Fabrication of Panel-Level Glass Substrates with Complete Design Freedom using LIDE

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Abstract

In this work, we present examples of highly reproducible, accurate and extremely cost-effective wafer- and panel-level fabrication of glass interposers, free of any process-dependent design limitations where any distribution and density of Through-Glass Vias (TGV) with any cross-section geometries and aspect-ratios, is possible.

Glass has recently garnered significant interest for its many applications in the semiconductor packaging industry, particularly as a core substrate material for interposer applications. Glass has a unique set of material properties with great relevance for this industry, such as very high electrical resistivity, low loss tangent and low dielectric constant. Glass also exhibits low warpage due to its relatively low Young's Modulus while still being compatible with Silicon in terms of CTE and, when processed using a technology that doesn't induce the generation of any defects such as microcracks or thermally-induced stress, it is highly reliable during processing and operation. Laser Induced Deep Etching (LIDE®) technology is a 2.5D glass processing technology with complete design freedom purposedly developed for cost-effective, high-volume fabrication of defect-free glass components.

Despite its many advantages as an interposer material in relation to Si, its application has been hindered by the lack of reliable, precise, and cost-effective processing technologies. LIDE® consists of a two-step process: i) a very fast maskless and direct-write laser process induces subtle and very localized modification in the glass substrate, requiring a single laser pulse to modify the whole glass thickness; and ii) a wet-etching process done in batch, where the whole glass substrate is subjected to the action of an etchant and where the removal of glass occurs at an accelerated rate in the laser-modified regions. This process flow allows LIDE to fabricate several thousands of TGV per second, completely free of any defects, with a sub-micron point-to-point accuracy and ± 5 µm accuracy (cumulative) across a 510 mm x 515 mm glass panel (Cp > 1.33), in any glass type, with aspect-ratios from 1:10 to 1:50 (diameter:depth).

Key words

Glass, Interposer, Panel-Level, TGV, Through Glass Via, Wafer-Level

I. Introduction

The excellent material properties of glass have recently been the focus of great interest for various applications in the semiconductor packaging industry, particularly in its use as a core material for embedding structures and as interposer [1]–[4]. Due to recent advancements in microprocessing technologies for glass, it's no longer seen as a low quality, passive material with limited application in the semiconductor industry. Glass contains a unique blend of exceptionally interesting material properties that cannot be found in any other material category, while also being a relatively low-cost base material: it's a natural insulator and exhibits low loss tangent and dielectric constant. Besides its electrical properties, other characteristics particularly relevant to high performance interposer applications are its high mechanical reliability when processed without any defects, dimensional stability particularly at high temperature, low warpage, high chemical stability, and the possibility to tune its CTE [1], [5].

The characteristics of glass and its potential use in a broad range of applications with potential advantages of the legacy materials is well known [6], nevertheless, its widespread application of has been hampered by the lack of suitable processing technologies[7]. Several new methods to microprocess glass have been developed [8]–[12] to address this and realize the true potential of glass as an active material in the electronics industry, with a focus on the formation of through-holes for through-glass vias (TGV), however, most come with either technical drawbacks and/or are not cost-competitive, falling short of their goal.

Here, we demonstrate that due to the unique capabilities of Laser-Induced Deep Etching (LIDE), the potential of glass as an alternative to legacy materials such as silicon or organics, for interposer applications, can be realized. The unique properties of glass can now be brought to fore in a cost-effective manner, opening doors to new significant developments in the electronics industry such as the high-volume panel-level fabrication of glass interposers for high performance computing applications.

