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Advances in CO₂-Laser Drilling of Glass Substrates

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Abstract

The CO₂-laser drilling in Schott D263Teco thin glass having a thickness of 500 μm is intensively studied. The nearly cylindrical holes having diameters smaller 100 μm could be drilled in 0.25 seconds per hole. Reliability investigations by performing temperature cycling show cracks in 51% of the drilled holes in the glass substrate. The reason is thermally induced stress during thermal CO₂-laser ablation. Different thermal pre- and post-treatments have been successfully studied avoiding such cracks (98.4% crack-free holes) and show the high potential of CO₂-laser drilling for through glass via (TGV) processing in glass substrates for micro-system applications.

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1. Introduction

Currently, decreasing pitch size of conductor traces, small scale through-vias and high alignment accuracy are the key requirements for high-density integrated packages. The integration potential of organic laminates (e.g. FR4) is limited because of dimensional instability under thermal load. The alignment of interconnects between different layers is challenging where oversized patterns have to compensate the process tolerances. As a result the pitch size for devices assembled on FR4 is limited. Alternatively, the 3D-System-in-Package (SiP) based on silicon interposer platform is a very active area of ongoing research [1]. Due to the availability of wafer level processing, silicon substrates can be processed with the same pitch size and accuracy as the highly integrated circuit (IC) components that will be assembled. Furthermore, the CTE matches perfectly if the substrate and IC’s are made of the same

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material. The resulting stress on the solder join is reduced. However, a drawback is the semiconductor property of silicon which requires conductive through-vias and wiring to be isolated from the semiconductor bulk material. For optical applications the silicon substrates are only transparent for wavelengths larger 1107 nm, limiting the applicability for the visible wavelength range.

A glass based packaging technology overcomes the limitations mentioned above. The benefits of glass are the excellent optical properties and it is well known for its high potential in the field of integrated optics. Beyond that, glass has dimensional stability under thermal load, alignment benefits as a result of transparency, compatibility to wafer level processing, coefficient of thermal expansion (CTE) matching to silicon and good dielectric properties. Thin glass in wafer form is available at a minimum thickness of 30 μm. Wafer level processes can be adapted from CMOS processing while new processes for through glass vias (TGV) have to be explored in more detail. The high potential of the glass based packaging was already demonstrated for high-speed data transmission applications. A thin film glass interposer based on TGV’s was fabricated as shown in Fig. 1 [2]. Surface mounted devices (SMD) like an array of four vertical cavity surface emitting lasers (VCSEL), an array of four photodiodes (PD), a transimpedance amplifier (TIA) and a laser driver IC are flip-chip mounted on top side of the interposer. The interposer itself is mounted on a printed circuit board (PCB) as demonstrated in Fig. 2. The optical signal is transmitted through the transparent substrate of the interposer and optically coupled over an integrated mirror and a waveguide array in a second optical glass layer underneath the interposer to the MT-connector interface for fibre cable coupling. The demonstrated transceiver module has four bidirectional channels, each having a data rate of 10 Gbit/s [3].

An immense amount of different glass brands are offered by the glass industry today. The right selection of glass for applications in a given electronic or optoelectronic field depends on the glass properties and the suitable process routines. The available format and thickness play a significant role for decision-making so that standard process routines (e.g. CMOS) can be adopted by just changing the substrate from silicon to glass for selected applications. A selection of brands offered by Schott AG, a world leading glass company, suitable for wafer level packaging, are introduced in Table 1.
Beside commercial available TGV wafers [2], TGVs can be produced using drilling technologies like ultra-sonic drilling, sand blasting, wet etching, dry etching or laser drilling in combination with filling the holes with conductive materials. Limitations are long structuring times or holes with large diameters (>100 μm) in glasses having a thickness of 500 μm.

Laser drilling has the potential to overcome all these limitations. Especially the CO₂-laser is well known in the industry as laser for metal machining. Because of its wavelength and relatively long pulses the drilling is based on thermal ablation. Consequently the laser has a thermal impact on the glass that generates mechanical stress in the drilling zone which can result in crack formation during the cooling or any time later. As result the reliability of CO₂-laser drilled glass substrates can be reduced. In this paper we have explored very fast CO₂-laser drilling of holes having a diameter smaller 100 μm in combination with different thermal pre- and post-treatments for reducing mechanical stress and increasing reliability.

