Microstructure Formation on Glass Substrates for High-productivity Fabrication of Micro-vias Using 248 nm Excimer Laser

Yasufumi Kawasuji*[1], Yasuhiro Adachi[1], Kazuhiko Moro[1], Kouji Kakizaki[1], and Masakazu Washio[2]

[1]*Gigaphoton Inc., 400 Yokokura-shinden, Oyama-shi, Tochigi 323-8558, Japan*
[2]*Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8558, Japan*

**Corresponding author's e-mail: yasufumi_kawasuji@gigaphoton.com*

High-productivity fabrication of micro-vias in glass substrates is required for post-5G high-frequency signal interposers. This paper describes the fabrication of high-quality micro-vias with a high aspect ratio by ablation using a 248 nm excimer laser. To clarify the details of the ablation process, we investigate the surface microstructure generated by excimer laser irradiation. The results indicate that laser irradiation produces a surface microstructure that enhances the absorption of laser energy.

DOI: 10.2961/jlmn.2023.02.2005

Keywords: glass, microstructure, micro-via, excimer laser, ablation

1. Introduction

Micro-via fabrication on glass is promising for producing post-5G interposer packaging substrates. Micro-vias are holes in an interposer packaging substrate to allow electrical signals and power to be transferred between each side of the substrate [1].

Single-crystal silicon has been used for conventional interposer substrates. However, silicon requires an insulating layer on the via walls due to its electrical conductivity. Furthermore, the large dielectric loss tangent for silicon means that significant signal loss occurs during high-frequency signal propagation in the interposer package.

On the other hand, glass is low in cost, has excellent insulation properties, and has a low dielectric loss tangent, which makes it very suitable for high-frequency signal propagation. Therefore, glass materials are expected to be used as interposer substrates in the future. However, there is a problem with cracking during micro-via processing due to the high brittleness of glass[2-4].

In the present study, we investigated the interaction between a 248 nm excimer laser beam and glass to achieve high-productivity micro-via fabrication.

2. Objective

Laser ablation of transparent materials such as glass is different to that of non-transparent materials such as metals, because light energy in the former case is absorbed not only at the surface but also within the bulk.

In the present study, the excimer laser pulses had a width of greater than 30 ns, which is much longer than the time required for multiphoton absorption to occur.

Based on the manufacturer's data, the non-alkali glass used in this experiment has a transmittance of approximately 5% for a thickness of 700 μm under irradiation with a 248 nm excimer laser[5]. This corresponds to an absorption coefficient of 4300 m^{-1} based on the Beer-Lambert-Bouguer law. Based on this absorption coefficient, the amount of laser energy absorbed within a depth of 1 μm from the surface is only 0.4% of the total energy, and most is transmitted through the glass. However, laser ablation occurs only at a depth of 1 to 2 μm from the surface. This phenomenon cannot be explained based on the absorbed energy calculated from the absorption coefficient. It is therefore considered that surface modification increases the amount of laser energy absorbed in the near-surface region.

In a previous experimental study, the ablation rate for long laser pulses (74 ns time-integrated square (TIS)) was found to be larger than that for short pulses (32 ns TIS), resulting in a higher drilling rate in the former case [6].

3. Experimental setup

Figure 1 shows a schematic diagram of the test setup used to micro-drill glass substrates with an excimer laser. The specifications of the excimer laser light source (GT600K, Gigaphoton Inc.) are given in Table 1. All experiments were performed in ambient air and under the same conditions expected for practical applications. The laser fluence was adjusted using an optical attenuator. The beam shape on the material surface was formed using an aperture and a lens. The experimental parameters are shown in Table 2. The pulse width of the excimer laser was 74 ns TIS. Figure 2 shows the pulse waveform. The specifications of the test sample are given in Table 3. Further details regarding the experimental setup (microscopic images) are described elsewhere [6].