II. Glass in Electronics Applications

A. *The properties of glass*

Traditionally, glass is defined as an amorphous solid in which silica (SiO_2) is the fundamental constituent. Regardless of its composition, glass is known for exhibiting a high optical transparency, very high electrical resistivity, high temperature and chemical stability, and advantageous mechanical properties such as low Young's modulus and the absence of plastic deformation. This last point is often overlooked because glass is – rightly – assumed to be a brittle and fragile material: when elastically deformed beyond its failure strength, it suffers a fragile fracture initiated on one or more defects present within it, such as microcracks. It follows, therefore, that if the presence of defects could be significantly reduced, the failure strength would increase. This is demonstrated in Fig. which shows the relationship between the defect or flaw size and the failure strength (or break strength), establishing a relationship between the dimensions of these flaws and the process that originated them. Flaws or defects generated during the microprocessing of glass for the formation of TGV, for example, will significantly reduce its failure strength. If these could be eliminated completely, as is the theoretical failure strength of glass would be higher than 1,000 MPa. The mechanical characteristics of glass are commonly overlooked due to the assumption that its low mechanical reliability is inherent or, when actually understood to be mostly derived from its processing technology, it's thought to be unavoidable. Changing this now wrong perception is key to enable the widespread use of an incredible material that could lead to significant technological developments.

Material properties such as high electrical resistivity, low loss tangent and low dielectric constant, and tunable coefficient of thermal expansion, CTE, (Fig. 1) open the doors to high density interposers for high performance computing[13]–[15], very high frequency RF applications [7], and others [15]–[17].

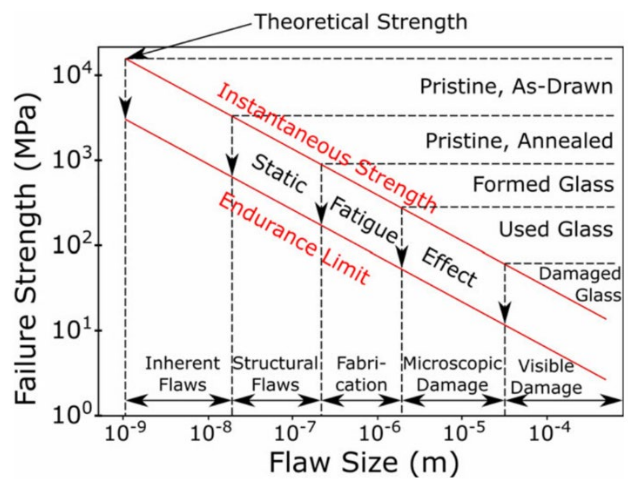

Fig. 1 Fracture strength of glass substrates, as function of the dimension of the defect/flaw [18].

While glass consists mostly of silica, by changing its composition it's possible to slightly change most of its properties and access a wide variation in each, essentially enabling the tuning of the properties of glass. The most commonly used glass types can be divided into three main categories, also shown in Table I: i) fused silica – pure, amorphous silica with extremely low CTE, extremely high electrical resistance, and very low Dk and Df, ideal for very high frequency RF applications; ii) "alkali-free" aluminoborosilicates – low alkali content and high transformation temperature glass, available in a very wide range of CTE, ideal for display-related processes and applications; iii) alkali-rich borosilicates – the high alkali content allows its use in anodic bonding together with a CTE matching that of Si.

Table I. Material properties of the main categories of glass, and silicon.

	Fused Silica	Alkali-free Glass	Alkali-rich Glass	Silicon
CTE (10^{-6}/K)	0.5	3.2 – 8.7	3.3 – 7.2	3.3
E (GPa)	72	74	64	160
ρ (Ω·m)	10^{16}	10^{12}	10^{8}	10^{-2}
Dk	3.8	7.3	5.9	12
Df	< 0.0004	172	30	150