2. CO₂-laser drilling of glass

The laboratory setup for the laser based micro-machining consists of a pulsed CO₂-laser source, beam guiding and forming optics, especially a movable focusing lens, and a motorized x-y-table with a wafer chuck. As a matter of principle there are a lot of variables influencing the machining result. The most important parameters are the laser power or power density respectively, the pulse width and frequency as well as the focus position. By an appropriate setting of these parameters almost cylindrical holes (low conicity) with a diameter smaller 100 μm were realised in 500 μm Schott D263Teco thin glass (Fig. 3). The processing time of such a hole is only 0.25 seconds. The fast drilling speed, unrivalled compared to other lasers (like short-pulse or excimer lasers), and much lower equipment costs make the CO₂-laser very suitable for economic industrial micro-machining of glass substrates. In addition the resulting surface is, caused by the melting phase, very smooth and the diameter and conicity of the hole can be adjusted by parameter variation. Due to the thermal ablation process the development of thermally induced stresses cannot be avoided, but with the found parameters the stress could be reduced on such a level, that drilling of an array having a pitch of 400 μm was possible as shown in Fig. 4.

### Table 1. Glass brands from Schott AG suitable for wafer level packaging [4]

| Brand       | Lithosil | B33     | B270     | D 263Teco | AF32eco | MemPax   |
|-------------|----------|---------|----------|-----------|---------|----------|
| Type        | fused-silica | boro-silicate | crone glass | boro-silicate | al-boro-silicate | boro-silicate |
| Process     | micro-float | micro-float | up-draw | down-draw | down-draw | down-draw |
| Process thickness | 700 μm | 700 μm | 800 μm | 30 μm | 100 μm | 100 μm |
| Format      | panel/wafer | panel/wafer | panel/wafer | panel/wafer | panel/wafer | wafer |
| Alkaline content | alkali-free | 4 wt% | 17 wt% | 13 wt% | alkali-free | 4 wt% |
| CTE         | 0.5 ppm | 3.3 ppm | 9.4 ppm | 7.2 ppm | 3.2 ppm | 3.3 ppm |
| tanδ (1 MHz) | 14·10⁻⁴ | 37·10⁻⁴ | n.a. | 61·10⁻⁴ | 28·10⁻⁴ | 37·10⁻⁴ |
| ε, (1 MHz)  | 3.8 | 4.6 | 7.0 | 6.7 | 5.1 | 4.6 |
For evaluating the reliability of such an array a temperature cycling, which simulates the aging of the substrate, were performed. Therefore the temperature was alternated from -55°C to 125°C for 500 cycles. After the cycling 51% of the holes in the glass substrate showed cracks or damages as result of stress relaxation. Such a cracked glass substrate is unsuitable for further processing. In order to evaluate the thermally induced stresses quantitatively, a photoelastically analysis based on the Sénarmont method was used for measuring the optical path difference at different spots on the glass sample [6]. An Olympus BX-51 microscope with Sénarmont compensator was applied for analysing drilled holes as shown in Fig. 5.

So far laser drilling was performed without pre- or post-heating of the glass substrate. If the substrate is heated during processing the thermally induced stress can be decreased by reducing the temperature gradient in the glass. On the one hand pre-heating of the entire substrate during drilling or on the other hand a local pre-heating of the drilling spot/area are proposed for decreasing the temperature gradient as illustrated in Fig. 6. Also a thermal post-treatment of the structured glass is recommended for eliminating or reducing all the thermally induced stress on a proper level. We utilized these three different process methods:

a) **Heating the substrate during laser drilling**: The entire substrate gets heated up to a defined temperature. Experiments with temperatures between 100-400°C were performed. The drilled holes are still surrounded by low stresses. Drilling speed remains short (0.25 seconds per hole).
b) **Local pre-heating of the drilling spot**: The unfocused laser beam is used for local pre-heating of the glass substrate around the drilling spot before the laser beam is focused for drilling the hole as shown in Fig. 7. Heating of the entire substrate is avoided that enables larger substrate formats and much higher process accuracy because of a stable process environment. None of the drilled holes cracks directly after processing, but still high stress is induced. Drilling speed increases up to 14 seconds per hole because of the pre-heating and lens movement.

c) **Thermal post-treatment of the drilled substrate**: The entire substrate was placed into an oven for thermal relaxation of the induced stress. Experiments with different treatments using peak temperatures between 300°C and 557°C (annealing point of Schott D263Teco) and peak times between 30 minutes and 24 hours were performed. For instance, curing at a temperature of 529°C for 30 minutes removes the stress completely.