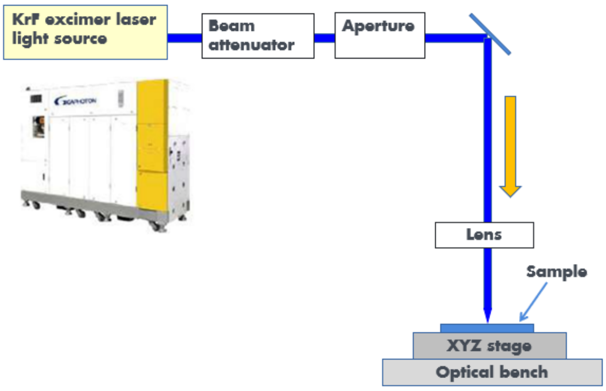

Fig. 1 Schematic diagram of laser processing setup.

Table 1 Main output parameters for Gigaphoton GT600K excimer laser light source.

Laser output parameter	Value
Wavelength [nm]	248
Pulse energy [mJ/pulse]	100
Repetition rate [Hz]	10-6000
Output laser power [W]	600
Pulse width TIS [ns]	74

Table 2 Experimental parameters.

Experimental parameter	Value
Aperture diameter [mm]	0.5 (round shape)
Focal length of lens [mm]	54 (at 248 nm wavelength)
Sample position	The sample surface plane is conjugated with the aperture plane.
Distance between aperture and lens [mm]	1700

Table 3 Specifications of test sample

Sample parameter	Specification
Material	Non-alkali glass
Type	Eagle XG
Thickness [µm]	500
Manufacturer	Corning

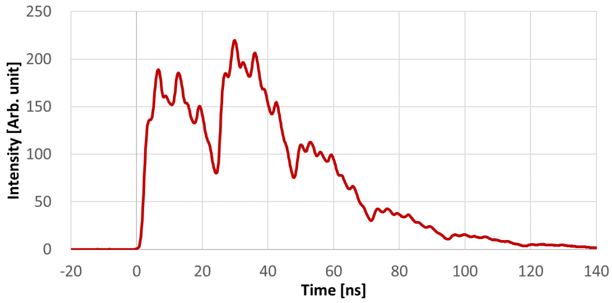

Fig. 2 Excimer laser pulse waveform(pulse width 74 ns TIS)

4. Experimental results

The surface of the glass was next irradiated with 1, 3, 5, and 10 excimer laser pulses to investigate the processing mechanism, and the surface was observed using scanning electron microscopy (SEM). Figure 3 shows SEM images of the surface irradiated with 3, 5, and 10 pulses. Figure 4 shows cross-sectional SEM images (obtained by cutting the glass) for samples irradiated with 1, 3, 5, and 10 pulses. Figure 5 shows a magnified image of Figure 4(d) for 10 laser pulses. Figure 6 shows a magnified image of Figure 3(c) for 10 laser pulses, and Figure 7 shows a higher-magnification image of Figure 6.

Figure 7 shows that the 10-pulse irradiated surface has a microstructure composed of submicron particles. In addition, in Figures 4(c) and 4(d), respectively, it can be seen the surfaces are similar following 5 and 10 laser pulses. Therefore, the microstructure is considered to be generated within the first 5 pulses.

Figures 4(a) and 4(b) show that the ablation depth is very small (less than 1 µm) following 1 to 3 pulses. In contrast, the ablation depth following 5 pulses is almost 10 µm in Figure 4(c). This is thought to be due to the formation of surface microstructure during the first 3 or 4 pulses; for 5 pulses or higher, this microstructure then leads to enhanced absorption of laser energy, causing rapid ablation.

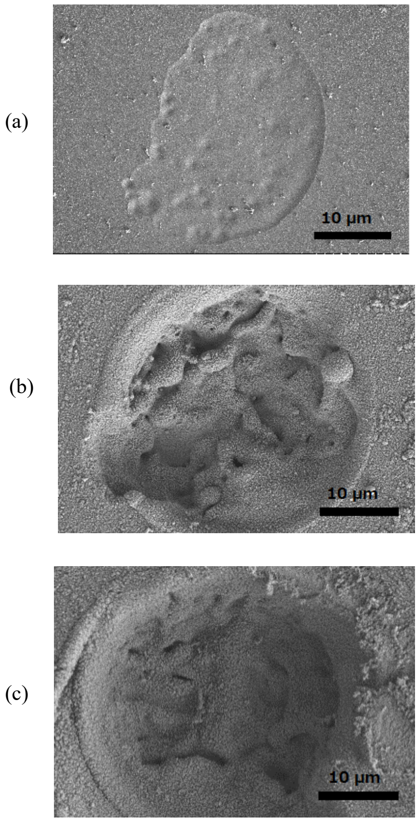

Fig. 3 SEM images of glass surface irradiated with (a) 3, (b) 5, and (c) 10 laser pulses.