B. Glass microprocessing technologies

Glass can be microprocessed with various technologies, from mechanical abrasive processes such as CNC milling, typically used to form display glass for handheld electronic devices, to masked wet-etching techniques to generate low aspect-ratio surface features, to the use of sequences of high energy density laser pulses to progressively ablate glass and form a through-hole, for example. Invariably, these technologies come with significant drawbacks responsible for the low uptake of glass as a core active material in the electronics industry: i) limited processing capabilities (low aspect-ratio features, narrow feature geometry and dimension range, limited material selection), ii) generation of defects in the glass (microcracks due to abrasion or high energy involved in the ablation process) and, iii) high added technological cost, turning a relatively low-cost material into a premium one in terms of cost but without premium quality or characteristics. Hybrid processes such as laser assisted wet-etching have been developed as alternative technologies to generate TGV with lower rates of defects such as microcracks, while promising higher accuracy and higher processing speed/lower processing cost. Laser Induced Deep Etching, or LIDE, is one of such hybrid processes. However, LIDE stands out in many ways: it uses a direct-write laser process, without masking or lithography, to modify the glass without any restrictions in terms of geometry. Since it doesn't ablate the glass, only one laser-pulse per modification is required to affect the whole thickness of the glass substrate (Fig. 2). Several thousands of modifications per second can be generated with very high precision, which will be turned into TGV during the following wet-etching step. This very high throughput and precision allows the fabrication of highly dense arrays of TGV throughout the whole glass substrate, generating several millions of TGV per wafer or panel (Fig. 3). In this second process step, the already laser-modified glass substrates are exposed to the action of a wet-etchant which will preferentially remove the laser-modified regions [19], [20]. The resulting glass substrates will be completely defect-free and with very high overall quality and because both process steps are extremely economical, LIDE-processed glass is highly cost-effective and compatible for use in high-volume applications such as interposers, as a core material in various types of semiconductor packaging.

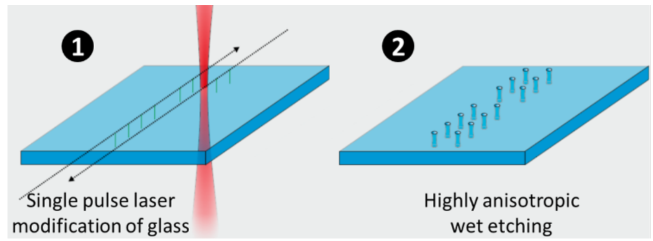

Fig. 2 LIDE two-step process: 1) single pulse laser modification of the whole glass thickness, followed by 2) unmasked batch wet-etching with highly anisotropic wet etching of the laser-patterned regions to form the TGV.

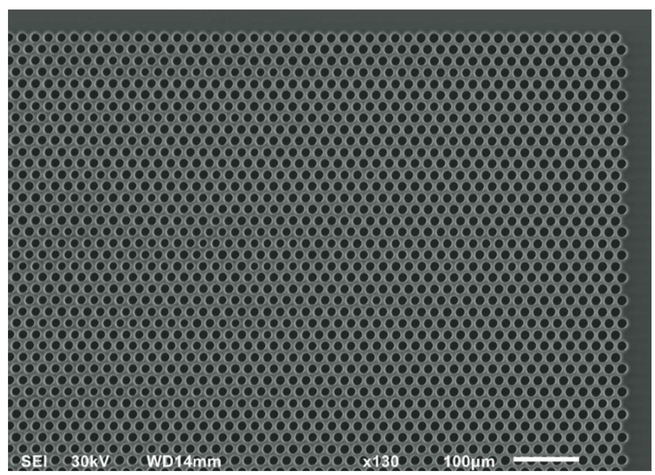

Fig. 3 Top-view SEM micrograph of a highly dense array of TGV, with TGV diameter of 20 µm and center-to-center pitch of 25 µm (gap between TGV edges of 5 µm).

C. Unlocking the potential of glass

The properties of glass have been of great interest for very long time, however, it's a complex material to process. Besides the negative impact most technologies have on its properties and reliability, the main hindrance to its widespread utilization has been, arguably, its cost. In order to enable glass as a truly viable material in the semiconductor industry, four main aspects need to be addressed [6]: i) panel-level fabrication – the industry's trend from wafers to panels is clear, making the panel-level processing of glass an essential aspect of any glass technology; ii) low-cost base material – while still significantly cheaper than Si, technical glass is still produced in relatively low quantities but the advances in its processing and consequently higher adoption make it an ever more attractive material; iii) low-cost glass microprocessing – until recently, even simple features such as TGV arrays came with a high technological cost and low yield due to defect; iv) low-cost post-processing – due to the low adoption of glass, the ecosystem around its post-processing is not yet well developed, and the number of industry players capable of performing metallization in high aspect-ratio TGV, RDL deposition, bumping, etc., is very small. Currently, only the last point is still in an early stage, but there are notable early adopters of glass and LIDE or other glass microprocessing technologies, that are providing the necessary momentum to eventually reach a sufficiently mature stage.

