).

The figure shows that the depth of the etched groove depends on the width of the mask opening. In short, the etching rate gradually increases independent of the composition of the etching gas as the width increases. This phenomenon indicates aspect-ratio-dependent etching (ARDE) or reactive ion etching (RIE) lag, which can be observed with the DRIE of silicon. Concerning the increase in width, mixing Ar with the carbon-fluoride gases caused a fairly large difference between the mask opening and the etched groove, compared with that of the C4F8 gas. This shows that the added Ar gas contributed to the physical etching and that lateral etching slightly advanced, meaning that the polymer film was effectively removed by adding Ar gas. If the physical etching rate is larger than the polymer-deposition rate, lateral etching will advance. This is because there is no protection layer on sidewalls. We think that the rate imbalance is one of the reasons why the difference in width becomes larger. However, the difference in width was kept less than 12 µm when the depth was around 300 µm. If the depth is less than 300 µm, the difference in width will be much smaller than 12 µm.

Figure 9 shows the dependence of the measured sidewall angle on the width of the mask opening. With C4F8 gas, the sidewall angle gradually increased and reached its peak at 80° as the width decreased, but with the mixed gases composed of C4F8, Ar and CHF3, the angle was approximately 80°, which was somehow independent of the width of the mask opening. When the width of the mask opening was 1.0 mm, the sidewall angle increased by approximately 8.0°. Accordingly, mixing Ar with carbon-fluoride etching gases can improve the sidewall angle. In other words, Ar gas needs to be added to control the groove profile. In addition, the combined process resulted in a sidewall angle of 85°, remarkably independent of the width. This means that the combined process leads to an outstanding improvement in the sidewall angle. To summarize, our fabrication processes can improve and control the groove profile by removing the excessive polymer film from the sidewall.

Figure 10 shows a cross-sectional view of a groove etched with a mixture of C4F8, Ar and CHF3 gases before the removal
of the silicon mask. At the bottom edge of the groove, we observed non-volatile reactants, which are thought to be Na2O. It was easier to find the reactants as the etching depth advanced. In other words, the reactants were not observed in the etched groove whose depth was less than 50 µm. It seems to be more difficult for the reactants to sputter out as the depth of the etched groove becomes larger, e.g. 300 µm.

Figure 11 shows a cross-sectional view of a groove etched with a mixture of C₄F₈, Ar and CHF₃ gases after the removal of the silicon mask, and figure 12 shows a top view of the groove. The bottom of the groove was less rounded, compared with the etching result shown in figure 5. This seems to be because the addition of Ar contributed to the removal of the excessive polymer film produced during DRIE. However, as shown in figure 12, the bottom edge was rough due to micro-masking by the non-volatile reactants. This result is not preferable from the point of view of transparency.

The DRIE results of the combined process are shown in figures 13–15. Figure 13 shows an enlarged cross-sectional view of an etched groove before the removal of the silicon mask. Figure 14 shows a perspective cross-sectional view of the etched groove fabricated by the combined process after the removal of the silicon mask by KOH etching. These figures indicate that sidewalls were not rounded but straight, compared with the previous results shown in figure 5. In addition, the sidewalls in these figures were slightly inclined off the vertical wall, but the sidewall angle obviously improved. Figure 15 shows a top view of the etched groove after the removal of the
silicon mask. The bottom surface was smoother than that in figure 12; the etched groove was still transparent. As shown in figure 14, the bottom surface was almost flat. These results indicate that the combined process can remove non-volatile reactants as well as the excessive polymer film produced during DRIE. To summarize, the combined process can fabricate an etched groove with a smoother bottom surface and almost vertical sidewalls.

Consequently, our two fabrication processes effectively contributed to removing the excessive polymer film on the sidewall, and they were useful in forming a deep groove with a sidewall angle of more than 80°.

6. Conclusion

Profile control of a borosilicate-glass groove formed using DRIE was successfully carried out by effectively removing the excess polymer film produced during DRIE. DRIE with Ar added to carbon-fluoride etching gases and a combined process composed of DRIE and ultrasonic cleaning in DI water are effective ways of removing the polymer film. We fabricated a deep groove with a maximum sidewall angle of 85°, independent of its opening width with these processes.

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