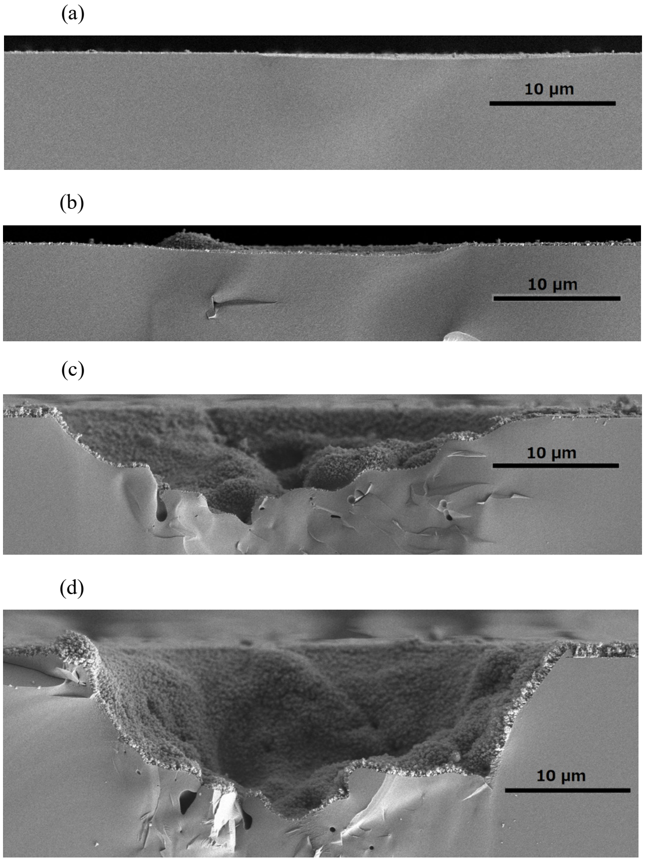

Fig. 4 Cross-sectional SEM images of glass after irradiation with (a) 1, (b) 3, (c) 5, and (d) 10 laser pulses.

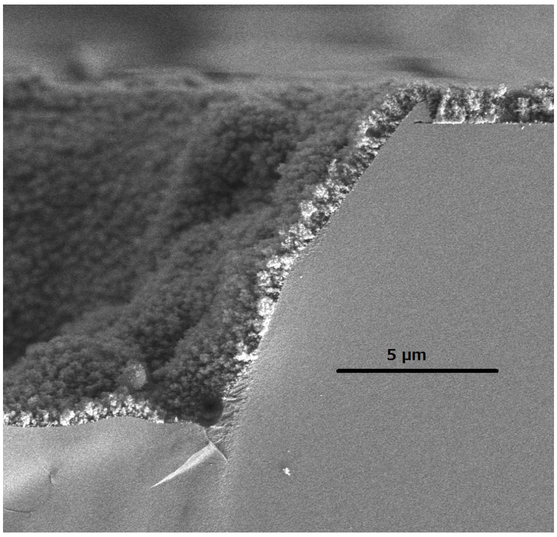

Fig. 5 Magnified cross-sectional SEM image of glass microstructure after irradiation with 10 laser pulses.

Figure 8 shows a side-view optical micrograph of tip formation in a via with the surface microstructure evident. When producing via holes, such tip formation may enable high-aspect-ratio micro-via processing.