Besides the economics of glass in the semiconductor industry, seamless integration into the semiconductor manufacturing process for current potential applications, particularly when aiming at substituting standardized materials in well-established applications, such as Si and organics in interposers. Simple one-to-one substitutions of the materials by glass are normally possible and with significant advantages in terms of properties/performance but also cost. However, only by adding several different features and capabilities to the same substrate can the implementation of glass become inevitable. Providing a wide range of TGV diameters and controlling their cross-section geometry is essential for the use of TGV in different applications but also to simplify its post-processing by adapting to the needs of the metallization technologies, for example, leveraging already well-established processes and removing further friction to the use of glass. Having a glass microprocessing technology capable of not only fabricating through- and blind holes, but also features such as open and closed cavities, trenches, cut-outs, and features to simplify die singulation further down the process flow, such as deep trenches for saw dicing or Dicing Before Grinding (DBG), increases the value proposition of glass and enhances the value proposition for the use of glass and its processing technologies (Fig. 4).

Therefore, a glass microprocessing technology capable of offering high-throughput, low-cost fabrication of highly dense arrays of TGV of any dimension, aspect-ratio, and taper angle, in a highly accurate and repeatable manner, on large scale wafers and panel formats, would certainly revolutionize the usage of glass in the semiconductor industry. Such a technology would enable glass to substitute Si in applications that would benefit from the unique properties of glass and/or the material and technological cost advantages, and facilitate the development of new applications.

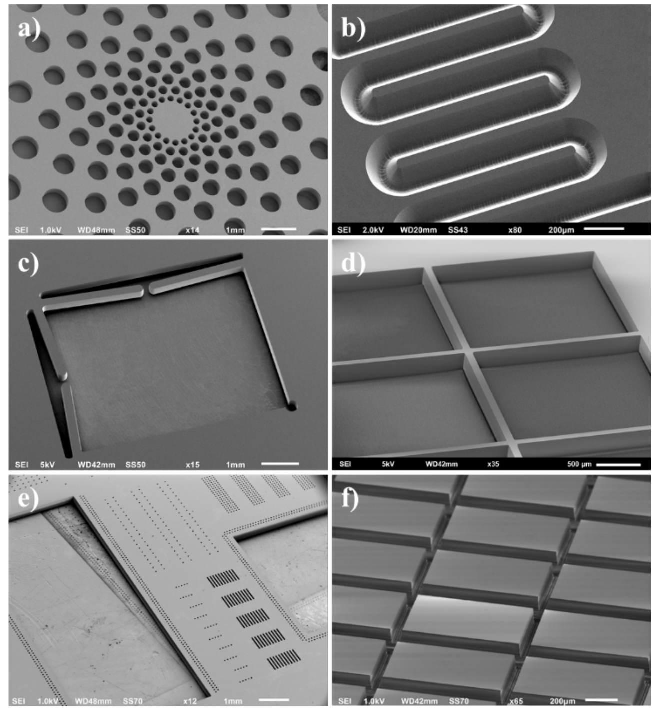

Fig. 4 Various SEM micrographs of examples of microstructures in glass fabricated by LIDE technology: a) arbitrarily shaped through-cuts, b) meandering trenches, c) open cavities with mechanical springs, d) closed cavities with precisely defined edges and depth, e) all of the above, fabricated in the same process step and substrate, f) deep trenches for die singulation by saw dicing or back grinding in a Dicing Before Grinding (DBG) process.