3. **Drilling results**

The results of comprehensive laser drilling experiments on glass samples having dimensions of about 20 x 20 mm² showed that standard drilling without any further treatment was possible for arrays having a pitch of at least 400 μm. But without thermal treatment during or after laser drilling, 51% of the hole arrays, with a pitch of at least 400 μm, showed cracks after temperature cycling (T=-55°C to 125°C for 500 cycles). In case of laser drilling of hole arrays with smaller pitches, the stresses around the hole superimpose and cracks appear immediately. According to that a crack free hole array was not producible. Applying the above introduced process methods the percentage of crack free holes could be increased as summarized in Fig. 8. Local pre-heated holes were more stable. Only 13% of the pre-heated holes had cracks after the temperature cycling. By pre-heating the glass it was now possible to drill arrays with smaller pitches than 400 μm. A thermal post-treatment is essential to remove all remaining stresses in case the entire substrate was not heated during drilling. For up-scaling the process to 4-inch wafer level size we used the combination of local pre-heating and thermal post-treatment to drill 574 holes in a Schott D263Teco wafer having a thickness of 500 μm (Fig. 9). The holes were arranged as 15 x 15 array having 1 mm pitch and a 15 x 15 array with 0.2 mm pitch.

![Fig. 8. Statistic of different process methods after temperature cycling (T=-55°C to 125°C for 500 cycles)](image1)

![Fig. 9. 4-inch wafer with 574 holes arranged as two arrays having pitches of 0.2 mm and 1 mm](image2)
Afterwards a thermal post-treatment of the entire substrate in a batch process ensures a crack free, drilled substrate, without remaining induced stress, and a long-lasting stability.

4. Drilling process development for glass wafers

The experimental work showed different results for drilling hole arrays with varying pitches. Therefore a process flow was created (Fig. 10), which summarizes a recipe for CO$_2$-laser drilling of arrays. For structuring an array of holes having pitches smaller 400 $\mu$m, we propose heating the substrate during laser drilling or local pre-heating of the drilling spot. Heating the entire substrate during laser drilling is recommended but could not be applied in our practical work, focusing on drilling glass substrates on wafer size, because of thermal isolation issues between chuck and optical bench. For arrays with larger pitches drilling without pre-heating is still recommendable, because of the enormous time saving. At the end we add a thermal post-treatment of the drilled substrate using a temperature of 529°C for 30min to diminish the entire thermally induced stress.

![Fig. 10. Process flow for CO$_2$-laser array drilling based on the related experimental results, especially regarding drilling time and reliability.](image)

For evaluating the practicability of CO$_2$-laser drilling of glass wafers we performed an application oriented drilling task. Therefore a layout was designed for a 4-inch wafer which consists of 52 thin glass interposers or glass chips as shown in Fig. 11.
Fig. 11. Layout of the glass wafer with 52 interposers/chips for the practical test series

Every chip involves 16 thermal TGV’s with small pitch in the center of the chip, which were made of local pre-heated holes, and 120 electrical TGV’s with a larger pitch at the edge of the chip, which were drilled without any pre-heating (Fig. 12). Subsequently the wafer saw a thermal post-treatment to diminish the entire thermal stress. In Fig. 13 the evaluation result of one test wafer is summarized. 67% of the glass chips were without any failures and are marked green. Besides the number of holes having micro-cracks, and where they were located on the wafer, is shown. The overall number of cracks is dominated by fine pitch hole array cracks, where in four cases all thermal TGV’s cracked. If the hole arrays have a pitch smaller 400 μm, one crack influences and reaches neighbouring holes and finally the whole fine pitch array is destroyed. In contrast only 3 of 120 electrical TGV’s were cracked.

Fig. 12. 4-inch wafer with 574 holes arranged as two arrays having pitches of 0.2 mm and 1 mm

Fig. 13. Evaluation of the first of three processed wafers

Considering the results of two more test wafers that have been evaluated, the average percentage of crack-free glass chips is 62.2%. The average percentage of crack-free holes is 98.4%.
5. Summary

The presented work was focused on drilling holes in glass wafers for optoelectronic packaging applications. CO₂-laser drilling technology was selected because of the high drilling speed and low equipment costs for drilling of micro-holes having a diameter smaller than 100 μm. The technology was successfully developed and applied for drilling arrays of holes in 500 μm thick Schott D263Teco glass wafers. The drawback of the thermally induced stresses, that reduce the reliability of such structured glasses, was analysed in detail and overcome by applying thermal pre- and post-treatments. Finally a process flow for laser drilling of glass was developed, with 98.4% crack-free holes. Further work focuses on machine integration of applied technology as well as fully crack-free drilling.

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