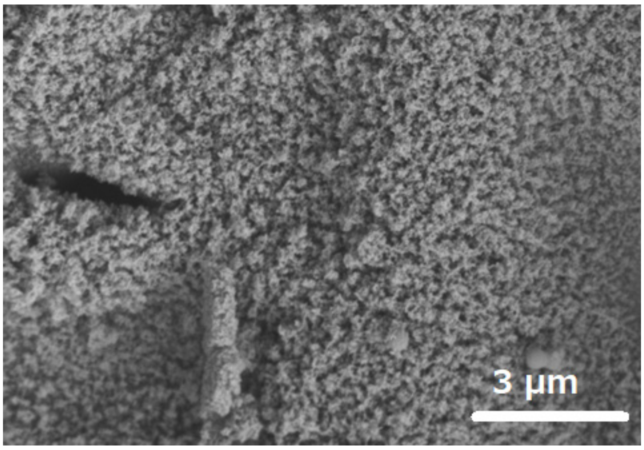

Fig. 6 Magnification of SEM image in Figure 3(c) for 10 laser pulses.

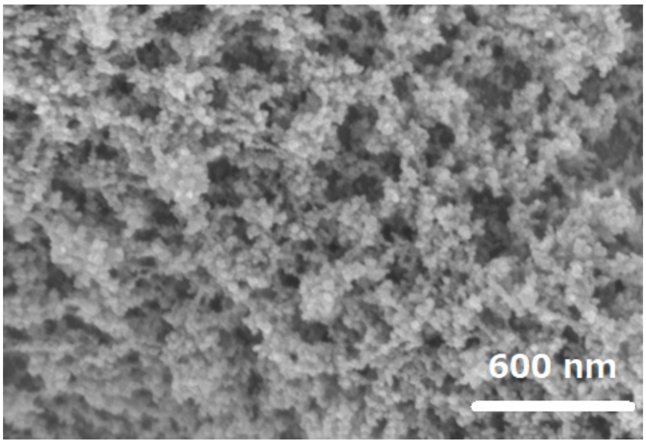

Fig. 7 Magnification of SEM image in Figure 6 for 10 laser pulses.

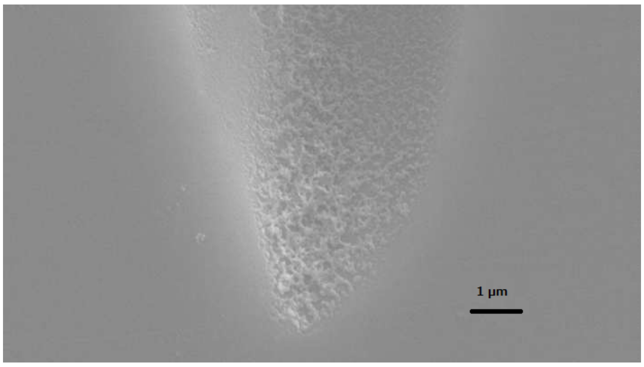

Fig. 8 Side-view optical micrograph image of via tip.

Energy dispersive X-ray spectroscopy (EDX) analysis was conducted to investigate the cause of the microstructure. Figure 9 shows the EDX analysis points for the SEM image shown in Figure 6. Three different areas containing microstructure were analyzed. Figure 10 shows the EDX analysis results for the microstructure and the bulk glass. Areas containing the microstructure exhibit a higher oxygen content and a lower content of Si and other elements than the bulk glass.

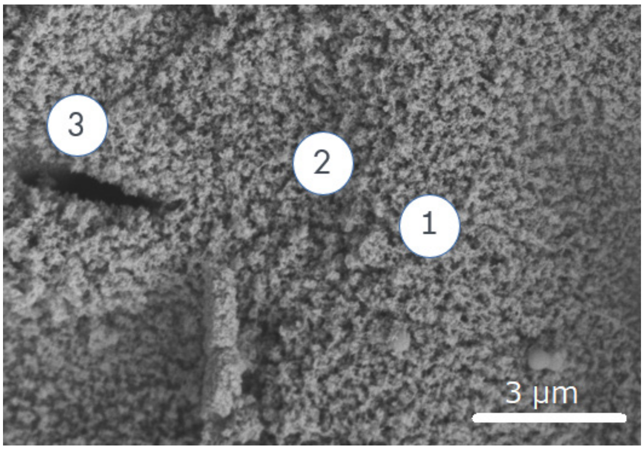

Fig. 9 EDX analysis points for microstructure in Figure 6.