LIDE is a technology that can offer all these capabilities to generate essentially any type of feature in glass, but particularly suited to fabricating TGV. It can create very high dense arrays of TGV without pitch restrictions, on wafers and panels up to 300 mm diameter and 515 mm x 510 mm, respectively – following current and future industry form factor trends. Its ability to generate TGV with positional and dimensional tolerances $< \pm 5$ µm with Cpk > 1.33, with any dimension and aspect-ratio, makes it particularly suitable to make glass the go-to material for specialized interposer applications such as high-performance computing. This is demonstrated in Fig. 5, which shows examples of hourglass-shaped TGV, with different taper angles and aspect-ratios.

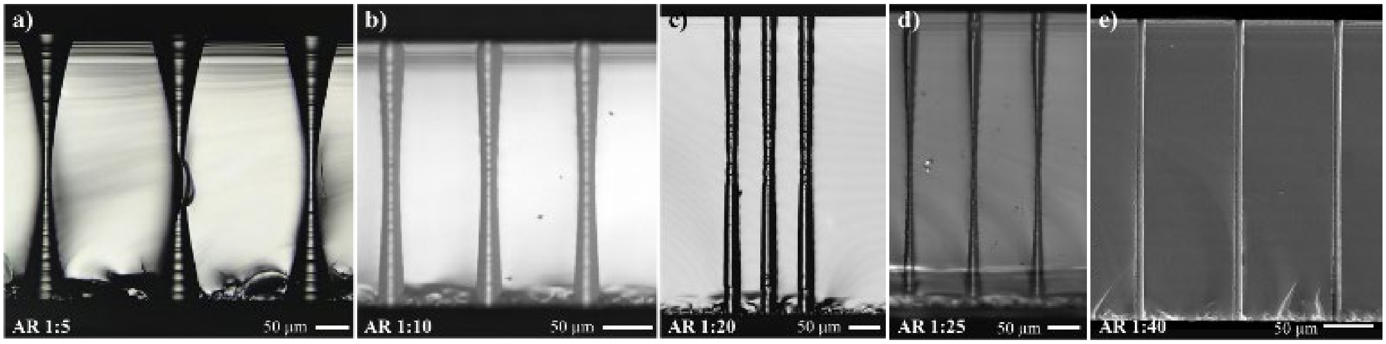

Fig. 5 Laser optical micrographs showing a wide range of TGV cross-section geometries and aspect-ratios (diameter:height), fabricated with LIDE. By controlling the taper angle of the TGV sidewall, essentially any taper angle in any glass type can be obtained, adapting to the metal via filling technology and application. NOTE: the damage shown in the optical micrographs is not caused by the LIDE technology but, instead, by the scribe-and-break process used to expose the cross-section, for characterization.

Due to LIDE's cost effectiveness, glass could start being used not only in niche applications that require the unique properties of glass, but also higher volume/lower-cost interposer applications, since glass is a relatively inexpensive material. A potential temporary obstacle to the rapid implementation of glass in these applications is the lack of well-developed supply chain around glass, particularly its metallization. However, LIDE can generate TGV in hourglass or V-shape, through-glass or blind, and with any taper angle (Fig. 6 and Fig. 7), facilitating the leveraging of legacy post-processing technologies such as for TSV (Through Silicon Vias) in Silicon and reducing further barriers to the widespread use of glass.

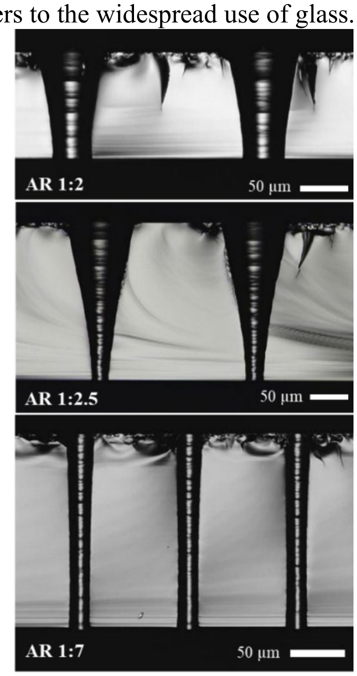

Fig. 6 Laser optical micrographs showing examples of V-shape through glass vias with different sidewall taper angles and aspect-ratios.

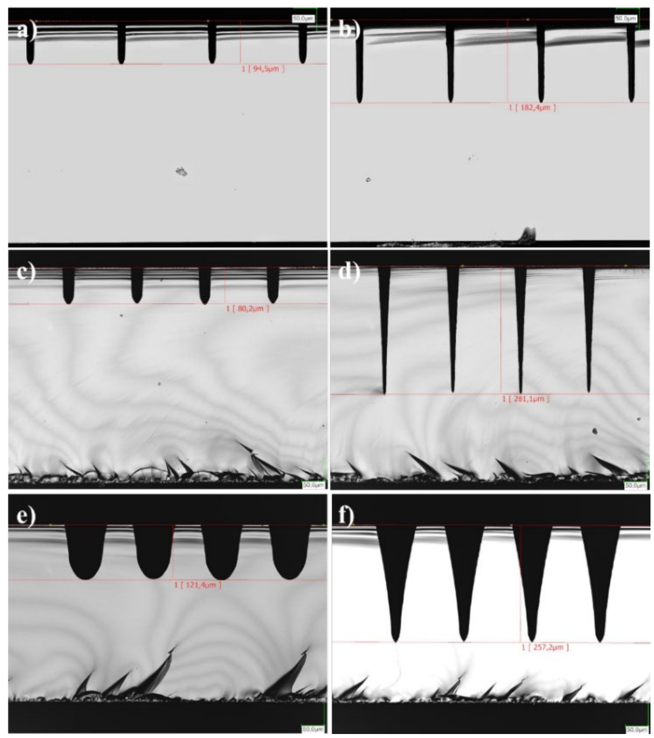

Fig. 7 Laser optical micrographs showing examples of blind vias with different cross-section geometries and taper angles, and different depths. Both these parameters can be controlled when structuring glass with LIDE. NOTE: the damage shown in the optical micrographs is not caused by the LIDE technology but, instead, by the scribe-and-break process used to expose the cross-section, for optical characterization.

Nevertheless, it's essential to drive these capabilities forward in order to take advantage of very high-aspect ratio TGV from 1:10 and up to 1:50 (diameter:height). The current state-of-art capabilities of glass microprocessing are summarized in Table II.

Table II Summary of state-of-art glass microprocessing capabilities (based on the LIDE technology).

Characteristic	State-of-art capabilities
Types of features	TGV, blind vias, open and closed cavities, trenches
TGV minimum diameter	10 µm
TGV maximum diameter	No limitation
Minimum pitch	2 µm (pitch << diameter)
TGV drill rate	Up to 5,000 TGV/s
Positional accuracy	± 5 µm cumulative, Cpk > 1.33
Taper angle	~0° - 10°
Minimum thickness	50 µm
Maximum thickness	1 mm
Wafer-level processing	Yes, up to 300 mm diameter
Panel-level processing	Yes, up to 515 mm x 510 mm
Glass type	All
Burr	None
Microcracks	None
Debris	None
Chipping	None

Conclusion

The niche and low-volume application of glass as a core material in the great majority of high-tech industries, particularly the semiconductor industry, can be explained by the lack of accurate, defect-free, and cost-effective processing technologies. The rare combination of material properties in glass and their variety has always made it the target of great interest for applications that can benefit from its high electrical resistivity, thermomechanical and chemical stability, exceptional RF properties, and others. The semiconductor industry has been the ground for one of the fastest and most extreme evolutions both in terms of technological capabilities but also their high economic efficiency. As such, the already complex development of a glass microprocessing technology capable of breaking into this industry has only been made progressively harder. The Laser Induced Deep Etching (LIDE) technology has made that leap and provided glass with its much-needed enabler, by allowing the defect-free, high throughput and low-cost processing of glass, capable of generating any dimension and geometry of TGV with complete design freedom, in any glass type, and in both wafers and panels.

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