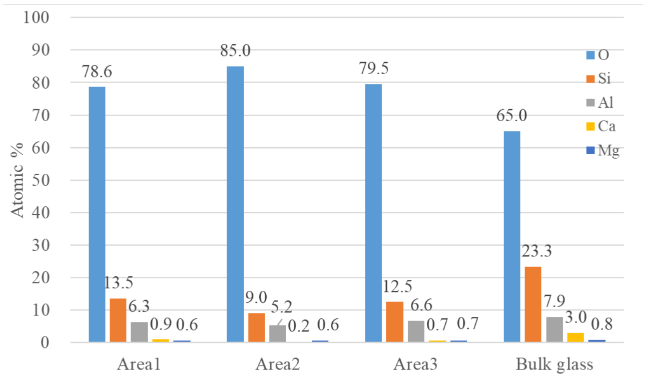

Fig. 10 EDX analysis results for microstructure in Areas 1 to 3, and for bulk glass.

These results indicate that the microstructure is produced by oxidation of the glass. Since the bulk glass is amorphous, it is thought to contain Si-O and Si-O_2 components, and the Si-O component is oxidized to form SiO_2. Even if all silicon atoms are oxidized to SiO2 and all aluminum atoms are oxidized to Al2O3, excess oxygen remains. This may be a unique oxidation process that does not normally occurs oxidation process. Further research should be needed to investigate the process.

5. Discussion

The results of this study indicate that the amount of laser light absorption on the surface is enhanced by the microstructure of the glass surface likely due to multiple scattering within the microstructure.

Figure 11 shows a conceptual diagram of the processing mechanism. Microstructure is generated on the glass surface by irradiation with an excimer laser (Phase 1: 1 to 3 pulses). Ablation then proceeds as the microstructure absorbs energy (Phase 2: 4 to Rayleigh length depth ablation). High-aspect-ratio vias are produced due to internal reflection of the laser light (Phase 3: Rayleigh length depth ablation to penetration depth), and the laser finally fully penetrates the glass plate (Phase 4: penetration depth).

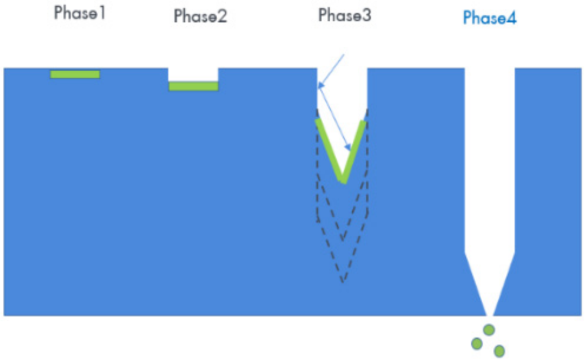

Fig. 11 Conceptual diagram of excimer laser micro-via ablation process for glass.

6. Summary

We investigated the mechanism by which ablation occurs at the surface of non-alkali glass under 248 nm excimer laser irradiation, in spite of the small amount of absorption(0.4%) in the surface region. We found that a microstructure is initially generated on the glass surface during irradiation. This increases the amount of laser energy absorbed, likely due to multiple reflections, and leads to rapid ablation. It was found that the microstructure is composed of oxidized submicron particles.

7. Acknowledgement

This paper is based on results obtained from "Research and Development Project of the Enhanced Infrastructures for Post-5G Information and Communication Systems" (JPNP20017), subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

References

[1] A. Usman, E. Shah, N. B. Satishprasad, J. Chen, S. A. Bohlemann, S. H. Shami, A. A. Eftekhar, and A. Adibi: IEEE Trans. Compon. Packaging Manuf. Technol., 7, (2017) 819.
[2] J. Ihlemann and B. Wolff-Rottke: Appl. Surf. Sci., 106, (1996) 282
[3] R. Karstens, A. Gödecke, A. Prießner, and J. Ihlemann: Opt. Laser Technol., 83, (2016) 16
[4] J. Ihlemann, B. Wolff and P. Simon, Appl. Phys. A, 54, (1992) 263
[5] CORNING Incorporated, Eagle XG AMLCD Glass substrates material information MIE301 2006
[6] Y. Kawasuji, Y. Adachi, K. Moro, K. Kakizaki, and M. Washio: J. of Laser Micro/Nanoenginnering, Vol.17, No.3 133

(Received: March 16, 2023, Accepted: July 25, 2023)